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Introduction

This publication is the Proceedings of the 35th International Symposium on Automation and Robotics in Construction (ISARC). The symposium which had 490 attendees was held in the Maritim proArte and at the Technische Universität in Berlin, Germany during 20-25 July 2018. The Proceedings include an illustrated review of the program (in German language, previously published in BAUINGENIEUR), the names of organizations and persons who contributed to the technical program, and the 174 technical papers from 36 countries authored for this international meeting.

The manuscripts were presented during 29 sessions, among them: safety and health, information modeling, advanced sensing and imaging technologies, automation, robotics, control systems, intelligent computing on data processing, internet of things, 3D printing, emergency response, construction management, infrastructure and tunneling, augmented and virtual reality, data visualization, unmanned aerial vehicles, education, and ergonomics.

Please note: All ISARC proceedings since 1984 are available at no cost at http://www.iaarc.org.

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Dr. Jochen Teizer, Ruhr-Universität Bochum (General Chair, ISARC and Hackathon)

Dr. Markus König, Ruhr-Universität Bochum (Co-Chair, ISARC)

Dr. Timo Hartmann, Technische Universität Berlin (Co-Chair, Hackathon)

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Program Schedule

	Friday July 20	Saturday July 21	Sunday July 22	Monday July 23	Tuesday Jul 24	Wednesday July 25
	Intl. AEC/FM Hackathon					
			ISARC 2018			
						Technical Tour
08:00 a.m.		Hacking & Industry	Hacking & Team Presentations	Keynotes & Academic	Keynotes & Academic	Construction Site Visits
Noon	Opening & Workshops	Presentations	Prizes &	Presentations	Presentations	
06:00 p.m.	Reception & Team Building		ISARC Reception		Awards & Gala Dinner	
10:00 p.m.						

ISARC 2018: Internationale Konferenz und Hackathon zur Automatisierung und Robotik im Bauwesen

J. Teizer

1 Einleitung

Die „International Association for Automation and Robotics in Cosntruction" (kurz IAARC: www.iaarc.org) ist das weltweit führende Netzwerk von anerkannten Fachleuten aus der Wissenschaft und Industrie zur Entwicklung und Anwendung von Automatisierung und Robotik im Bauwesen. Seit 1984 bietet IAARC das jährlich stattfindende „Internationale Symposium on Automation and Robotics in Construction" (ISARC) an. ISARC bietet Führungskräften und Anwendern aus Verbänden, bauausführenden oder beratenden Unternehmungen, Technologie- und Softwarefirmen, Architektur- und Planungsbüros, Hochschulen und Universitäten eine außergewöhnliche Lern- und Austauschmöglichkeit, um Innovation in Prozessen und Technologieanwendungen in allen Projektlebenszyklusphasen voranzutreiben.

Nach 20 Jahren wurde wieder einmal Deutschland mit Berlin als Austragungsort der 35. ISARC-Veranstaltung gewählt. Vom 20. bis 25. Juli 2018 kamen insgesamt 490 internationale Teilnehmer aus 36 Nationen zusammen (**Bild 1**). Darunter befanden sich neben Professoren, Doktoranden und Studenten auch 120 Vertreter aus Politik und Bauwirtschaft. Es wurden aktuelle Forschungsergebnisse und praxisrelevante Innovationen vorgestellt.

Den Auftakt machte ein dreitägiger Hackathon mit mehr als 190 Teilnehmern, die in 27 Teams zusammen mit Industriepartnern Prototypen als digitale Lösungen entwickelten. Die Spannbreite der vorgestellten Themen reichte von der Integration von IoT-Systemen über intelligentes parametrisches Design, Anwendung von Virtual und Augmented Reality bis hin zum 3D-Druck.

Organisiert wurde die Konferenz von Dr. Jochen Teizer und Prof. Dr. Markus König vom Lehrstuhl für Informatik im Bauwesen der Ruhr-Universität Bochum sowie Prof. Dr. Timo Hartmann vom Institut für Systemtechnik der Technischen Universität Berlin. Unter der Schirmherrschaft des Bundesministeriums für Verkehr und digitale Infrastruktur und des Hauptverbands der Deutschen Bauindustrie e. V. unterstützen zahlreiche Sponsoren das Programm der ISARC 2018, darunter die Deutsche Forschungsgemeinschaft (DFG), weitere Bausoftwareunternehmen, Planungsfirmen und Technologie- und Systemintegratoren. Baufirmen ermöglichten als Teil des Rahmenprogramms zwei Baustellenbesichtigungen in Berlin, auf denen aktuellen Trends der Digitalisierung des Bauwesens, unter anderem BIM auf der Baustelle, praxisnah vorgestellt wurden (**Bild 2**).

Im Folgenden werden einzelne Veranstaltungshöhepunkte während der ISARC 2018 im Detail erläutert.

Bild 1. Logo der ISARC 2018.

Bild 2. Baustellenbesichtigung des Axel Springer SE Neubaus

Dr.-Ing. Jochen Teizer
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Bild 3. IAARC Board of Directors mit dem VAE-Minister für Infrastrukturentwicklung und VAE-Botschafter für Deutschland

Bild 4. Intl. AEC/FM Hackathon in der Peter-Behrens-Halle der TU Berlin (Teambasiertes Arbeiten und Präsentationsfläche für Breakout-Sessions der Industrie, im Hintergrund)

2 IAARC

In der Geschichte der IAARC wurden einige wichtige Entwicklungen vorangetrieben, die mittlerweile in der Baupraxis eingesetzt werden. So wurden bereits vor der Jahrtausendwende beispielsweise die Themen Building Information Modeling (BIM), 3D-Druck, Radio Frequency Identification (RFID) für Materialtracking und Robotik als industrielles Bauverfahren maßgeblich von Forschern und Entwicklern der IAARC beeinflusst. Das IAARC Board of Directors (BoD) ist daher für die strategische Ausrichtung der IAARC-Organisation verantwortlich. Ausgewählte internationale Vertreter aus der Wissenschaft, Technologieentwicklung und Baupraxis nehmen daran teil, um unter anderem die strategischen Ziele in der Automation und Robotik des Bauwesens zu definieren und zu koordinieren. Dieses Jahr konnte auch eine Delegation der Vereinigten Arabischen Emirate (VAE) und des Schwedischen Bauverbands begrüßt werden (**Bild 3**).

Dr. Abdullah Bin Mohammed Belhaif Al Nuaimi (Minister für Infrastrukturentwicklung), in Anwesenheit des VAE-Botschafters für Deutschland Ali Abdulla Al Ahmed, erklärte wie wichtig Innovation im Bauwesen sei. Der Minister machte in seiner Eröffnungsrede sowie während verschiedener Diskussionen mit den Teilnehmern sehr deutlich, dass die Automatisierung und insbesondere die Robotik das Arbeiten auf der Baustelle und auch in den Ingenieurbüros in Zukunft grundlegend verändern wird.

Auch der Schwedische Bauverband, vertreten durch Führungspersönlichkeiten mehrerer Bauorganisationen, pflichtete bei, dass Wissenschaftler/innen, Unternehmen und Anwender viel enger miteinander kooperieren müssten, um vorhandene Innovationspotentiale rascher in der Praxis zu implementieren. Nur so bleibe die europäische Bauindustrie wettbewerbsfähig.

3 Intl. AEC/FM Hackathon

Erstmals fand begleitend zur ISARC ein internationaler Hackathon statt. Es kamen 190 Entwickler, Studierende, Nachwuchswissenschaftler und junge Berufstätige aus Start-ups, Universitäten und Bauindustrie zusammen, um gemeinsam Software- und Hardware-Lösungen zu bestehenden Problemen der Bauindustrie zu konzipieren, prototypisch umzusetzen und testweise zu erproben. Das Programm des Hackathons richtete sich vor allem an jüngere Teilnehmer, deren Unternehmergeist geweckt oder gestärkt werden soll. Innerhalb von drei Tagen konnten so innovative Ideen gemeinsam mit Firmen umgesetzt werden und berufliche Perspektiven im Bauwesen eröffnet werden (**Bild 4**).

Bild 5. Präsentationen der 27 Hackathon-Teams vor der internationalen Expertenjury

Bild 6. Ein striktes Zeitlimit (max. 5 min) betont die Problemstellung, den Lösungsansatz, die Ergebnisse und die Wirtschaftlichkeit jedes Hackathon-Themas.

Bild 7. Robotergestütztes 3D-Drucken

Bild 8. 490 internationale Teilnehmer an der ISARC 2018 in Berlin

Nach der Teilnahme an halbtägigen Workshops zu den Themen Building Information Modeling (BIM), Big Data Mining, Remote Sensing, Internet of Things (IoT) und Augmented and Virtual Reality (AR/VR) bildeten sich 27 Teams welche unterstützt durch die Expertise internationaler Mentoren an einzelnen, selbstdefinierten Problemstellungen der Bauindustrie arbeiteten. Innerhalb von zwei Tagen wurden beachtliche Erfolge erzielt und anschließend die herausragenden Teams anhand der Bewertung einer internationalen Jury mit insgesamt sieben Preisen ausgezeichnet (**Bild 5** und **Bild 6**).
Unter den teilnehmenden Teams fanden sich anspruchsvolle Themen in der AR/VR, BIM-basierter Takt- und Steuerungsplanung, Robotik zur Herstellung von Straßenmarkierungen, Verkehrsflusssimulation zur Unfallanalyse, Modularisierung, Arbeits- und Gesundheitsschutz, intelligente Sensoren für Baustoffe und automatisierten Fertigung von Bauteilen (**Bild 7**).

4 ISARC 2018

Das Programm der ISARC 2018 umfasste 168 hochwertige Beiträge aus der Wissenschaft und der Industrie zur Digitalisierung des Bauwesens, unter anderem der Bauplanung, des technologieunterstützten Lean Construction, der sensorbasierten Datenerfassung (z. B. Verortung durch RFID/LoRa, GNSS, Laser Scanning, Drohnen), der computergestützten Datenauswertung (Big Data Mining), der erweiterten und virtuellen Realitäten (AR/VR) in der Aus- und Weiterbildung von Fachkräften bei Wartung, Montage, und Monitoring der Prozessabläufe, der Bauwerkinformationsmodellierung (BIM), der Baumaschinen- und Baugeräteautomation, der Modularisierung und Vorfertigung (u. a. Roboteranwendungen und 3D-Druck als neue Bauverfahren), der Internet der Dinge (IoT) (u. a., Cloud-Entwicklungen und mobile Endgeräte für den Einsatz auf Baustellen), sowie zahlreiche weitere interessante und aktuelle Themenfelder um Bauprojekte zuverlässiger planen, abwickeln und

Bild 9. Keynote von Dr. Ilka May zum Thema Gamification in der Bauindustrie

betreiben zu können (**Bild 8**). Auch das Schaffen nationaler und internationaler BIM-Standards zur digitalen Projektzusammenarbeit unter Verwendung von offen Schnittstellen (z. B. IFC: Industry Foundation Classes – ein offener Standard im Bauwesen zum Datenaustausch von Gebäudemodellen) war ein Thema der ISARC 2018 und dem internationalem AEC/FM Hackathon in Berlin.
Zwei Keynote-Präsentationen, gehalten durch Dr. Ilka May und Prof. Frédéric Bosché, verdeutlichten eindrucksvoll den Einsatz von Technologien der Computerspielentwicklung und der virtuellen Realität in Bauprojekten (**Bild 9**).
Die nächste ISARC 2019 findet vom 21. bis 24.Mai 2019 in Banff, Kanada statt (www.isarc2019.org). Vorrangige Themen der ISARC 2019 werden Modularisierung, Vorfertigung, Automatisierung und Robotik sein.

Unter http://www.iaarc.org/ sind alle ISARC Conference Proceedings seit 1984 abrufbar. Dort sind insgesamt mehr als 6 000 wissenschaftliche Publikationen frei verfügbar.

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Real-time Positioning via LoRa for Construction Site Logistics

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Abstract –

Tracking and monitoring resources in construction is of great interest to an industry that is in the continuous pursuit of reducing waste. Real-time location sensing technology like Global Navigation Satellite Systems (GNSS) and/or in combination with Radio Frequency Identification (RFID) have already been introduced in commercial applications to report the position of valuable construction resources such as equipment or materials. While several other communication protocols exist, unfortunately little is known about the performance and applications of LoRa (Long Range), a wireless data communication technology for very-long-range transmissions up to several kilometers at low power consumption. This paper first introduces the need for such technology and then explains the integration of LoRa in an Internet of Things (IoT) network, which enables to connect, collect, and exchange data for construction applications. The novel focus of this study is the evaluation and testing of LoRa in realistic construction work environments. The experiences made with the developed LoRa-technology are in particular useful for demonstrating the applicability of LoRa in the construction logistics and lean management sectors.

Keywords –

Building Information Model (BIM), construction resources, Global Navigation Satellite System (GNSS), Internet of Things (IoT), logistics, Long Range (LoRa), Radio Frequency Identification (RFID), tracking and monitoring, Ultra Wideband (UWB).

1 Introduction

Today's construction sites in Europe have become more international due to laws in the European Union (EU) that call for competitive tenders for most of the public works. A bundle of evaluation requirements exist; some examples are: (a) company experience (i.e., previous work, years in business, geographic territory, previous customers), (b) organizational structure (i.e., management processes, operational procedures, hiring and training programs, turnover), (c) quality performance, (d) safety records, (e) senior management experience, (f) current projects, and (g) financial strength. These and more influence the selection of a qualified contractor. While owners, financing lenders, and insurance agencies demand lowest possible risk in any of the aforementioned criteria, little focus has been set on measuring a contractor's ability to track and monitor its operation aside from running its business.

Another motivation for conducting this study originates from research on lean construction. Results on monitoring shell and interior construction show that waste times of 19 % are directly avoidable [1]. Some of the most wasteful activities observed in this study are reported as unnecessary ways and handling of material (10%), searching for equipment (6 %), and waiting for equipment (3 %). The same study sees further potential for the optimization of construction operations: an additional 16% of the total working time could be saved by reducing manual transport (9 %), information gathering and delivery (4 %), and clearing and rearrangement (3 %). Multiple other research studies, some of them using advanced technologies, found similar potential savings once construction site operations follow lean principles, i.e., optimizing the usage and disposition of construction machines, reducing material search times and idle times of equipment [2].

Fortunately, in recent years leading contracting organizations have been starting the adoption of technology that assists in some of the time-consuming and vulnerable tasks of performing the daily management of operations at their construction sites. One of such tasks, as highlighted originally in research by [3-5], is tracking and monitoring construction materials and equipment. Grau et al. [5], for example, called for a reduction in wasted work time for unnecessary ways and waiting and non-optimal disposition of equipment or materials. Their study demonstrated an 8:1 return on the investment and an overall 4.2% productivity gain once intelligent material tracking is applied.

While monetary benefits such as the expected gains from productivity improvements are often the main driver for a change in the existing construction business processes and operational practices, availability and retention of qualified workforce is yet another major issue that has to receive more attention in many contracting organizations [6]. Construction workforce at all levels has typically different backgrounds, e.g., education, experience, skills, and language. Measuring the impact of applying novel technology into practice and how well it potentially benefits or is eventually disliked by the workforce has yet to be explored in greater detail.

For the above mentioned reasons, namely leveraging technology for construction site operations monitoring and adoption by its workforce, this study investigates a novel communication protocol called LoRa (Long Range). The following sections of this paper are structured as follows: first a brief introducing on the shortcomings of existing tracking and monitoring technologies in construction is presented. The sections thereafter explain the developed LoRa-approach by measuring the location error, checking the reliability, testing the usability, and evaluating the practical benefits for implementation in construction operations. A discussion on the remaining limitations and an outlook for future work conclude this paper.

2 Background

While a vast body in the construction-related literature exists on location tracking and status monitoring, the scope of this review focuses on the use cases for the Internet of Things (IoT) and technologies as they relate to construction material and equipment location tracking and monitoring.

2.1 Internet of Things (IoT) in construction

The Internet of Things (IoT) stands for the digital mapping of the physical world and the ability to monitor and manage real things in the digital sphere [7]. With the IoT, data gathering by sensors and processing digitally via the cloud, for example, can be performed in a much faster and less complex way than real world objects and processes. This enables acceleration and optimization by data-driven decisions of many construction systems and businesses.

Already available in the IoT is the digital information from build-in sensors, computers and personal devices like smartphones. In a next step additional distributed sensors, for example installed on construction materials and equipment, complement this set of data. The data transfer of such assets is typically wireless without requiring human-to-human or human-to-computer interaction. The data is also collected on clouds for easy access and for further evaluation.

Decision criteria for wireless distributed sensors are typically the cost of hardware and use, usability, reliability, robustness, and lifetime. For any successful innovation in construction, these factors have to be fitted to specific needs in an organization's use cases.

Since the operation of many construction sites is still very complex and dynamic, much of it would benefit from wireless distributed sensor applications, in particular as they relate to location tracking and monitoring. Often named use cases (bold boxes) and some of their positive influences (grey boxes) thereof for location sensing are shown in an overview in Figure 1.

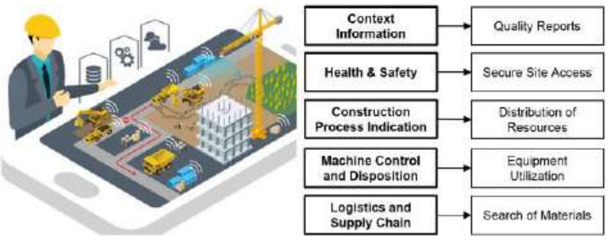

Figure 1: Typical construction uses cases and outcomes of distributed sensing [courtesy of Robert Bosch GmbH]

2.2 Location tracking and monitoring

Several ways exist to measure, communicate, and use positioning data. We define the term *location tracking* for the continuous gathering and transmission of a resource's (material or equipment) positioning data over time, while we speak of monitoring in terms of the simultaneous processing of the data to yield information which is then used in specific construction applications, such as resource location or resource status monitoring.

There are several dedicated systems for determining geolocation and time information. One of the most popular ones are grouped under the umbrella of *Global Navigation Satellite Systems (GNSS)*: GPS, GLONASS, Galileo, or BeiDou. These consist of satellites that continuously transmit data about their current position and time. On earth, a receiver monitors multiple satellites (a minimum of 4 of any GNSS) and logs the precise position in a high resolution time interval [8]. Clock calibration data and correction data is stored in the almanac (an internal database).

While the use of GNSS in *professional surveying applications* such as performed in earthwork activities (i.e. automated machine guidance) requires very high precision, many outdoor construction applications focus on *location awareness applications* that demand lower precision (typically within the meter range) [4-5, 9-11]. In both scenarios, the largest errors in GNSS positioning are attributable to the atmosphere such as distortions caused by the ionosphere (i.e. signal delays caused in space), troposphere like bad weather (i.e., cloud coverage), or multipath in dense work environments (i.e., reflections or obstructions from nearby high-rises).

Correcting such errors is expensive and often requires additional technologies. For example, telematics solutions for construction equipment are typically based on GNSS receivers for localization sensing. They use cellular networks for sending the data to a database where it is further processed. Although a GNSS receiver with current data in its almanac can acquire satellite signals more quickly (which helps determining the position faster), several minutes are generally needed to initialize the signal reception. This requires the receiver to be turned on (thus consuming power) and works only outdoors with a clear view (i.e., line-of-sight) of the sky. Alternative methods to get a faster GNSS-fix exist. A-GPS, for example, get their almanacs and approximate position from network stations (BTS, NodeB, eNodeB) based on GSM or LTE technology. It is therefore generally cost-prohibitive for tracking applications that would require to equip large numbers of items. Although their form factors (i.e., dimensions) have decreased in size over time, these reasons ask for alternative technologies.

A second technology closely related to this study and already applied in construction operations is called *Radio Frequency Identification (RFID)*. RFID solutions allow tracking, but require a tag located on the desired object. There are active, semi-active/passive and passive RFID tags consisting of scanners or antennas that read them [4-5, 12-13]. Depending on the type of RFID, the read range of the antenna can be from centimeters (passive tags) to several dozen or hundreds of meters (active tags) [14]. The advantage of passive RFID technology is that no internal power source is needed on the tags. These tags can be small in size, inexpensive once fabricated in large numbers, and attached to almost every type of material (even metal) [15].

Since RFID often transmits just the tag's identification number over shorter distances, no additional data like its precise positioning coordinates are available. A user demanding the terrestrial geolocation of construction assets in a large laydown yard, for example, thus has to combine RFID tags and antennas with a mobile GNSS receiver on a ground-based vehicle [5] or an unmanned aerial vehicle (UAV) [16]. Further software technology for data processing and visualization or managing of the timestamped geolocation information is also needed. As explained, the costs for implementation, use, and maintenance add up quickly (i.e., requiring also a licensed person for safely operating a UAV).

Other communication protocols based on radio frequency, including Near Field Communication (NFC) and Bluetooth Low Energy (BLE) for mobile applications, offer – as outlined in research – shortcomings. Imprecise and short read range limit their application in location tracking [17]. To name a few additional communication protocols that have been applied to or tested in construction are Zig-Bee, Z-Wave, Wi-fi, and Ultrawideband [18-19]. Although they were applied in specific scenarios perhaps relevant to construction, for example wireless personal area networks (WPANs) for high data transfer rates in home automation and communication, some of their distinct limitations are: high power consumption, additional signal sensing infrastructure requirements (e.g., number of nodes), low security standards, and limited range.

An alternative approach for location tracking are mobile radio standards. The Global System for Mobile Communications (GSM), for example, was first deployed in Finland in 1991 for fully digitalized mobile networks [20]. More recent distributed sensor-IoT solutions in smart city applications use unlicensed ISM bands (Industrial, Scientific, and Medical Radio Bands). They work in ranges of some kilometers and with very low bandwidths, so called Low Power Wide Area Networks (LPWAN). Most common LPWAN networks are Sigfox and LoRa. Both are a special design of autarkic distributed sensors with very low power consumption and cost of use. The main difference to LoRa is that SigFox is a network provider and any sensor devices to be used with SigFox has to be integrated within the SigFox network. LoRa is an alliance with more bandwidth than Sigfox and allows to build or use an existing LoRa network.

2.3 Introduction to Long Range (LoRa)

LoRa is filling a gap in wireless communications (Figure 2). Public LoRa-networks are currently being deployed all around the globe [21]. Just like mobile phones in a mobile phone network, LPWAN devices will be able to operate in public LoRa networks [22]. Private gateways will supplement public networks in the transition period.

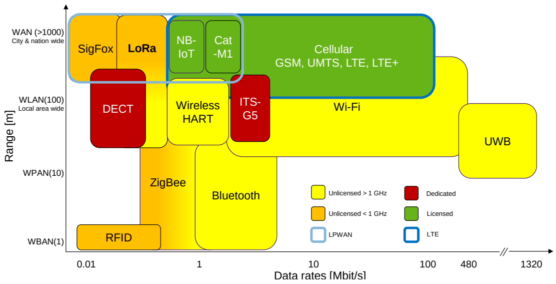

Figure 2: LoRa filling a gap for wireless communications

LoRa is specialized for the requirements of the IoT. LoRa offers secure bi-directional communication, localization, and mobility of services without the needs of static and complex installations. The open non-profit association called the LoRa Alliance has set itself the objective to standardize LPWAN to enable the IoT to guarantee interoperability in one open global standard. LoRa typically has a star-of-stars-topology. As shown in Figure 3, the end-devices (LoRaWAN slaves) communicate via LoRaWAN with the gateways that are within reach. A gateway serves as a transparent bridge by using a network connection (e.g., realized via GSM) to send the received data to a network server or vice-versa.

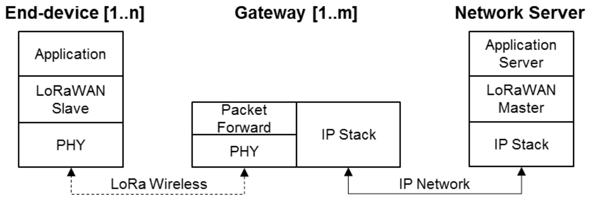

Figure 3: Communication in a LoRaWAN network (modified, after [21])

The communication between the gateway and end-device depends on data rates and frequency channels [23]. LoRaWAN data rates reach somewhere from 0.3 kbit/s to up to 50 kbits/s. However, because of the regulated restrictions on the 868 MHz frequency, only a maximum broadcasting time of 2% of the run time is permitted. At first look this restriction might limit many useful applications for LoRa in construction. However, the maximum throughput and probability of successful transmissions enable the tracking of thousands of objects.

Another increasingly important topic is security. LoRaWAN offers a multi-layer encryption for protecting sensitive data [24]. Regulations are Network Level Security and Unique Network Key (EUI64). A Unique Application Key (EUI64) provides security at the application level, and Device-specific button (EUI128). The encryption is particularly helpful once public wide area networks replace the local gateways on a construction site. Depending on a use case, sensors equipped with a LoRa end-device can transmit messages and receive acknowledgements or responses by listening to the network. This happens after sending requests on fixed intervals or in an always-on mode. The more power consuming is the always-on mode. The always-on mode, however, reduces the latency for time critical purposes, such as applications in infrastructure health monitoring. Optimized power consumption results in a battery life of many years. Theoretically, this enables LoRa sensors and devices to send and receive information even when located indoor or underground [23].

3 LoRa architecture

Many practical applications exist for LoRa in construction. Examples of much needed use cases in construction that can be solved are: locating and dispositioning assets, tracing off-site construction and checking-in inbound deliveries, finding of implements and tools, organizing fleets and cooperatives, monitoring machinery, geo-fence alerting, managing inventory and optimizing workflows, shock or temperature monitoring, maintenance or theft alerting, counting operation hours, and billing and providing evidence of back-office services. These examples in mind led to the design of a suitable LoRa-IoT architecture. The result is shown in Figure 4. While only providing low data rates, the main advantage of using GSM/LTE is the outdoor distance coverage. It makes it attractive for use in the proposed wide area field test. For sending the sensor data incl. the received position data from a built-in GNSS receiver the 300 ms latency of the LoRa is more than sufficient. The technology, incl. the LoRa device called thereafter TRACI, was later tested in realistic working environments common for construction.

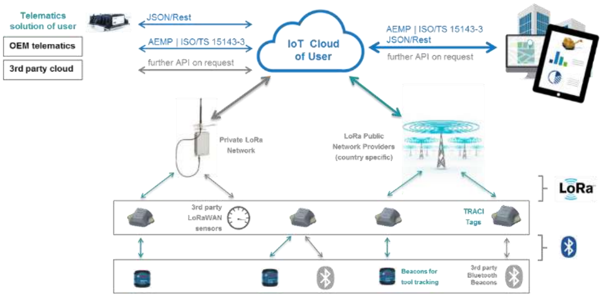

Figure 4: The LoRa architecture [image courtesy of Robert Bosch GmbH]

A TRACI tag with its integrated sensor stack delivers the following data, among other data:

- Network: LoRa - EU868 - Europe 863-870MHz
- Radios: Bluetooth 4.2 / passive NFC
- 3-axis accelerometer (+/- 2g 1mg; +/- 4g 2mg; +/- 8g 4mg; +/- 16g 8mg; fmax 2kHz),
- 3-axis magnetic field (3-axis, (+/- 1300µT 0.3µT),
- GNSS (ublox module) sensors
- Size and weight: 0,11 x 0,082 x 0,038m; 0.17 kg

4 Case study application and results

4.1 Geolocating

The position of the TRACI tag it determined through use of an embedded GNSS module. It has been found from interviews with leading construction organizations, that many use cases in construction require a position accuracy of less than 10 m which current Time Difference of Arrival (TDOA) methods for LoRa currently cannot deliver. Position accuracies of smaller than 200 m for LoRa TDoA can only be achieved with a high density of LoRa base stations (at least 3 gateways).

While this may serve some construction applications, like theft protection of expensive equipment, achieving lower error rates with denser networks would substantially increase the overall implementation and operational cost [22]. This is why TRACI needs a build-in and low-cost GNSS module and its performance must be tested.

The GNSS hardware (as explained before) used in this study achieved a *Center Error Probable 50%* (CEP50) of 2.3 meters (Figure 5). This result is based on a 24 hour measurement duration with 86,400 values. In the measurements performed for Figure 6 the use of GLONASS and Galileo, as additional satellite systems to GPS, did not lead to a measurable improvement in the position accuracy of the TRACI tag. Additional observations from tests with the developed LoRa device in a laboratory environment included:

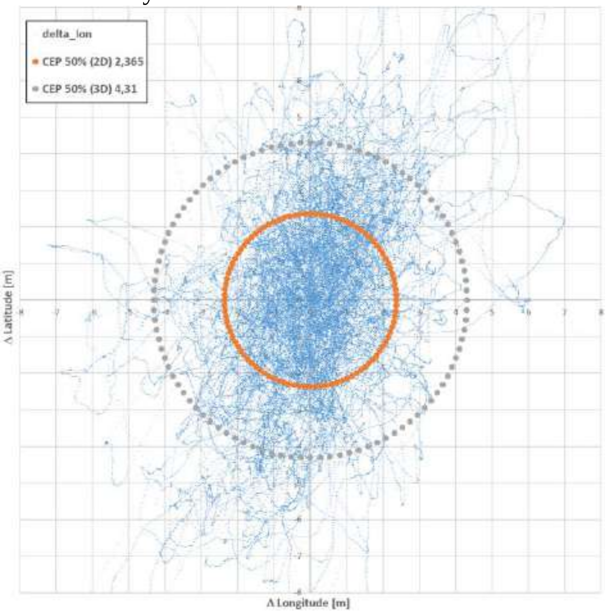

Figure 5: CEP50 for TRACI device (GPS only)

- Higher position accuracy comes at cost of battery life time. Figure 6 shows that a CEP50 increase from 2 to 3 meters can - in some cases - reduce the GPS-fix time from 100 seconds to below 20 seconds. Taking into consideration that TRACI's GPS-module consumes around 50 mA when active, reducing the CEP50 requirement can improve the battery life time of such sensors significantly.
- Due to the constraints of the limited bandwidth of LoRa, the sensor data is processed in the device itself with use case specific firmware. Sensor data is aggregated and processed in the application layer of the software. Doing so enables the transformation or gathering of (a) acceleration data or magnetic field data into operating hours of machines, and (b) strength of electric current or spatial orientation of the device itself. The aggregated data is then transmitted via LoRa to a cloud backend in compliance with the ISM-band duty cycle. From the cloud the data is shared via a JSON/REST API that allows stakeholders to add further value and build applications for different use cases.

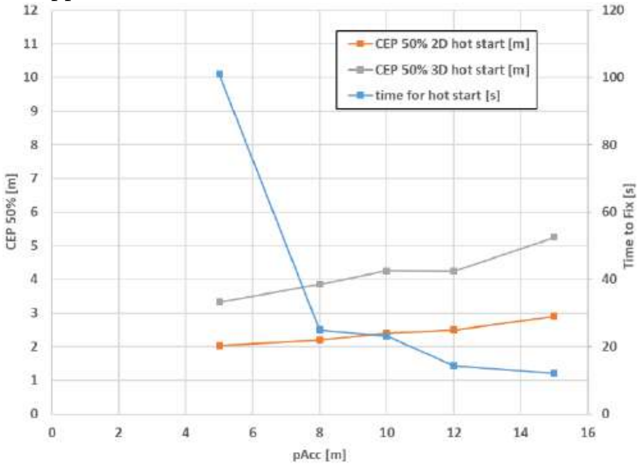

Figure 6: GPS fixe time over position accuracy (pAcc) for different CEP50

4.2 Equipment monitoring

The objective of the first field implementation of the TRACI tag was to automatically monitor a tower crane's operating time. Measurements were performed on a Wolff flat-top crane on a building construction site with a total number of 9 cranes. Usually, the TRACI tag measures operation hours based on vibration. The goal of this measurement, however, was to determine whether the acceleration signal of the motor of the main winch could derive the operation information. In case the acceleration signal is not strong enough, operation hours can also be counted with the help of its embedded 3-axis magnetic field sensor. For this reason, the feasibility of using the magnetic field signal of the motor was also assessed during the measurement (Figure 7). The gathering of the acceleration as well as the electromagnetic field data of the motor of the main winch (Figure 7, left image) resulted in data (Figure 8).

Figure 7: Implementation of Lora-tags on tower crane motors (i.e., raise/lower, move in/outwards, turn)

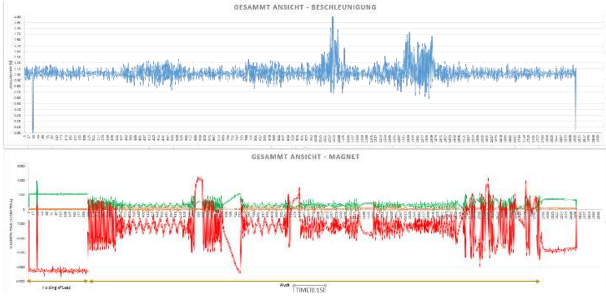

Figure 8: Typical machine data when accelerating the crane block: electromagnetic data shows the tower crane's activity (0 equals no crane activity)

From the large data set that was recorded, a snapshot of 190 seconds will be explored to highlight some of the findings. The motor's magnetic field signal shown in Figure 9 shows a measurement that was recorded while the crane performed several hoists (lifting and lowering) with a load of 1,700 kg at different speeds. Findings from the observation were:

- While further measurements with lighter loads did not lead to significantly different signals, loads had little influence on the magnetic field measured with the sensor.
- Acceleration measurements of the crane structure during idle time showed that the signal noise from wind and other external influences lead to vibrations on the crane with an amplitude of around 0.2 g absolute.
- The acceleration signal in Figure 8 shows, that the acceleration in most working conditions does not exceed the normal structural idle noise on the crane. Hence, the acceleration signal is not sufficient to reliably deliver the operating hours of the motor and subsequently the crane.
- The acceleration peaks at the beginning and end of the measurements are due to changes in the measurement range of the sensor and are not caused by the crane itself.
- The magnetic field components, represented by the three lines (red, green, and orange) show a strong signal which can be used for evaluation the working hours of the motor.
- The sampling rate in the data visualization tool used led to aliasing effects, which become obvious in a distorted and non-continuous signal behavior. The actual oscillation of the magnetic field does happen at a higher frequency than displayed. However, the amplitude of the signal shown in Figure 8 and the sampling rate of the sensor itself do allow for a precise determination of the actual operation hours of the motor, based on the magnetic field change only.
- Furthermore, the oscillation when working can be discriminated from the electrical holding of the load without mechanical breaks, which can be seen in Figure 8 in the first section of the measurement. Being able to differentiate between the two active modes of the motor leads to a more precise evaluation of the actual work happening.

These findings led to a more detailed investigation of the crane's activity. As shown in Figure 9, on one particular work day (24 hours), the crane was in operation a total of 7 hours and 6 minutes. For reasons of better visualization, the observation time was grouped into 40-min intervals. By analyzing the TRACI data only, the crane showed activity (bars in green color) in the intervals 22-26, 38, and 40-56. Within the intervals of activity, TRACI reported that the utilization of the crane varied (as shown by the percentage values). At all other times, TRACI reported no operation of the crane (red bars). The crane's utilization reported by TRACI was compared using the multi-moment-analysis (triple M) method [25]. The thin line (black) in Figure 9 indicates the results of a knowledgeable person briefly observing the crane at repeating, but specific time intervals. As can be seen, the manual not always overlaps with the automated data. On this particular day, this person did not record any crane activity in 6 while deviating in 4 other intervals for more than 30% from the results of the automatically recorded data. While these error show one disadvantage of the manual multi-moment-analysis method, data analysis and reporting can be delayed as well.

Figure 9. Crane use vs. idle time

The overall utilization of the crane given a 10 hour work shift over a 4 work day period can be assessed as the following.

- Day 1: 318 min or 53% of 600 min.
- Day 2: 287 min or 48%.
- Day 3: 314 min or 52%.
- Day 4: 284 min or 47%.

As a result, about half of the work time during the 4 days that crane was not utilized. An experienced manual note taker further assessed productive vs. wasteful activities of the time when the crane was in action on the first and last observation days. While these manually observed data points may not be compared with data from TRACI, the note taker reported productive work execution in:

- Day 1: 53.8% of 318 min.
- Day 2: 52.3% of 287 min.
- Day 3: 52.6% of 314 min.
- Day 4: 50.9% of 284 min.

This results in an overall productive utilization rate of the tower crane of about only 25%. While this data is not representative for other work days on this particular construction site, it may hint towards a larger potential for crane use optimization. This case study ended with some additional reasoning how automatically-generated crane data and its analysis might enhance its operation:

- The idle times of a crane can be recognized and subsequently optimized. Proper equipment resource allocation, such as crane availability to the competing work crews on the ground, can significantly impact a project's construction schedule, and in particular in high-rise construction where hoist times are often critical [26].
- The automatic recording and processing of crane data could be used, among other noteworthy examples, in (a) billing a subcontractor's crane use time, (b) recording the overall crane operating hours for resource leveling among all subcontractors, (c) alerting and calling for preventative maintenance tasks, and (d) overall progress monitoring of site activities based on historical estimates or real-time data.

5 Conclusions and Outlook

The construction industry is currently experiencing a change towards digitalization. Building information models (BIM), Internet of Things (IoT), mobile or smart wearable devices have become buzzwords for construction applications intended to follow lean principles. IoT for construction yet has to fully implement simultaneous data gathering, analysis and visualization. While a multitude of sensors exist to collect data, Local Range (LoRa) fills a gap in existing data communication protocols. This study has shown in an independent case study of how a novel IoT-LoRa architecture and its developed technology might be applied in construction. The study leveraged LoRa-tags in combination with magnetic field sensors on a tower crane for monitoring its activity. The results show that the technology exceeded the human capacity for the recording and the analysis of the plentiful of data that is available in construction. Future research though has to carefully evaluate the reliability of any of these technology in daily work practices (perhaps at much larger operation scale) as well as its impact on human workers. Further work may therefore focus on exploring human-technology interfaces and the richness of new information that is generated once it is applied to information models [27]. Once envisioned in applications for intelligent decision making tools, in particular as they relate to construction site logistics applications, much of the existing problems, such as uninformed decision making or unawareness of project or resource status, might be solved.

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Strategic optimization of 3D concrete printing using the method of CONPrint3D®

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Abstract –
The resource efficiency and labor productivity in the construction industry are still viewed critically. Concrete 3D-printing processes have the potential to significantly improve both factors. Currently, research activities in this field are growing rapidly worldwide, thus similar advances and market developments can be expected, as have already occurred in other sectors of the stationary industry. The TU Dresden relies on the development of the CONPrint3D® (Concrete ON-site 3D-Printing). It specifically relies on: established machine technology, the production of fully filled concrete structures, sustainable concrete formulations with a maximum grain size of up to 16 mm and the use directly on the construction site. In contrast to small-scale 3D-printing processes, the data processing chain for large-format 3D-printing with concrete still has considerable deficits. In order to depict the complex solidification properties of the building concrete, computer simulations are indispensable as a basis for the development of an optimized printing strategy. In this paper, investigations on the strategic process optimization of concrete printing using the method CONPrint3D® are presented. First, the relevant boundary conditions of concrete 3D-printing are described. Subsequently, calculation methods of the trajectory planning are presented.

Keywords –
3D-printing; Concrete; Optimization; Simulation; Continuous path control

1 Introduction

The concrete installation directly on the construction site is very labor-intensive and time-consuming. The costs of formwork accounts for a high proportion of the shell costs, at around 25 % to 35 %, and the construction period is largely determined by the formwork. [1] As a result, the development of a construction method without any formwork, which uses continuous 3D concrete printing, can yield great savings. In other industries, such as medical or aerospace industries, 3D printing technology has developed rapidly in recent years and is now being used not only for prototyping, but also increasingly for the manufacturing of marketable components.

Experts agree that the use of 3D printing technology in construction offers both significant economic potential and new architectural design. Economic considerations for CONPrint3D® resulted in cost savings of around 25 % and four to six times shorter execution times compared to conventional masonry construction. [2]

Compared to the stationary industry, the boundary conditions are completely different for computer-aided manufacturing in the construction industry. Changing environmental conditions (such as site location, subsoil characteristics or environmental impacts) makes it difficult to introduce automated production methods on site. The increasing digitization and establishment of new planning methods, such as Building Information Modelling (BIM), can ease the introduction of automated processes on construction sites. A BIM model already contains all the data necessary to control the machine technology. The BIM data only has to be prepared for an optimized construction process and converted into data formats which are readable for the machine.

The key process in data preparation is the "slicing" of the 3D model. The term means the division of the 3D object into two-dimensional layers having a defined layer height. While slicing the structure, important input parameters are defined for the printing process, such as the printing paths, printing speeds or the material discharge quantity. Subsequently, a machine control code, usually in the form of a G-code, is outputted. The optimization of the printing strategies is extremely relevant to ensure the efficiency of the process. The construction process is usually computer simulated before printing.

This paper discusses the 3D concrete printer as a robotic platform based on CONPrint3D®. In the 2nd section, the concept is presented. In the 3rd section, design requirements are described. In the 4rd section calculation methods of the trajectory planning are presented. The 5th section gives a small outlook.

2 CONPrint3D® Concept

Since 2014, an interdisciplinary team at TU Dresden has been researching the development of an innovative concrete construction process. Based on the principle of extrusion, load-bearing building structures are to be continuously produced by 3D shaping fresh concrete. Figure 1 shows the main components of CONPrint3D®.

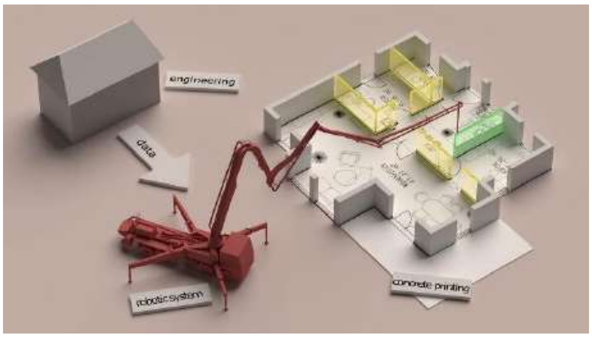


Fig. 1: Essential components of the concrete 3D printing process CONPrint3D®

As a mechanical platform, a modified truck-mounted concrete pump is used. Additional control technology and a newly developed print head ensure the continuous extrusion of the concrete and the geometrical precision on the construction site. The basis of the control process is a BIM-based planning. The necessary control data in the form of geometric data and material data are extracted from a 3D building model, then processed and transferred to the modified concrete pump. This allows the direct implementation of a previously created concreting plan in the machine control for automated movement. At the end of the geometrically precise distribution boom, the fresh concrete from the print head is laid out layer by layer with lateral shaping elements (see Figures 2,3). This

Fig. 2: Geometrically precise installation of the concrete by modified truck-mounted concrete pump

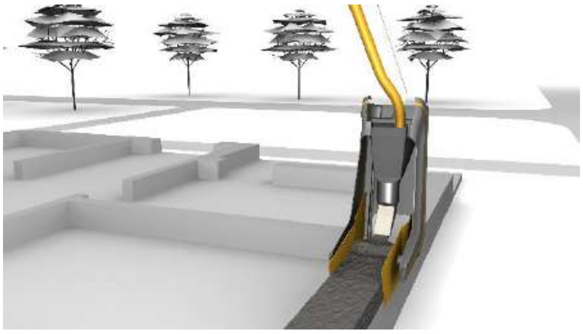


Fig. 3: Extrusion-based installation of fresh concrete using a newly developed print head

is how the building is constructed using the layering principle.

The research activities are clearly different from other global development work. The basic principles of the CONPrint3D® process are:

1. The execution takes place directly on the construction site (in-situ concrete construction).
2. The machine base represents a construction machine established on the market: the truck-mounted concrete pump.
3. Concretes with a maximum grain size of aggregates of up to 16 mm are used for the process.
4. Monolithic, fully filled concrete structures are created.

The research team of the TU Dresden consists of three institutes. The Chair of Construction Machinery handles the mechanical implementation. The Institute of Building Materials develops the special concrete technology. The economic implementation on the construction site and the productivity of the application as well as an optimized data management are ensured by the Institute for Construction Management.

Within a theoretical study, the feasibility of all three areas was initially ensured. Within laboratory tests on a scale of 1: 5 (see Figures 4 and 5), suitable concrete

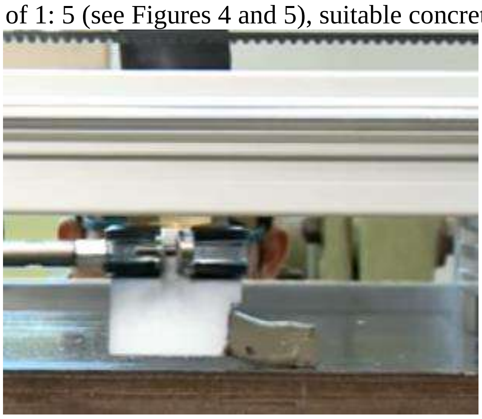


Fig. 4: Concrete technological extrusion trials on a scale of 1: 5

Fig. 5: Printed concrete components for the investigation of the layer composite

recipes were developed, decisive strength values determined and the layer composite investigated. More detailed results are included in further contributions of the research team [2, 3, 4, 5, 6].

In a primary development step, CONPrint3D® aims to produce unreinforced concrete structures. The integration of reinforcement elements and other materials (eg. TGA installations, plaster or thermal insulation) is planned only in the long-term development. First of all, CONPrint3D® focuses on producing unreinforced walls directly on the construction site in order to replace traditional masonry and drywall construction. Thus, the main field of application of CONPrint3D® is in residential construction.

3 Design requirements

In the literature, Additive Manufacturing (AM) methods are often referred as 2½-D methods. The layers are generated in the x-y plane, the so-called printing plane. The layer thickness is usually constant. This creates the third dimension in the z-direction only by the superimposition of the individual layers. [7]

CONPrint3D® is characterized by the fact that the wall cross-sections are completely filled with concrete by a driving movement. In addition, sharp-edged 90° corners are to be generated. In other research activities, smaller concrete strands are printed resulting in round corners with small radii. The different methodological approaches are compared in figure 6.

In order to produce wall connections with CONPrint3D® in a force-fitting manner, conventional solutions already exist in masonry construction, which can be transferred. Accordingly, there are fundamentally three ways to produce force-fitting wall connections:

- Constructive gearing by alternating layer arrangement,
- Surrounding of the walls to be connected,
- Connection by stainless steel flat anchor systems.

Fig. 6 left: Approach of CONPrint3D®
right: Extrusion of smaller concrete strands with round corners and subsequent concrete filling [8]

The examination of the geometric requirements reveals that three different categories of wall connections can be distinguished:

- Corner joints,
- T-connections,
- Intersections.

In this article, the constructive execution of corners is to be considered more closely. The non-positive wall connection should be made by constructive gearing. Table 1 describes the printing structure of force-fitting corners.

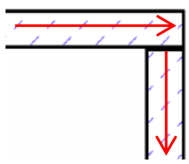
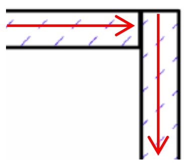
Wall connection	Layer 1, 3, 5, …	Layer 2, 4, 6, …
Corner		

Table 1: Printing-strategy to produce a force-fitting corner

In order to produce a force-fitting corner connection by constructive gearing, two different printing paths are required, which repeat alternately over the entire wall height. In contrast to other global research activities, which track strands pressure, only one printing path is to be developed, thereby followed in every layer.

In order to create a wall corner connection with the given geometry of the CONPrint3D® printhead (see Figure 7), certain movements must be considered. This is illustrated in figure 8.

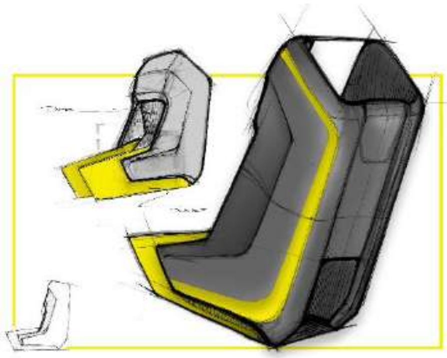


Fig. 7: Design of the printhead [3]

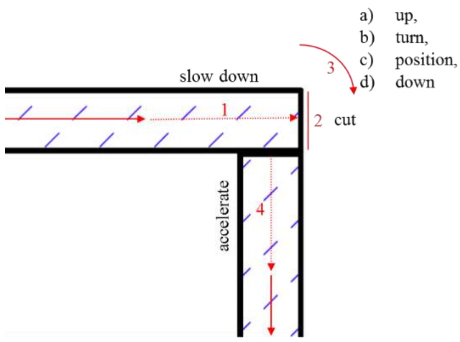


Fig. 8: Movement of the printhead at a corner

In the area of the recesses (door and windows) no material is discharged. The soffit is realized by a) decelerating, b) Cutting off the concrete, c) Driving without material discharge, or d) accelerating with material discharge. Above the windows, a prefabricated lintel is inserted similarly to the masonry construction. The layer height depends on the nozzle opening and the printing materials. With CONPrint3D®, layer heights of 5.0 cm can be reliably achieved.

4 Planning the Trajectories of the Printer

The task to develop the trajectories of the end effector motion of a manipulator is reduced to describing a sequence of motions in the plane X_P, Y_P parallel to the plane X_0, Y_0 of the robot coordinate system. The Z_P coordinate does not change within one stacking cycle, and then increases by an amount Δh, corresponding to the thickness of the stacked layer.

Figures 9 and 10 show examples of floor plans for different monolithic objects. As can be seen from the diagrams in figures 9 and 10, the trajectories of motion are either a set of rectangles or circles. When constructing the static frame of an apartment house (see Figure 9), it is necessary to formulate an array of coordinates of points on the basis of the building plan and to determine the sequence of traversal of rectilinear sections.

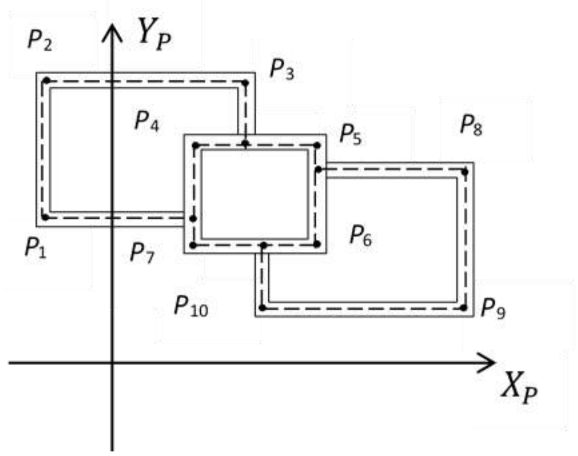


Fig. 9: Static frame of an apartment house and the trajectory of motion of the end effector

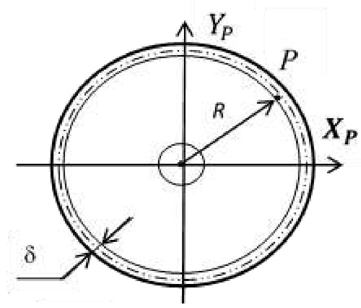


Fig. 10: Plan for a monolithic tower and the trajectory of motion of the end effector

Each section can be described by equations of the form:

- for sections parallel to the X-axis

$$X_0 \to P_{jS}(x_{jS}, y_{jS}), P_{jE}(x_{jE}, y_{jE})$$

$$y = y_{jS} V y_{jE} \to x_{jS} \le x \le x_{jE}; \quad (1)$$

- for sections parallel to the Y-axis

$$Y_0 \to P_{iS}(x_{jS}, y_{jS}), P_{iE}(x_{jE}, y_{jE})$$

$$x = x_{iS} V x_{iE} \to y_{iS} \le y \le y_{iE}. \quad (2)$$

When building tower-type structures, the printer is placed on a telescopic carrier platform in the center of the structure. Therefore, its trajectory is a circle (see Figure 10) of radius R_{0P} lying in the horizontal plane X_P, Y_P:

$$(x - \Delta x_{0P})^2 + (y - \Delta y_{0P})^2 = R_{0P}^2,$$

where $\Delta x_{0P}, \Delta y_{0P}$ – is the deviation of the load-bearing platform from the design axis of the erected structure. These parameters are automatically controlled by laser control systems and are entered into the robot control system. Planning of movements of robots is performed in generalized coordinates. This means that for each section of the trajectory of the nozzle, it is necessary to obtain a temporal law of variation of each generalized coordinate of the manipulator, which provides the required motion, i.e. it is necessary to formulate for each sector a vector

$$q(t) = [q_{1i}(t), q_{2i}(t), \dots, q_{ni}(t)],$$

where i is the number of the trajectory section and n is the number of degrees of freedom of the manipulator.

Solving the tasks of movement planning of the working body for manipulation robots with a nozzle on the final link is performed in the following sequence. In the general case, at the beginning of the task, it is necessary to formulate the laws of the change in the time of the position and orientation of the working member and the speed of its movement:

$$\begin{cases} tr_i(t) = [x_i(t), y_i(t), z_i(t)], \\ v_i(t) = \left[v_{xi}(t), v_{yi}(t), v_{zi}(t)\right], \\ \psi_i(t) = [\theta_i(t), \varphi_i(t), \beta_i(t)], \\ \omega_i(t) = \left[\omega_{\theta i}(t), \omega_{\varphi i}(t), \omega_{\psi i}(t)\right], \end{cases} \quad (3)$$

where $tr_i(t), v_i(t)$ – are the position and velocity vectors at the current time t when moving on the i-th section of the trajectory; $\psi_i(t), \omega_i(t)$– are the orientation and angular velocity vectors on the i-th section at time t.

The above equations can be directly used to obtain the temporal laws of variation of generalized coordinates. However, in most cases, this problem is unsolvable in explicit form. Another important use of equations (3) is the accuracy control of the result by means of the degrees of freedom. In the general case, any rectilinear portion of the trajectory of the grasping movement with uniform motion at a speed $v_i = \left[v_{vi}, v_{yi}, v_{zi}\right]$ can be described by the vector:

$$tr(t) = \begin{bmatrix} x_S + v_{xi}t \\ y_S + v_{yi}t \\ z_S + v_{zi}t \end{bmatrix} \to \begin{bmatrix} x_{Si} \le x_i \le x_{Ei} \\ y_{Si} \le y_i \le y_{Ei} \\ z_{Si} \le z_i \le z_{Ei} \end{bmatrix}, \quad (4)$$

where x_{Si}, y_{Si}, z_{Si} – are the coordinates of the starting point of the trajectory; x_{Ei}, y_{Ei}, z_{Ei} – are the coordinates of the trajectory end-points.

When planning the movements of concrete printers along rectilinear trajectories, the areas can be in the form of arcs of a circle. A characteristic feature of building robots is that the working planes are usually parallel to the planes X_0Y_0 (P_{XY}) (see Figure 11).

Consider the basic relations for the description of movements. When the robots operate in the plane parallel to the plane Z_0X_0, the motion along the arc of the circle is described by a system of equations of the form:

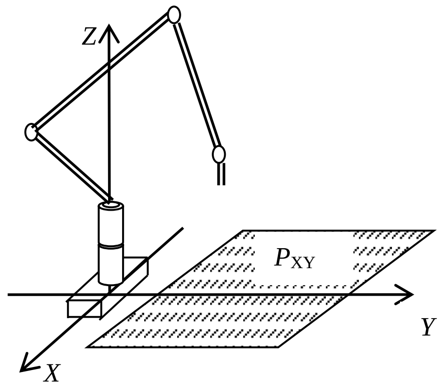


Fig. 11: Location of the working surface in the robot coordinate system

- option 1

$$\begin{cases} x = x_r + R\,\sin\omega t \\ y = y_r = const \\ z = z_r + R\cos\omega t \end{cases}; \begin{cases} v_x = \omega R\cos\omega t = v\cos\omega t \\ v_y = 0 \\ v_z = -\omega R\,\sin\omega t = v\,\sin\omega t \end{cases}$$

$$\to 0 \le \omega t \le \pi; \quad (5)$$

- option 2

$$\begin{cases} x = x_r + R\,\cos(\pi - \omega t) \\ y = y_r = const \\ z = z_r + R\sin\omega t \end{cases}; \begin{cases} v_x = v\,\sin\omega t \\ v_y = 0 \\ v_z = v\,\cos\omega t \end{cases};$$

$$\to 0 \le \omega t \le \pi; \quad (6)$$

where R – is the radius of the trajectory section; ω – is the angular velocity of motion; x_r, y_r, z_r – are the coordinates of the center of the circle. If the motion is carried out in the plane X_0Y_0, then it is described by a system of equations of the form:

- option 1

$$\begin{cases} x = x_r + R\,\sin\omega t \\ y = y_r + R\cos\omega t \\ z = z_r \end{cases}; \begin{cases} v_x = \omega R\cos\omega t \\ v_y = \omega R\,\sin\omega t; \\ v_z = 0 \end{cases}$$

$$\to 0 \le \omega t \le \pi; \quad (7)$$

- option 2

$$\begin{cases} x = x_r + R\,\cos(\pi - \omega t) \\ y = y_r + R\sin\omega t \\ z = z_r \end{cases}; \begin{cases} v_x = \omega R\sin\omega t = v\sin\omega t \\ v_y = \omega R\cos\omega t = v\cos\omega t \\ v_z = 0 \end{cases}$$

$$\to 0 \le \omega t \le \pi; \quad (8)$$

In many cases, when planning the movement of the manipulator after describing the trajectory of motion in the form (4), the length of the trajectory or the path of motion is determined. In the case of rectilinear sections, the coordinates of the boundary points are $P_S^{(i)}, P_E^{(i)}$:

$$l_{tr}^{(i)} = \sqrt{\left(x_E^{(i)} - x_S^{(i)}\right)^2 + \left(y_E^{(i)} - y_S^{(i)}\right)^2 + \left(z_E^{(i)} - z_S^{(i)}\right)^2} \quad (9)$$

where i – is the number of the section. For arcs of a circle lying in the plane X_0Y_0, based on the coordinates of the boundary points $P_S^{(i)}, P_E^{(i)}$ and the arc radius R, the length of the trajectory l_{tr} is calculated in accordance with the equation:

$$l_{tr}^{(j)} = \int_{x_S}^{x_E} \sqrt{1 + y(x)}\, dx \ \rightarrow \text{plane } X_0Y_0. \quad (10)$$

In the general case, when the trajectory section is curvilinear and described by the equation of a plane curve $f(x, y)$, then the trajectory length is calculated as an integral:

$$l_{tr} = \int_{x_S}^{x_E} \sqrt{1 + df(x)\,/dx}, \quad (11)$$

where $df(x)\,/dx$ – is a continuous derivative of a function on a section $x_S \leq x \leq x_E$. For a spatial curve given in parametric form

$$x = x(t), y = y(t), z = z(t) \rightarrow t_S \leq t \leq t_E,$$

the length of the trajectory is expressed by the formula:

$$l_{TR} = \int_{t_e}^{t_s} \sqrt{(x(t))^2 + (y(t))^2 + (z(t))^2} \quad (12)$$

The total length of the trajectory consisting of n sections is defined as the sum of the lengths of these sections:

$$L_{tr} = \sum_{e=1}^{n} l_e$$

Knowing the length of each section of the trajectory, and the technology-limited speed of their execution, the time of passage of each section and the whole trajectory as a whole is estimated preliminary:

$$T_{tr} = \sum_{e=1}^{n} t_e = \sum_{e=1}^{n} \frac{l_e}{v_e}$$

Having planned operations at the seizure level or tool, it is necessary to build a program for changing the generalized coordinates of the manipulator and at the same time to verify the practical feasibility of the planned movements on each section of the trajectory. When planning in Cartesian coordinates, on the basis of the dependences $tr(t)$, $v(t)$, the values of the generalized coordinates $q_i(nT)$ at discrete instants of time, as well as the velocities $\dot{q}(nT)$, which are used to form the control actions in the next control step are determined. However, this approach requires, at each step of the control, the solution of inverse kinematics problems and significant computer time, which does not always allow real-time operation of the control system. In this regard, when controlling the robot, it is recommended that the motion planning be performed in generalized coordinates. In this case, for each boundary and node points of the trajectory, on the basis of the solution of the inverse position problem, generalized coordinates characterizing the configuration of the mechanism at these points are determined. For each coordinate, the constraints and realization of movements are checked by the executive-level management system. Planning of movements in this case ends with the construction of functions $q_i(t) \rightarrow i = 0,1,2...,n$ with the necessary condition $q_i(t_j) = q_i^{(j)} (j = 0,1,...,m)$. In this case, the planning is carried out in real time and the controlled variables are directly generated.

The planned trajectory $q_i(t) \rightarrow t_S \leq t \leq t_E$ forms a continuous path of movement for the manipulator arm. Continuity and fluidity of the tool movement are mandatory requirements for the movement of the robot. When robotizing this operation, one needs carefully to plan not only the movement of the tool, but also its speed and acceleration of movement [9,10].

5 Summary and Outlook

Concrete 3D printing processes have high economic potential. Initial cost-effectiveness considerations for CONPrint3D® are likely to result in building cost savings of approximately 25 % and significant reductions in execution time compared to conventional construction methods. In the first part, the article dealt with the special features of CONPrint3D® and considerations on the motion profile of the printhead. In the second part, mathematical basics of the Trajectory Planning of the Printer were presented.

The path planning is carried out taking into account the restrictions on the continuity and smoothness of the trajectory and also in accordance with a given set of constraints on the position, speed and acceleration of the generalized coordinates at the reference points of the trajectory. When solving the problem of planning the trajectories of motion, sections of acceleration and braking of the printhead are provided. Planning of the trajectory is carried out in space and time, which ensures the passage of the printhead the nodal points of the working space at a given time period. The solution of the planning task is determined by the appointment of the robot, its kinematic characteristics, performed by the technological operation and the technical environment conditions.

In order to achieve the process-reliable construction site application, adapted 3D printing strategies have to be developed and implemented in a continuous digital process chain. Digital data preparation and processing is currently not ready for application. As part of the research project digiCON^2 (digital CONcrete CONstruction), an adapted data management system for CONPrint3D® is being developed (duration 01/2018 to 12/2019, funding provider: Federal Ministry of Education and Research). The aim of the international research project is to complete the digital process chain from BIM to machine-specific optimized G-Codes. At the Technical University of Dresden, research will continue to be carried out in order to achieve the goal of construction site application.

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A Cyber-physical System of Diagnosing Electric Drives of Building Robots

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Abstract-

This article studies the development of a cyber-physical system for diagnosing and forecasting the technical condition of electric drives in robots used for construction. The structure of the cyber-physical system is described and the defect statistics for asynchronous drives submitted. Additionally, a critical analysis of existing diagnostic methods, the selection of the optimal set of diagnostic parameters and existing methods for measuring and analyzing the parameters used for the drives adopted in construction robots for is described. Herein, a method capable of distinguishing a faulty state from a load change based on wavelet transformation and neural networks (diagnosing the technical condition of robot drives) is proposed. Finally, we provide the simulation and experimental results of the proposed method.

Keywords –

Cyber-physical system, building robots, electric drives, diagnosing of technical conditions, forecasting, wavelet transformation, neural networks classification

1 Introduction

Increasing the requirements for reliability and efficiency of construction robots entails the need for constant monitoring of the technical condition of all actuators with further optimization of the operating mode of individual components and hence of all equipment as a whole. This can be achieved by using a technical condition monitoring system built into the robot's end-effectos, which continuously measures parameters with sensor system, analyzing the information obtained and determining the current technical condition, forecasting the development of defects, and optimizing the parameters of the object's operation mode. Implementation of this approach to improving the functioning efficiency of the equipment assumes the integration of computing resources into physical processes, i.e. application of cyber-physical systems [1]. In such systems, sensors, mechanical equipment and information systems are connected during all stages of the life cycle and interact with each other using standard Internet protocols in order to predict and adapt to changes in operating conditions and technical condition of the equipment. The structural scheme of the cyber-physical predicting diagnosing system of the construction robot is shown in Figure 1.

The cyber-physical prediction diagnosis system has five levels: connection, conversion, cloud, cognition and configuration [2].

At the "Connection" level, sensors are selected and installed, which can be designed for self-connection and self-monitoring of the state of the object.

At the "Conversion" level, data from devices with autonomous connection and sensors measure the characteristics of critical problems and methods for analyzing the information that will be used to determine possible selected malfunctions.

Storage and processing of large amounts of diagnostic information is carried out in cloud servers. This will allow the information flow and communication between the drives of various construction robots. Based on that, the optimization of the technological process starts taking into account the state of a separate actuating element.

At the "Cognition" level, the results of diagnosing and forecasting are determined, which are presented to users and transferred to the mathematical model of the object for further optimization of the object mode operation.

The application of the cyber-physical approach is to develop a diagnostic platform. The forecasting systems will significantly improve the reliability of the construction robots. Information links between the robots at the construction site through the Internet protocol will allow optimizing the entire construction process, depending on the technical condition of each drive of the executive equipment. This will maximize performance and minimize the likelihood of failure.

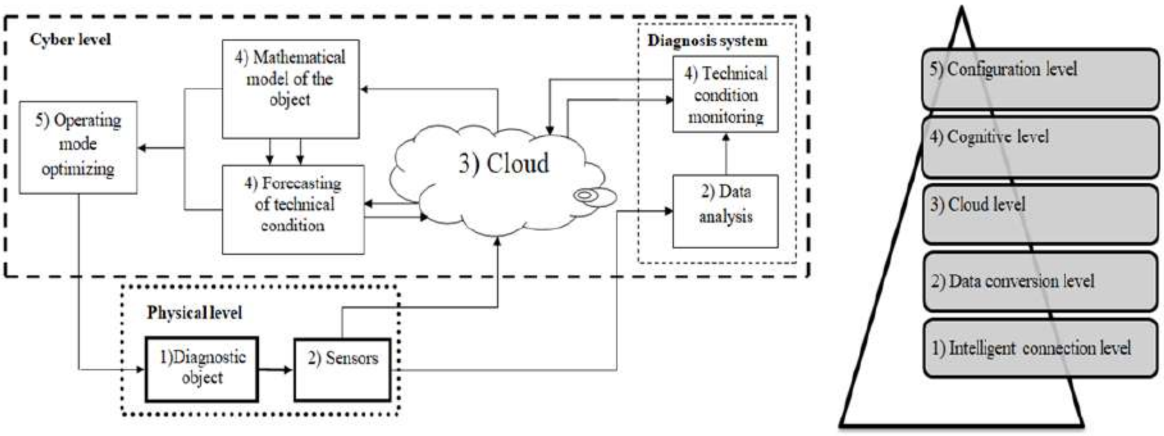

Figure 1. Cyber-physical system of the technical condition prediction diagnosis for electrical equipment

2 "Connection" level organization

The main component powering up the end-effectors of the robots is the electric drives of direct and alternating current (e.g. see Figure 2), which operate in a short-time mode and must have a high overload capacity and dust and waterproof design criteria known as IP standards.

The main type of drives used in construction robotics is a medium power asynchronous drive with a squirrel-cage rotor. The available statistics give the following data on the relative damage of the nodes of such engines (e.g. see Table 1) [3, 4].

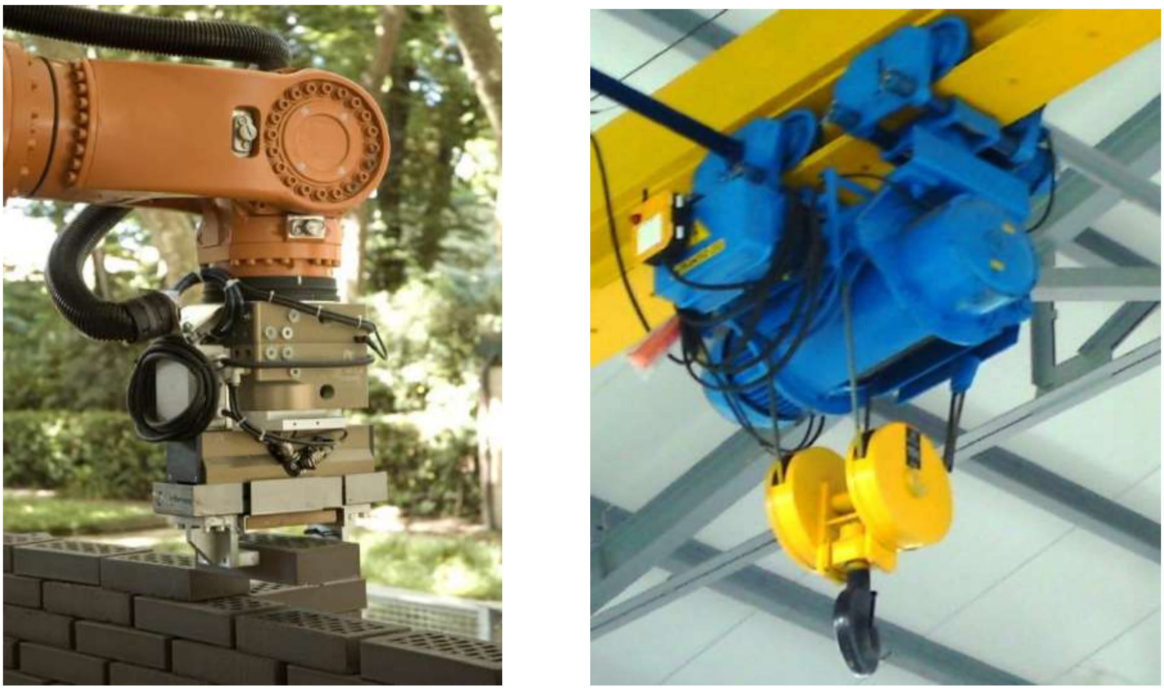

Figure 2. Electric drives in building robots

This figure shows that all engine failures of the aforementioned type are of mechanical or electrical origin. Thus, multi-parameters diagnostics methods are used that assume control of thermal, electrical and mechanical defects at the operating voltage [5]. In this case, the following applies:

- direct electrical control methods with galvanic connec-tion to the terminals of the motor leads (measurements or harmonics, or pulsations, or pulses of the supply current and voltage);
- methods of monitoring with the installation of sensors on the motor housing that fix electromagnetic or sound waves:

Table 1 Medium voltage motors typical defects

Fault	Percentage failure in operation
Discharge an sparking in current wire	40
Discharge and sparking in insulator. Heating of the terminal box	20
Insulation damage in stator winding	15
Sparking in magnet core. Heating of the defect zone	10
Heating of bearing	9
Discharge in cable insulation	4
Sparking in the squirrel cage	2

measurements of partial discharges, sound waves or capacitive currents to the ground while monitoring vibration;
- method of remote control: thermal imaging measurements of the temperature of the engine and bearing surfaces.

Joint use of these methods makes it possible to determine the technical state, but at the present time, the analysis of diagnostic information is currently done manually by troubleshooting experts, which is very not cost effective.

Hence, it is necessary to choose a list of diagnostic parameters that allow determining all possible classes of defects, having accepted sensitivity features over the changes in the values of structural parameters, minimum composition, accessibility for monitoring, measurement and software analysis without operator's involvement, cost and time effectiveness and sufficient degree of segregation when recognizing individual defects.

Construction robots operate in complex non-deterministic conditions with high alternating loads in conditions of high humidity and dust; their drives are often installed on a mobile base, which imposes significant requirements for the choice of methods and means of diagnosis such as:
- minimum composition of the measured parameters;
- the absence of complex bulky measuring equipment installed on the drive housing, which can affect the operation of process equipment;
- the ability to automatically analyze the measured parameters.

The most common diagnostic parameters for asynchronous drives are a partial discharge, supply and capacitive current, vibration and temperature [6]. A comparative analysis of the adequacy of methods based on the control of these parameters [7, 8], taking into account the limiting requirements, allows to make the following conclusions:
- the diagnostic of mechanical defects in medium power engines, instead of vibration analysis, harmonic analysis of motor feed currents (MCSA technology), harmonic analysis of capacitive currents to ground (CTG technology) can be used;
- as for the diagnostic of electrical defects, it is advisable to combine harmonic analysis of supply and capacitive currents in the ground circuit.

Analysis of the majority of electrical and mechanical faults of the asynchronous drive can be detected by monitoring the supply and capacitive current, which can be measured without the use of special sensors.

3 "Conversion" level organization

The analysis of current supply harmonics (MCSA-Technology) consists in the decomposition of the signal using Fourier transform and amplitude analysis at characteristic frequencies. Each fault has its own characteristic frequencies, including sub-harmonics, harmonics and intera-harmonics between the spectral lines of the reverse frequency - f_{rot}. For example, if there are harmonics of the reverse frequency (f_{rot}, $3f_{rot}$, $5f_{rot}$), there will be misalignment or no parallelism of the motor shafts and the mechanism. With several simultaneous defects of the shafting line, half and quarter harmonics appear ($¼f_{rot}$, $½f_{rot}$, f_{rot}, $1{,}5f_{rot}$). With the stator winding, the stator windings fob, $2f_{rot}$, $3f_{rot}$, etc.

The analysis of the harmonics of capacitive currents (CTG-Technology) studies the capacitive currents to ground. In the case of vibration, the capacities change with frequencies proportional to the vibration of the active part in the engine [9, 10], i.e. it is possible to determine the regularities of vibration phenomena in the engine itself, and therefore it exceeds the harmonic analysis of the currents feeding the motor in terms of information.

Schemes for diagnosing the engine when measured on the motor supply cable, i.e. characteristics of the motor feeding the network, is possible taking into consideration two conditional directions:
- the first direction is the low-frequency range representing the "mechanical defects": the informative characteristic of which are supply current spikes in the "power supply wires or motor leads", these defects can be detected by the harmonic analysis of the supply current (MCSA) during the galvanic analysis from the supply wire or input into the motor (e.g. see Figure 3, a).

- the second direction is for the circuit in the high-frequency range or "defects of the electric type": the informative characteristic of which is the voltage surges on the "motor power wires". These defects are fixed by the measurements of pulsations (voltage surges) on the motor power cables during galvanic analysis of capacitive currents from the motor to ground (CTG) (e.g. see Figure 3, b).

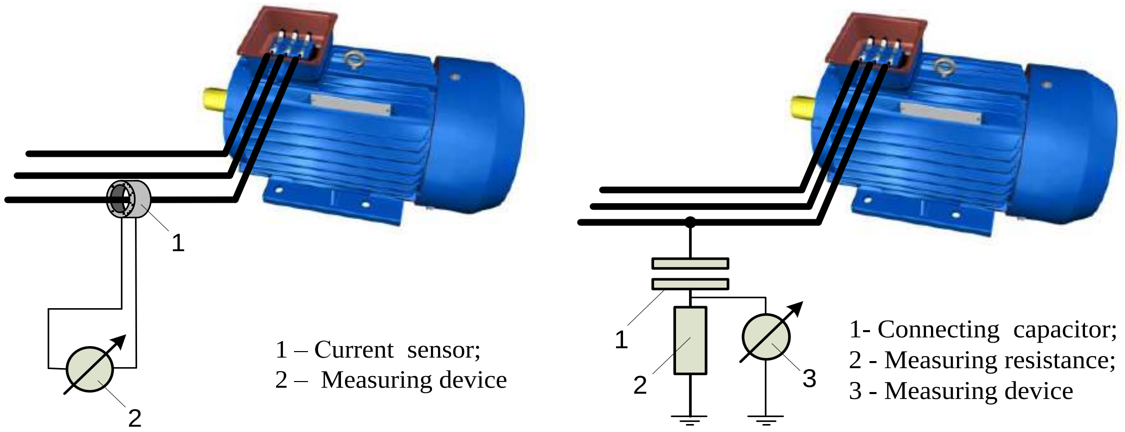

Figure 3. General scheme of galvanic connection for measurements and harmonic analysis of the current feeding the motor a) for the control of "mechanical defects" (MCSA-Technology), b) for the control of defects of "electric nature" (CTG-Technology).

4 Technical condition diagnosis method

At the present time the most popular method for current signals analyzing is Fourier transform, which has a number of disadvantages [11]. This method leads to the loss of valuable diagnostic information. In general, it is not suitable for use in the composition of the cyber-physical system.

An analogue of the Fourier expansion is the wavelet transformation is considered. It treats the signal as a two-dimensional sweep in time and frequency. The wavelet functions of the basis allow us to identify local signal features that cannot be detected using the traditional Fourier and Laplace transformations. The wavelet transformation of a signal is represented in the form of a generalized series or as Fourier integral over a system of basic functions [12]

$$\psi_{ab}(t) = 1/\sqrt{a}\,\psi((t-b)/a), \qquad (1)$$

constructed from the parent (original), the wavelet $\psi(t)$ possesses certain properties, due to the time shift operations b and the time scale change a. The factor $1/\sqrt{a}$ ensures that the norm of these functions is independent of the scaling number a. Small values of a correspond to small scales $\psi_{ab}(t)$, or high frequencies (ω~1/a), large parameters of a - to large scale $\psi_{ab}(t)$. The wavelet scale, as a unit of the time-frequency representation of the signals, is inversely proportional to the frequency (e.g. see Figure 4).

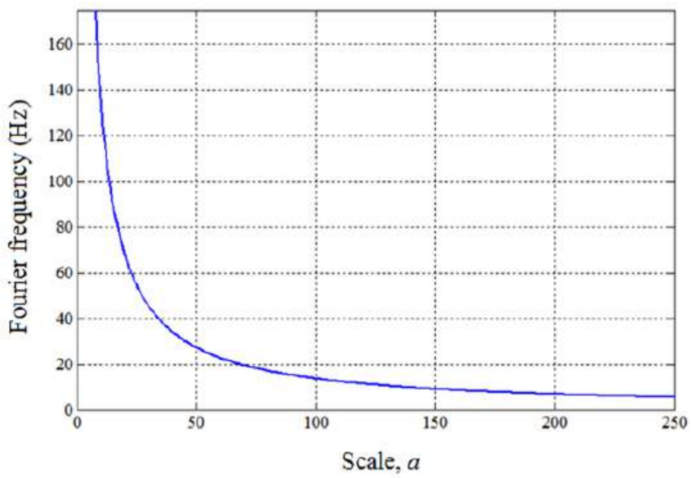

Figure 4. Correspondence of the Fourier frequency and the scale of the wavelet

To troubleshoot using wavelet transforms, it is necessary to recalculate the Fourier frequencies of the spectrum into the scale of the wavelet, according to the relationship in Fig. 5. The analysis of the signal at the received characteristic frequencies allows finding the object malfunctions. A large number of experiments conducted on DC and AC engines under various loading conditions made it possible to reveal the regularity illustrated in Figure 5.

The wavelet coefficients at the characteristic scales of the healthy and faulty motors significantly differ from each other. With a serviceable unloaded engine, they have minor oscillations at start-up, then the process is practically linearized. When a load occurs, the oscillatory process at the start of the engine is more pronounced, but then decreases with repetition at certain periodicity. While the process is stable, there is no significant increment in the amplitude of the oscillations with time (Fig. 5, a). The coefficients of the wavelet transformation of the faulty motor are much lower than the serviceable ones and have constant oscillations. This phenomena increases when the load appears (e.g. see Figure 5, b).

The plot of wavelet coefficients on an uncharacteristic scale for a faulty and faulty motor is identical (e.g. see Figure 5, c). The signal has a high density and small values of wavelet coefficients, while the signal is regular and completely repeated at a specified repetition rate. This regularity is valid for the current, voltage, and vibration for AC and DC drives.

The received five characteristic signals can be used to design the identification of the state of electric drives in the structure of the cyber-physical diagnostic systems based on an artificial intelligence approach.

To apply the obtained experimental information in cyber-physical diagnostic systems, it is necessary to develop a method for automatic signal analysis without the involvement of an expert. One of the methods for solving this problem is the development of a neural signal classification network [13]. As the initial data, the values of the wavelet coefficients are used on a characteristic scale uncharacteristic for the failure (e.g. see Figure 5). As an input, a matrix containing five lines of characteristic signals is given. The output of the network is the class of diagnosis: "1" - normal or "2" - defective.

To classify the technical state of an object, a neural network of direct signal transmission having the structure shown in Figure 6 is modeled.

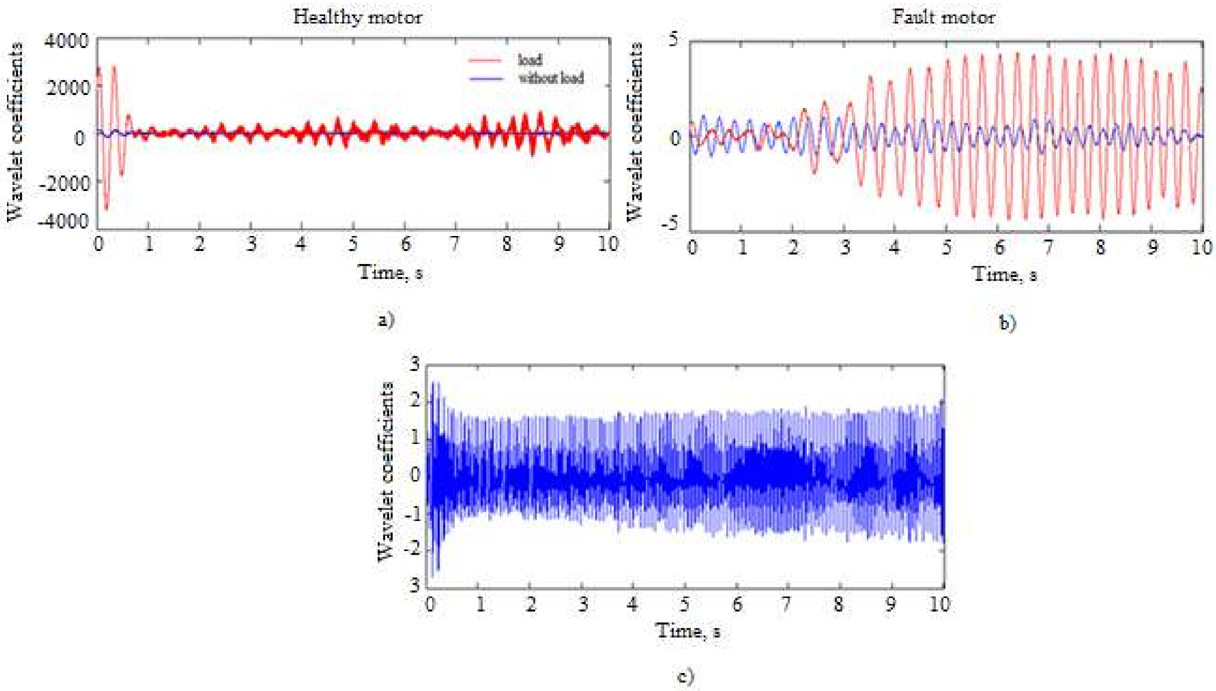

Figure 5. The wavelet current signal: (a) the characteristic scale of the serviceable engine, (b) the characteristic scale of the faulty engine, (c) the uncharacteristic scale of the faulty and faulty engines

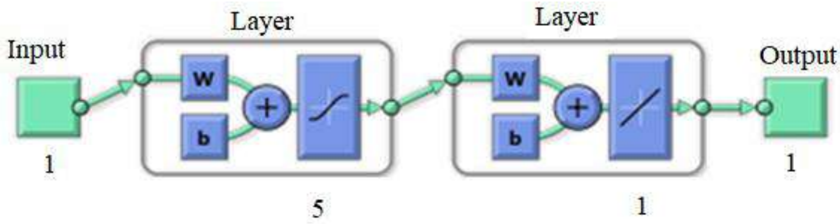

Figure 6. Structure of the neural network classification of the technical state of the electric drive

The network contains three layers: input, hidden and output layers. The hidden layer has five neurons with a tangential activation function while the output layer is a linear neuron. To train the neural network, the Levenberg-Marquardt algorithm [14] which is designed to optimize the parameters of nonlinear regression models is used. The network training and validation results are shown in Figure 7. The output of the neural network is a vector string containing the given technical state number "1" - normal, "2" defective. The size of the output vector is equal to the number of wavelet coefficients. Therefore, for the convenience of analysis, it is necessary to find the mean value and round it according to the rules of mathematics. As a result, you can evaluate the status of the diagnostic object.

To test the trained network, samples of the training set were randomly assigned to the input, and the network unmistakably assigned them to a given class. The status of the technical condition was checked during the diagnosis of the induction motor (e.g. see Figure 8). The analysis was performed on a faultless and faulty engine at various rotational speeds. To simulate a malfunction, an additional resistance was introduced into one of the phases of the stator winding, which is equivalent to closing the turns of the stator winding. This fault can be determined on the first three harmonics of the reverse frequency.

The wavelet coefficients of the supply current at these frequencies were fed into the trained neural network, which unmistakably classified the serviceable engine to class "1", and the faulty engine to class "2". An analysis of the other scales of both engines has shown that the state of the engine belongs to class "1". The received neural network therefore allows the determination of the technical state and the cause of the failure.

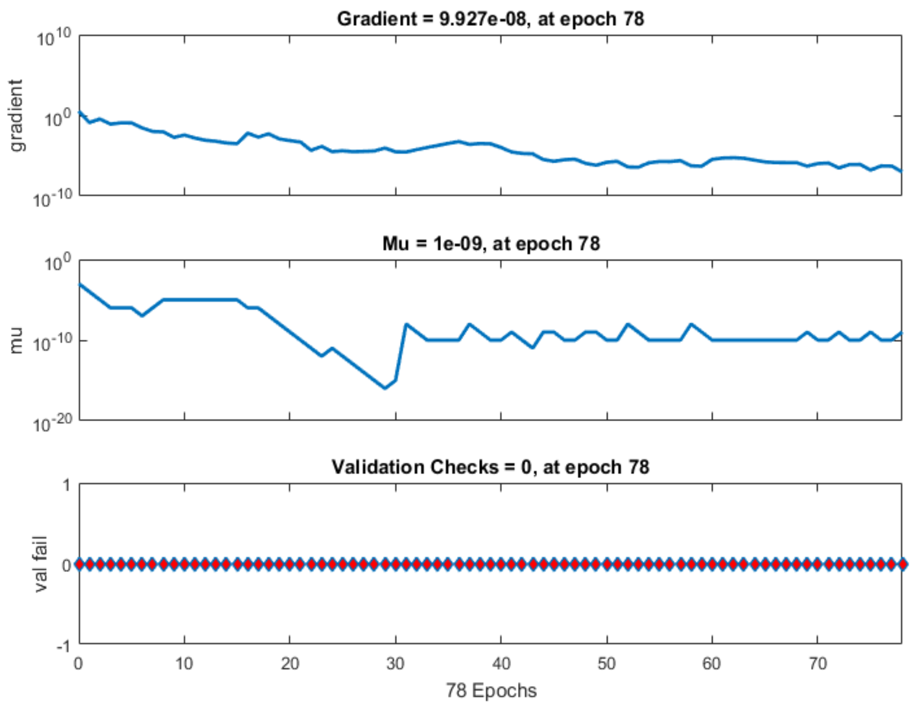

Figure 7. Learning outcomes of signal classification neural network

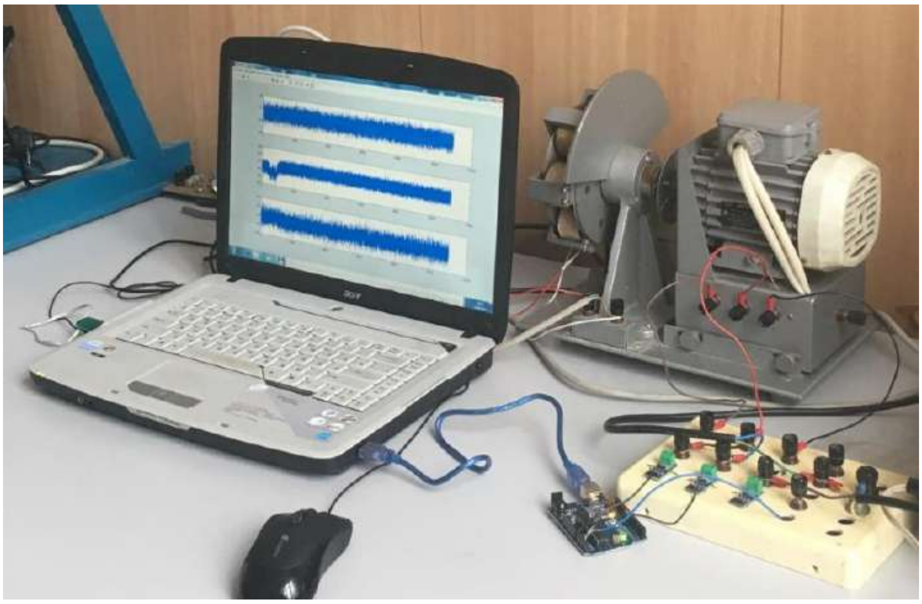

Figure 8. Experimental researches

A method for diagnosing electric drives of building robots has been obtained, which makes it possible, without using expensive measuring instruments, to determine their current state of failure, a malfunction from changing the operating mode. This will increase the efficiency of such robots and the quality of construction operations.

The performed efficiency analysis shows that the introduction of the proposed methods makes it possible to increase the productivity of the facility by 17-18%, the technical utilization factor by 14% and obtain an economic effect if the modernization costs do not exceed 20% of the cost of the facility.

5 Conclusion

In this paper, the design of a cyber-physical system for diagnosing and predicting the technical condition of electric drives of construction robots is presented. Furthermore, the structure of the cyber-physical system consisting of five levels is defined and the work of each system level is also described. The statistics of defectiveness of asynchronic drives were shown and their existing diagnostic methods considered.

The optimal set of diagnostic parameters for drives used in building robots was selected taking into account operating conditions. The existing methods for measuring and analyzing selected parameters have been described and a method for analyzing diagnostic parameters proposed. This method allowed the determination of the technical state of the robot drives under different load conditions of the drive. To implement this method, wavelet transformation and neural networks for the classification of signals were proposed. It was further established that any maternal wavelet may be used. Finally, the validity of the theoretical calculations and the adequacy of the model were confirmed by the large volume of experimental studies.

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Visualization of Integrated Model of Construction Projects

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Abstract –

Efforts to integrate construction planning have thus far focused on the interoperability of models and computer applications. However, merely linking different models, e.g. design and schedule, while useful, necessarily restricts planners to an iterative improvement of plans. This research defines a single integrated mathematical model with singularity functions to directly represent the different aspects that need to be considered in planning construction projects, such as their design, schedule, budget, site layout, etc. This allows all relevant aspects to be taken into account simultaneously when optimizing the construction plan. The new model can be used to visualize different aspects of a project, allowing the planner to interact with the model and manipulate it. Examples are provided for the intuitive visualization of the time-space that building components, site objects and construction activities occupy, of the dynamic relations and buffers between objects and activities, and of the impact of changes in the plan.

Keywords –

Scheduling, Singularity Function, Site Layout, Cranes

1 Introduction

The efficient and safe planning and management of construction projects requires an integrated modeling of their different aspects (or 'dimensions'). Much effort, centering on applying Building Information Modeling (BIM), has consequently been made in the domain of integrated project modeling (e.g. [1], [2]). But as the following section will explain, currently available multi-dimensional models generally consist only of partially interlinked models. While this allows making certain manual and iterative improvements in the construction plan, it does not fully support its efficient optimization.

Therefore we propose that a truly integrated model of construction projects should be based upon a single mathematical model that is capable of representing all their relevant aspects. This would allow construction plans to be continuously modified and optimized according to evolving project objectives and constraints. These constraints (e.g. scope, time, cost, and resources) are typically interrelated, yet competing with each other. Also, effective means for an integrated visualization of these different aspects of a project should be developed to provide planners and managers with their complex information in a way that will be easily understood. It will also allow them to directly manipulate the model, in accordance with the dynamically changing conditions.

This paper presents such a mathematical model for integrated modeling of construction projects, which addresses different elements, e.g. building components, construction activities, and temporary site objects, and the dimensions of time, cost and spatial location. The paper also presents a novel framework for visualizing the model, using three-dimensional (3D) diagrams that can represent any chosen triplet of aspects of the project.

2 Literature Review

Visualization is an emerging area, riding on a rapid increase in ubiquitous computing capabilities and access devices. Tools equip their users with powerful ways to communicate with near and far participants, understand complex interactions of aspects, and support decision-making. A list of 17 'grand challenges' for visualization, information modeling, and simulation includes needs to provide 'formats and mediums suited for construction", "format and interoperability to enable data sharing", and "[g]enerating models that adapt to real-world changes", plus calls to stronger connect academia with industry [3, p. 2] Currently only partially interconnected models of the aforementioned vital aspects of construction projects are available, which allow merely an iterative process of limited improvement, but no truly efficient optimization.

Sorting the literature by dimensionality of its models illustrates the relevant rather diverse body of knowledge:

- 2D: Linking work with time, linear, repetitive, and location-based schedules [4] represent productivity explicitly, not just duration in network schedules. Focusing on finances instead of product, cash flow diagrams can track cost and payments over time to determine cumulative balances throughout the life of a project [5]. Analogously, resource use over time can be optimized for even workflow (leveling) [6] or shortest project duration (allocation). Some models allow handling multiple resource types [7];

- 3D: Three-dimensional space dominates existing commercial computer-aided design (CAD) tools, whose dimensions are spatial. Suitable coloration and iconography can give information of planned versus actual progress [8]. But 3D can also offer spatial-temporal views, e.g. work paths across sites at different times [9]. It can apply logic operators between site objects [10]. Extending the traditional criticality and float concepts gives spatial-temporal schedules [11]. Even more varied representations of any permutation of three aspects generates all existing diagram types, plus various new ones [12];
- 4D: Four-dimensional (4D) models are dominated by animating 3D CAD images as short videos, e.g. to plan site operations with an easy-to-understand way. Alternatively, selected view may be shown as slices of a 'space-time cube' [13]. The entire 4D realm is closely related to BIM applications [14];
- 5D: While five aspects, namely technical, schedule, cost, context, and financing, have been presented jointly [15], they unfortunately remained limited to mere spider charts, which simply plotted empirical assessments of megaprojects on a 0-to-100 scale;
- nD: Further expansion require shifting to a purely mathematical model, where complete graphics are no longer feasible, but all aspects can be contained in an *n*-dimensional vector space. Three aspects of interest could always be selected for visualization.

But a conceptual gap in the aforementioned spatial-temporal mathematical model remain is its lack of site objects. Refining it will create a comprehensive 3D tool as a foundation toward future generalization [12]. Two sequential objectives are established to support this goal:

1. Derive a mathematical model to handle any temporary site objects in spatial-temporal 3D space;
2. Create and validate a visualization of the cost of temporary site objects within spatial-cost 3D space.

3 Methodology

In this paper a mathematical model is presented. It can represent different aspects of a construction project, such as time, work, and cost, using singularity functions. It supports continuous modification and optimization of the construction plan by expressing physical elements:

- Building components and assemblies;
- Stationary and moving construction activities;
- Planned work spaces and the work paths within them, and required safety buffers around them;
- Temporary site objects: Cranes, stockpiles and their changing sizes, earthmoving equipment.

Elements are linked by Boolean operators of AND, OR, and XOR or the material implication (IF-THEN). Visualization as 3D diagrams will provides the planner with the complex information in a way that is easily understood to support manipulating the model directly.

3.1 Singularity Functions

Singularity functions were first used in structural engineering to calculate the effects of distributed loads at different sections of beams [16]. The term singularity indicates that the function behaves discontinuously at a point, but is defined for all values of the independent variable [17]. Managerial dimensions of construction engineering and management feature such independent-dependent variable pairs, e.g. work quantity and time (linear schedules), resource counts and time (resource leveling and allocation), and cost and time (cash flows). This implies that the underlying formulation of loads on beams can be swapped for such quantifiable aspects of projects, and indicates that the mathematics should work, as prior research has successfully shown [e.g. 6, 5, 12].

3.1.1 Point-Scalar Form

Equation 1 defines the basic term of any singularity functions within a two-dimensional coordinate system. Pointed brackets are a case distinction operator to select from two options: If the independent variable x is equal to or larger than the activation cutoff a, then brackets are treated like conventional round algebraic ones, else if x is smaller than a then the operator returns zero. Note that Equation 1 is right-continuous; Equation 2 provides an analogous left-continuous version. Changing strength s and exponent n generates customized behaviors of the function, whereby the former acts as a scalar to increase or decrease its magnitude and the latter steers its growth.

$$y(x) = s \cdot \langle x-a \rangle_{\mathrm{R}}^{n} = \begin{cases} 0 & if\ x < a \\ s \cdot (x-a)^n & if\ x \geq a \end{cases} \tag{1}$$

$$y(x) = s \cdot \langle x-a \rangle_{\mathrm{L}}^{n} = \begin{cases} 0 & if\ x \leq a \\ s \cdot (x-a)^n & if\ x > a \end{cases} \tag{2}$$

3.1.2 Point-Vector Form

Singularity functions can be extended to 3D [9, 10]. Vector $\boldsymbol{v}$ starts at point (x_{1S}, x_{2S}, z_S) to grows in direction (Δx_1, Δx_2, Δz) per Equation 3. An independent variable h_1 from 0 to 1 within the operator controls how $\boldsymbol{v}$ grows until it finishes at ($x_{1S} + \Delta x_1$, $x_{2S} + \Delta x_2$, $z_S + \Delta z$). Such a point-vector form can model any line segment from start to finish within a 3D space system. For spatial-temporal schedule modeling, the first two elements in the three coordinates (x_1, x_2, z) will represent its spatial dimension, while the third coordinate z denotes the time dimension.

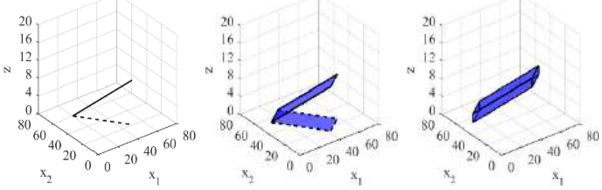
$$\mathbf{v}(h) = \begin{pmatrix} x_{1S} \\ x_{2S} \\ z_S \end{pmatrix}_{Start} + \begin{pmatrix} \Delta x_1 \\ \Delta x_2 \\ \Delta z \end{pmatrix} \cdot \left(\langle h_1 - 0 \rangle_R^1 - \langle h_1 - 1 \rangle_R^1 - \langle h_1 - 1 \rangle_L^0 \right) \tag{3}$$

3.2 Work Area Definition (Temporary Site Objects)

3.2.1 Earthmoving (Prism)

Many construction activities proceed linearly on a site, e.g. earthmoving or paving. Its equipment moves accordingly. The geometrical shape of that equipment in the 2D spatial plane is a rectangle, whose length is the moving distance (dashed line in Figure 1a) and width is a safety buffer for traveling equipment [10]. Adding the duration data for this earthmoving activity adds a slope in the 3D spatial-temporal coordinate system (solid area in Figure 1b) to the rectangle. Note that the projection of the sloped rectangular plane into the x_1-x_2 plane is the spatial work area of the equipment (dashed area in Figure 1b). Assume that a time buffer of 2 days must be maintained for an earthmoving activity. Then the sloped rectangular plane has a height of 2 days and expands the geometrical shape to a prismatic volume (Figure 1c).

The point-vector form of Equation 3 captures a start point plus an offset; only the offset part has a singularity function term. Applying this offset concept to a line will generate a rectangular plane, and offsetting it will create a prism [10]. The flowchart of Figure 2 defines a prism in 3D space mathematically with three offsets functions per Equation 4 (n = 1, 2, 3). Note that a term '+ $Offset_n$' is applied to all points in the geometrical shape *before* the term (i.e. start point, start line, and start plane). For Example 1, an earthmoving activity starts at (20, 60, 0) and moves to its finish position at (50, 20, 10) with a duration of 10 days. The spatial safety buffer is 10 m to each side (perpendicular to the moving direction). Time buffer is 2 days. Thus the inputs are: (x_{1S}, x_{2S}, z_S) = (20, 60, 0), $Offset_1$ = (30, -40, 10), $Offset_2$ = (8, 6, 0), and $Offset_3$ = (0, 0, 2), respectively, as Figure 1 shows.



(a) Line (b) Plane (c) Prism

Figure 1. Process to Generate Prism

1: Known variables
Start point (x_{1S}, x_{2S}, z_S) and $Offset_1$, $Offset_2$ and $Offset_3$

2: First offset generates line
Start point (x_{1S}, x_{2S}, z_S)
Finish point = start point + $Offset_1$

3: Second offset generates plane
Start line (shape from step 2)
Finish line = start line $\pm Offset_2$

4: Third offset generates prism
Start plane (shape from step 3)
Finish plane = start plane + $Offset_3$

Figure 2. Flowchart to Define Prism

$$Offset_n = h_{nS} \cdot \langle h_n - h_{nS} \rangle_R^0 + \begin{pmatrix} \Delta_{nx_1} \\ \Delta_{nx_2} \\ \Delta_{nz} \end{pmatrix} \cdot \left(\langle h_n - h_{nS} \rangle_R^1 - \langle h_n - h_{nF} \rangle_R^1 - \langle h_n - h_{nF} \rangle_L^0 \right) \tag{4}$$

3.2.2 Crane (Prism Sector)

The geometric shape of the work area of a crane is a cylinder in the 3D spatial-temporal coordinate system, whose mast is located at the center around which its jib rotates with a certain radius [18]. If a crane may only rotate within an angle on a construction site, e.g. to not swing over a sidewalk for safety reasons, then its work area is a prism sector in the 3D space. To define a sector per Figure 3, $Offset_2$ in the flowchart will be a rotation and mathematically expressed as a rotation matrix [17]. Equation 5 is the rotation function, where θ is the angle of rotation. Note that the singularity function term $\langle \theta - 0 \rangle^0_R \cdot \langle -\theta - (-2\pi) \rangle^0_R$ controls a range [0, 2π] of the angle. For Example 2, a crane mast is located at (70, 70, 0) and its jib radius is 60 m. The start position of the jib end point is (22, 34, 0) and the angle of rotation is $\pi/4$. The duration of the crane on the construction site is 10 days. Thus the inputs are: (x_{1S}, x_{2S}, z_S) = (70, 70, 0), $Offset_1$ = (-48, -36, 10), $Offset_2$ is the rotation matrix with θ is $\pi/4$, and $Offset_3$ = (0, 0, 10). Figures 4a-4c show how to generate the work area for this crane.

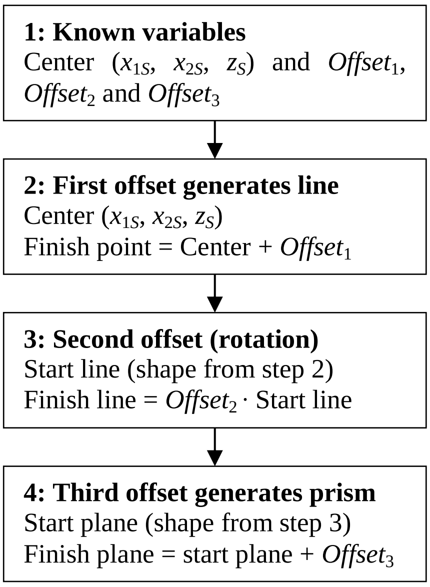
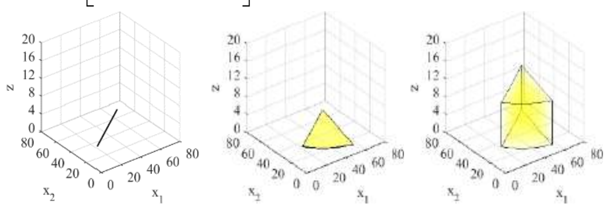


Figure 3. Flowchart to Define Sector

$$Offset_2 = R_z(\theta)\cdot\langle\theta-0\rangle_R^0\cdot\langle-\theta-(-2\pi)\rangle_R^0 \tag{5}$$

$$= \begin{bmatrix} \cos\theta & -\sin\theta & 0 \\ \sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix}\cdot\langle\theta-0\rangle_R^0\cdot\langle-\theta-(-2\pi)\rangle_R^0$$



(a) Line (b) Sector (c) Prism

Figure 4. Process to Generate Sector

3.2.3 Material Stockpile (Cone)

Material waiting to be lifted by a crane is assumed to be a cone, so that the area of the material stockpile will decrease to zero. If an original pile with radius R will be exhausted in D days, then the radius Offset1 decreases from R to 0. Thus, the radius change rate Δr = R / D. Assuming that the pile is exhausted continuously, the offset in the time direction Offset3 for each layer of the pile at a time point also grows continuously. For this, the temporal dimension of Offset3 (Δz) has infinitesimal duration ε, and its integral is D ($\int_{z_S}^{z_F} \Delta z dz = D$).

Figure 5 shows the flowchart to define a cone. The difference between Figure 5 and Figure 3 is that there is an iteration loop for modeling a cone: If the radius $Offset_1$ is larger than zero and $\int_{z_S}^{z} \Delta z dz$ is smaller than D, then subtract the radius change rate Δr from the radius until the radius becomes zero (material exhausted) and $\int_{z_S}^{z} \Delta z dz$ is equal to D. For Example 3, the center of a pile is located at (40, 40, 0) with an initial radius of 20 m. The duration to exhaust the stockpile is 10 days. In the 3D spatial-temporal coordinate system this pile has a height (or duration) of 10 days. The radius change rate Δr is 2 meters / day. Thus the inputs are: (x_{1S}, x_{2S}, z_S) = (40, 40, 0), $Offset_1$ = (-20, 0, 0), $Offset_2$ is the rotation matrix with θ is 2π, and $Offset_3$ = (0, 0, ε). Figures 6a-6c shows how to create the work area of this pile.

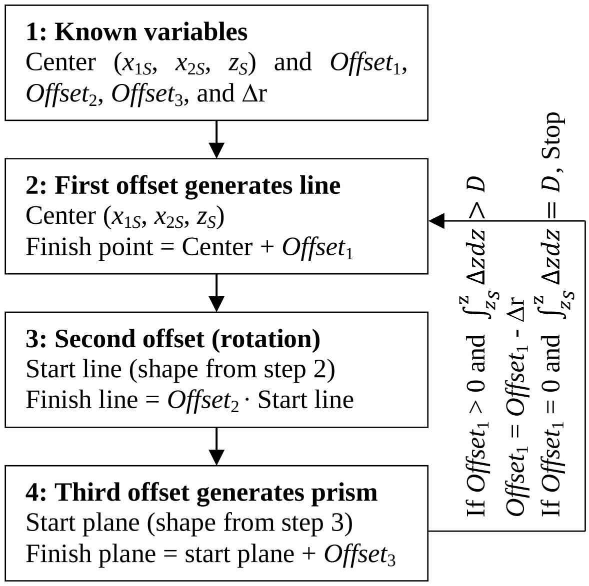
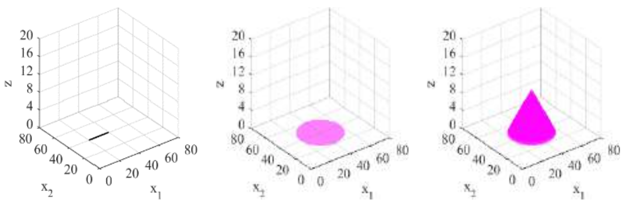


Figure 5. Flowchart to Define Cone



(a) Line (b) Circle (c) Cone

Figure 6. Process to Generate Cone

3.3 Spatial and Temporal Relations (Boolean)

Boolean relations can be used to define constraints between multiple temporary site objects in the spatial-temporal 3D space [10]. Four types are considered: Material implication IF-THEN, conjunction AND, disjunction OR, and exclusive disjunction XOR. The IF-THEN is only defined on the time dimension (i.e. two activities must occur sequentially – if the predecessor is finished, then a successor can start). The other three relations are used to define spatial-temporal constraints: Multiple temporary site objects must occur concurrently (AND); multiple temporary site objects can (but need not) occur concurrently (OR); or multiple temporary site objects must never occur concurrently (XOR). Boolean operations between two objects can be calculated with signals of these objects. Per Equation 6, the signal value of an object is 1 if a coordinate point is inside the work area of the object and 0 if it is outside. Rules for signal functions to conduct these four Boolean operations are summarized in Table 1. Boolean operations with signal functions are then multiplied with work areas functions to model temporary site objects and their relations in spatial-temporal 3D space. This fulfils Objective 1.

$$Signal(x_1, x_2, z) = \begin{cases} 0 & if \quad (x_1, x_2, z) \notin Object \\ 1 & if \quad (x_1, x_2, z) \in Object \end{cases} \tag{6}$$

Table 1. Boolean Operations and Signal Functions (adapted from [10])

Type	Rule A	Rule B	Rule result	Signal function
IF-THEN	1	1	1	N/A
	1	0	1	
	0	1	0	
AND	1	1	1	$Signal_A \times Signal_B$
	1	0	0	
	0	1	0	
OR	1	1	1	$Signal_A + Signal_B - Signal_A \times Signal_B$
	1	0	1	
	0	1	1	
XOR	1	1	0	$OR_{Signal} - AND_{Signal}$
	1	0	1	
	0	1	1	

3.4 Spatial-Cost Area Definition

In analogy to spatial-temporal work areas, spatial-cost can be modeled to visualize location and cost data, where the vertical axis is cost. This shows the total cost of different items on site and allows comparing options visually. To realize it in 3D, the assumption is: *Cost of a temporary site object is assumed as evenly distributed across its geometric shape of the spatial work area.*

The difference between a spatial-temporal work area and a spatial-cost area is that time grows continuously, whereas cost occurs discretely (e.g. daily, weekly, or once). For mathematical modeling, the temporary site object concept of Section 3.2 is used, but using the cost as the third dimension instead will return their functions for spatial-cost area, which is omitted here for brevity. From the general contractor's perspective, the shapes of spatial-cost areas of temporary site objects are:

1. Material: Cost occurs once when transporting it to the site. It is a cylinder with the height of its total cost;

2. Crane: Cost occurs periodically (e.g. weekly rental). Its shape are a multiple layers of a sector surface with the height of the cumulative total weekly cost;

3. Earthmoving: Cost gradually increases (daily). Its shape is a cuboid with a height of its total cost (or layers of a rectangular surface, whose number equals duration, with the height of the cumulative total cost for each day).

4. Indirect: Cost gradually increases (daily) and covers the whole project. Its shape is a solid with the height of its total cost (or layers of a whole site surface, for which the same rules will apply as for earthmoving).

Geometric shapes in 3D spatial-cost space are shown in the next section. Defining and visualizing cost data for temporary site objects fulfills Objective 2.

4 Application

The following example demonstrates how this new integrated model can analyze, visualize and improve the scheduling, cost and site layout planning of construction projects. In the example, two sequential activities (with a finish-to-start or IF-THEN relationship between them) are executed in a rectangular work area. Earthmoving equipment is used for Activity 1, whereas in Activity 2 a crane lifts material that is stored onsite. Consequently, AND relationships are defined between crane, material, and Activity 2. An XOR relationship is defined between the crane and Activity 1 to prevent safety hazards.

The model is applied to plan the activities so that their durations and costs are minimized. Two options will be compared. In Option 1, Activity 2 is carried out by one crew with a single crane. In Option 2, Activity 2 is carried out simultaneously by two crews with two cranes. The optimal option in terms of both duration and costs is identified by a least-cost scheduling approach, which reduces the duration of the activities in each option until their total cost has been minimized, without violating the previously described relationships.

Figure 7 shows temporal and spatial dimensions of activities and site objects in Option 1 with 3D time-space diagrams. In them, the locations of the objects on the site are indicated on the horizontal axes, whereas the duration of their presence on site is indicated on the vertical axis. This allows the user to easily change their location and/or timing while exploring options. Figure 8 analogously shows cost and spatial dimensions in the cost-space diagrams. In them the vertical axis indicates the cost of each object. This provides the user with an immediate understanding of cost implications of any change in the plan. Time-space diagrams and cost-space diagrams for Option 2 are shown in Figures 9 and 10.

The resultant site layout plan for Option 1 is shown in Figure 11, and its final schedule and costs in Tables 4 and 5. Figure 12 shows the site layout plan for Option 2. The final schedule and costs of this Option are shown in Tables 2 and 3. A comparison shows that Option 2 has a shorter duration (6 days versus to 9 for Option 1) and a lower cost ($305,000 compared to $327,500).

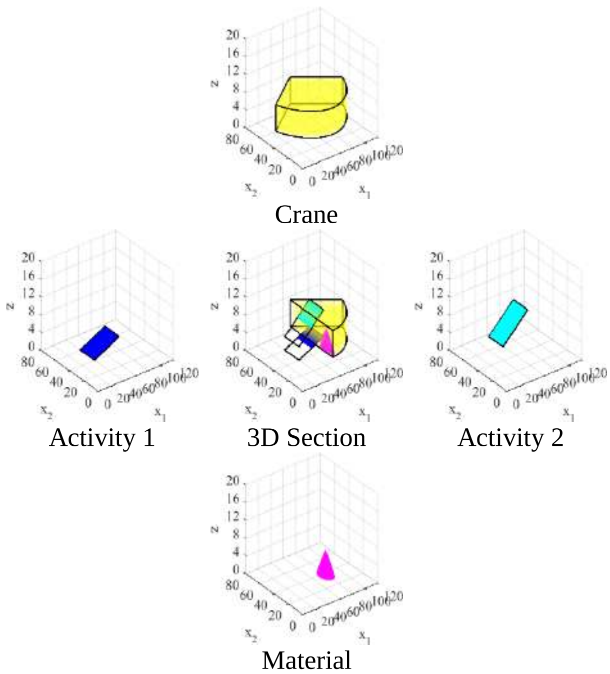


Figure 7. Time-Space Diagram (Option 1)

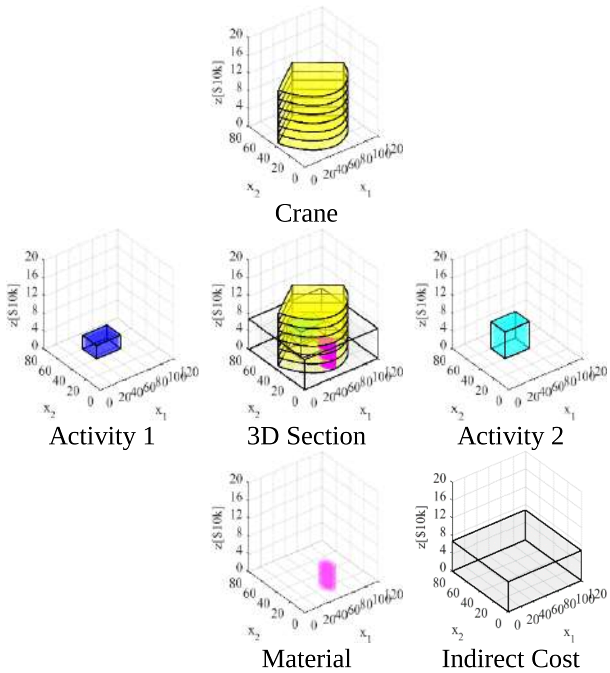


Figure 8. Cost-Space Diagram (Option 1)

Table 2. Schedule Data for Option 1

Activity	Duration (weeks)	Start (week)	Finish (week)
1	3	0	3
2	6	3	9

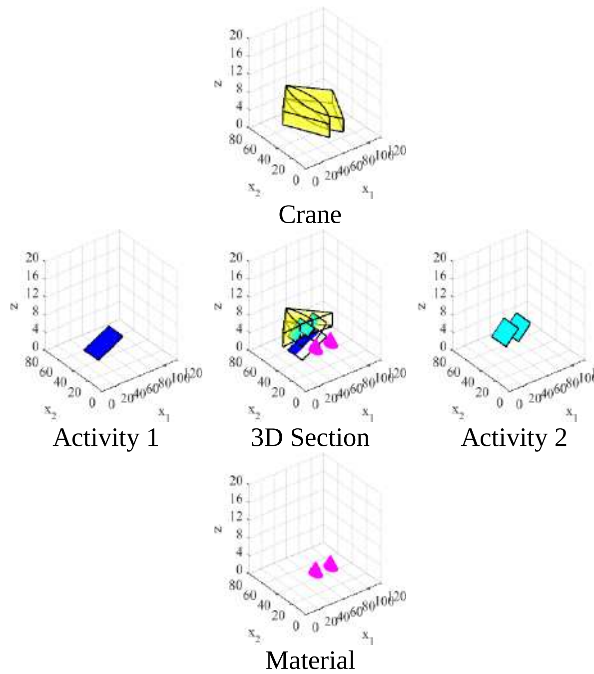


Figure 9. Time-Space Diagram (Option 2)

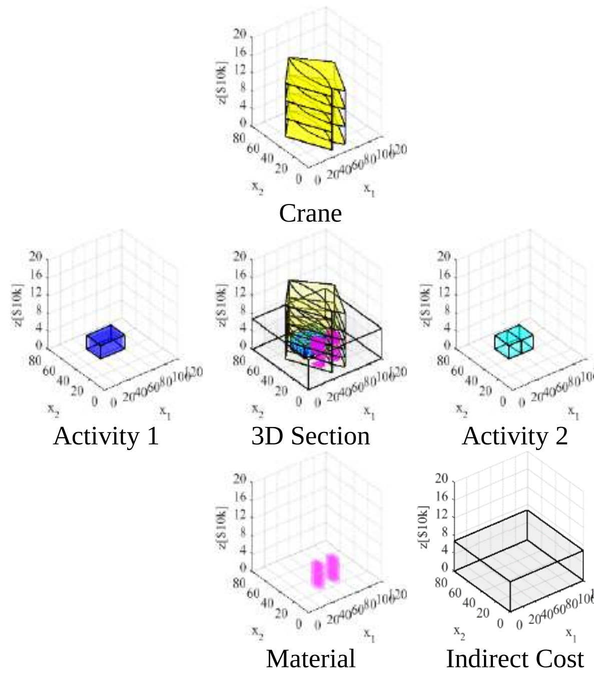


Figure 10. Cost-Space Diagram (Option 2)

Table 4. Schedule Data for Option 2

Activity	Duration (weeks)	Start (week)	Finish (week)
1	3	0	3
2	3	3	6

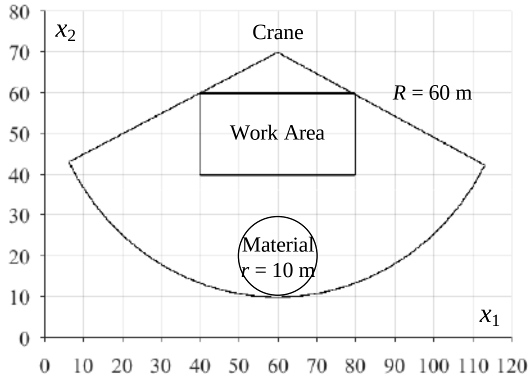


Figure 11. Site Layout for Option 1

Table 3. Cost Data for Option 1

Item	Cost	Subtotal
Manpower	\$2,000 per day (entire project)	\$90,000
Material	\$50,000 (week 3)	\$50,000
Crane	\$20,000 per week (weeks 3-9)	\$120,000
Indirect costs	\$1,500 per day (for entire project)	\$67,500
	Total cost	\$327,500

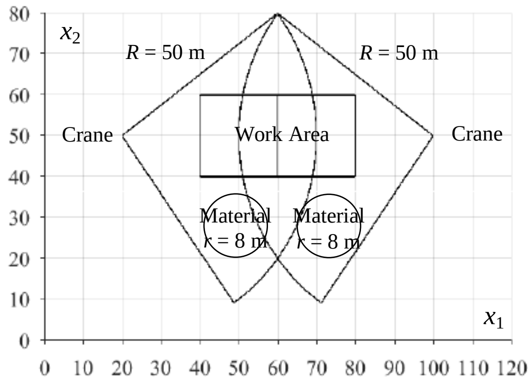


Figure 12. Site Layout for Option 2

Table 5. Cost Data for Option 2

Item	Cost	Total cost
Manpower	2,000 per day (weeks 1-3)	90,000
Material	50,000 (week 3)	50,000
Crane	20,000 per week (weeks 3-6)	120,000
Indirect costs	1,500 per day (for entire project)	45,000
	Overall cost	305,000

5 Conclusions

This paper has presented a novel integrated model to plan construction projects. As has been demonstrated, it can be used to maximize the efficiency of both the site layout plan and the execution of the planned activities, without compromising the safety. Options can be easily modified and compared through the new diagram types.

5.1 Contributions

This paper has made the following contributions:

- A mathematical model has been presented that can represent different aspects of a project, (e.g. time, work, and cost), and its physical elements (e.g. building components, activities, work spaces, and temporary site objects);
- Boolean operators (AND, OR, and XOR or the material implication IF-THEN) can define the constraints between activities and site objects;
- Novel 3D diagrams provide planners with a visualization of complex information in a way that it can be easily understood and changed.

5.2 Recommendations for future research

Future research should expand the proposed model into a true multi-dimensional model of construction projects. Such *n*D model is envisioned to integrate and simultaneously handle multiple managerial dimensions like time, work, cost, resources, etc. Selections thereof could be visualized. The use of weighted constraints in addition to binary Boolean operators should also be inserted to enable representing not just hard constraints, but also ‘soft logic’ such as priorities and preferences of planners for their site layout based on their experience.

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Supporting Post-Occupant Evaluation through Work Order Evaluation and Visualization in FM-BIM

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Abstract –

The application of BIM and data analytics in facility management is an area of growing interest and research. The ability to mine data from occupant complaints in real-time and visualize this at the building and building cluster scale provides new opportunities for facility managers to more effectively respond to occupant complaints and optimize the performance of the building. A project is currently underway at Ryerson University in collaboration with the facility management team to mine data from work orders and develop a comprehensive visualization strategy for FM-BIM integration. This paper presents the development of mapping and data visualization strategies to support the identification of priority areas and extraction of key occupant satisfaction trends. Key visualizations and BIM integration protocols from the campus deployment are presented and discussed to identify applicability of this data to support post-occupancy evaluation, limitations, and opportunities for further expansion and refinement.

Keywords –

Post-Occupant Evaluation, Work Order, BIM, Facility Management, Visualization, Operations & Maintenance

1 Introduction

People spend 80% of their lives indoors, where indoor environmental quality has significant effects on occupant comfort, productivity, and well-being. At the same time, buildings use approximately 40% of total energy globally, with the majority of this use – and associated cost - associated with day-to-day operations [1]. Within this context, Post-Occupancy Evaluations (POEs) are increasingly recognized as providing significant value to both increase occupant comfort and decrease energy and operations costs. Studies have found that buildings rarely perform as expected during occupancy, requiring intervention [2]. Despite this, POE is rarely effectively used in practice [3] and adoption rates remain low [4]. The motivation for this research is to develop strategies to support POE through the evaluation of already-collected data (work orders) to increase this adoption rate.

While there is little consensus regarding the definition of POE [4], several elements are commonly considered within the scope of such studies: indoor air quality (IAQ), indoor environmental (thermal, acoustic, visual & spatial) quality, space functionality, asset condition, cleanliness, aesthetics, sound privacy, workspace & building features, occupant behaviour, occupant health & safety, and user satisfaction/comfort [5-10]. User surveys are the most common source of information for POEs [5], and are often combined with in-situ measurements to contextualize user responses [3, 7].

The increasing adoption of Building Information Modelling (BIM) within the Facility Management (FM) context provides a significant opportunity to integrate a multitude of building information of value to POE studies. There have been several significant studies, for example [11-13] exploring the benefit of BIM within the FM context, and this body of research is well-summarized in recent literature reviews [14, 15]. A number of case studies [16-20] demonstrate the development of such models. Of specific relevance to this paper, Akcamete *et al.* [21] linked work order information with BIM in spaces to allow spatio-temporal analysis of maintenance history to support operations; this work focused primarily on maintenance costs and issue frequency but did not consider occupant experience directly. Motawa and Almarshad [22] developed a case-based reasoning system to create knowledge from work order information. Shoolestani *et al.* [6] developed SocioBIM to enable user comments and feedback on building condition and occupant concerns, which could be read by other users and the FM team. Gerrish *et al.* [23] integrated building management systems (BMS) with BIM to develop a dashboard but found unstructured data very difficult to integrate. To overcome this unstructured data issue, machine learning was used by Raghubar *et al.* [14] to automatically classify work orders by complaint type and map these to an FM-BIM using techniques developed by Khaja *et al.* [24].

Few studies have linked BIM with POE, notably the work of Göçer *et al.* [3, 9] who created a GIS and BIM-enabled platform to support bi-directional communication between FM teams and users and created a series of supporting BIM visualizations of POE survey results. This paper responds to existing research gap of POE integration within BIM [5] and presents strategies for leveraging maintenance work orders to enhance and complement POEs. An FM-BIM integration approach is integral to implementation, providing an information management framework and visualization capacity. A set of sample visualizations from a current case study demonstrates the application of these strategies.

2 Methodology

The development of the POE-BIM integration for the case study (a university campus) consisted of six steps: (1) documentation of POE information requirements; (2) review of work order content and alignment with POE inputs; (3) storyboarding of potential visualizations; (4) development of the necessary data structure to support FM-BIM integration; (5) data mapping; and (6) visualization creation.

When analyzed and organized correctly, work orders provide a large database that enables increasing evolution of Computer-aided FM (CAFM). Generally, previous research has described three approaches to POE: indicative, investigative, and diagnostic. A work order system that is intrinsically diagnostic and lends itself to supporting diagnostic POEs, has the potential to permit targeting of investigative POE toolkits in problem areas and provide justification for such future investment.

Work orders intrinsically provide strictly negative feedback as users are motivated by dissatisfaction to report issues. As a result, work orders must be understood as first indicating those areas where dissatisfaction exceeds a threshold for the user, thus only identifying priority areas; areas without significant issues will be indicated only by a lack of comment. Because of this nature of the input data, dissatisfaction was developed as the primary metric for such diagnostics.

Prior to defining a data structure for the POE information, the visualization concept was storyboarded to determine how this information could be most effectively integrated and presented for FM use. This strategy is central to user-centered design practice of Human-Machine Interfaces (HMIs) [25] to allow end-users to provide feedback on potential visualizations.

Once the information requirements and visualization concepts were developed, the supporting data structure was created to host the required information. Because all occupant-reported work orders are logged by room by the CAFM system, rooms were deemed the most appropriate hosts. Data mapping was achieved using Python coding in Dynamo, similar to the approach presented in previous studies [23, 24]. Visualizations were then developed using HMI design best practices from industry [26, 27] and academic literature [28, 29, 30]. The data source used for test deployment are the campus work orders from 07/2015 through 12/2017.

3 Work Order and POE Alignment

3.1 Information Required to Support POEs

The 'essence' of POE has been discussed using terms such as health, safety, security, functionality, cleanliness, asset condition, satisfaction, and comfort. The first three are best defined by the presence of alarms, incident reports, and security system information, which can all be integrated in an FM-BIM, but this is beyond the scope of this initial study. Acoustic, thermal, visual, and indoor air quality [5] define the indoor environmental quality (IEQ) of a space and address the latter two categories while reports of broken fixtures, furniture and equipment (FFE) and custodial and groundskeeping requests indicate compromised functionality and condition issues (covering both maintenance and cleanliness) of specific elements within the space.

3.2 Information Generated by Work Orders

A machine-learning enabled work order reporting system is being deployed that automatically classifies work order types [31] and prompts building occupants with follow-up questions during issue reporting. These questions, developed by the FM team, provide the necessary input to both enable engineers to quickly identify problem causes and deploy the necessary personnel to resolve the issue. A sample of these categories and associated questions is shown in Figure 1.

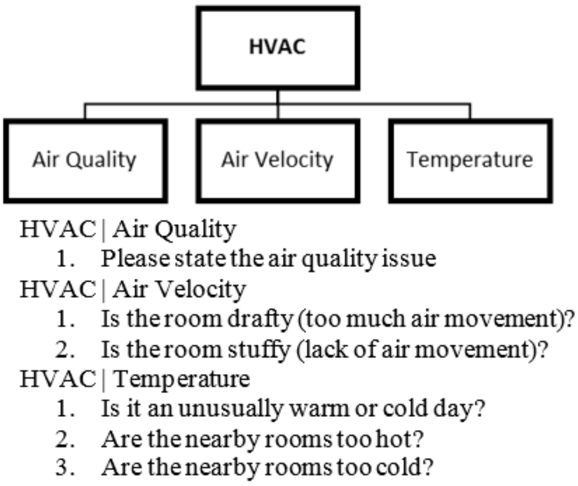

Figure 1. Work order classification structure and selected follow-up questions

This enhanced work order reporting system will allow a greater structure of information regarding occupant complaints to be obtained. Alignment with POE requirements is defined by six dissatisfaction subcategories: thermal, acoustic, IAQ, visual, condition, and functionality. These are presented alongside relevant work order categories and the information that can be gleaned from the enhanced system in Table 1. The sum of the dissatisfaction category scores is defined as the *Occupant Dissatisfaction* (OD), which serves as an overall metric and provides a basis for prioritization.

4 FM-BIM Integration

There are two key benefits to integrating POE diagnostic information into an FM-BIM. First, the multi-dimensional (nD) nature of BIM intrinsically supports data management and visualization necessary for spatio-temporal analysis of semantics. Second, complementary use cases executed in FM-BIMs such as space management, equipment characteristics and repair histories, and building automation system (controls and sensors) information, provide additional information on users, equipment, and measured space conditions, respectively, contextualizing complaints.

The FM-BIM integration consists of two key steps: pre-processing work orders to calculate dissatisfaction scores for each space over time, and mapping algorithms to integrate these score histories into the FM-BIM.

The pre-processing first uses a series of logical relationships based on the Table 1 alignment to assign a score of 1 (aligns) or 0 (does not align) for each dissatisfaction metric. Work orders are then sorted by metric. Since user complaints are reported by location, rooms are the most appropriate hosts for dissatisfaction data. Input arrays for the BIM are created such that each column includes data for the room while rows provide time series data in reverse chronological order. Each array is then saved as a comma-separated value (csv) file named for the metric type, e.g. thermal.csv. The monthly average based on two years of historical data is also calculated for each metric to provide a historical baseline for FM team reference and is saved as a separate baseline file.

FM-BIM mapping requires that a set of parameters for both monthly counts ({Thermal, Visual, IAQ, and Acoustic Dissatisfaction, Functionality, Condition} as integers), and baseline values ({same set} as numbers) to be created and mapped to rooms, levels, and buildings. Using a modification to the technique developed in [24], Dynamo is used to populate these parameters. For a given time selected, the appropriate row is identified and the mapping algorithm creates a vector of parameter values for each room. This data structure supports the integration of customized slider in the visualizations to permits navigation through time. The Dynamo script and code blocks (developed in Python) support this functionality and are presented in Figure 2.

Table 1. Work Order and POE Alignment

POE Category	POE Information Required	Work Order Category	Information generated by work order system
Acoustic Comfort	Type of Disturbance Disturbance Frequency	NOISE (all)	Description of noise Extent of complaint (spatial, temporal)
Thermal Comfort	Thermal Complaint, Draftiness	HVAC | Temperature HVAC | Air Velocity	Too hot or too cold Extent of complaint (spatial, temporal) Too much/not enough air movement
Indoor Air Quality (IAQ)	Air Quality, Freshness/Stuffiness	HVAC | Air Quality	Too much air movement (Drafty) Lack of air movement (Stuffy) Air quality description
	Olfactory Discomfort	ODOR (all)	Odor description, source (if known), Duration of complaint
Visual Comfort	Lighting Quality; Glare	LIGHTING (all) FFE | Coverings GRAFFITI	Lights burned out or flickering; Glare from non-functioning blinds or missing lens; Graffiti
Functionality	Broken Equipment	FFE | Fixture PLUMBING | Fixture	Details of broken or malfunctioning fixture(s) and equipment
Condition	Indications of spaces requiring cleaning, indications of wear, or poor asset condition	CUSTODIAL (all); PLUMBING | Leak; FFE | Paint	Reports of stains, graffiti, spills, etc. as well as leaks and other condition-related issues

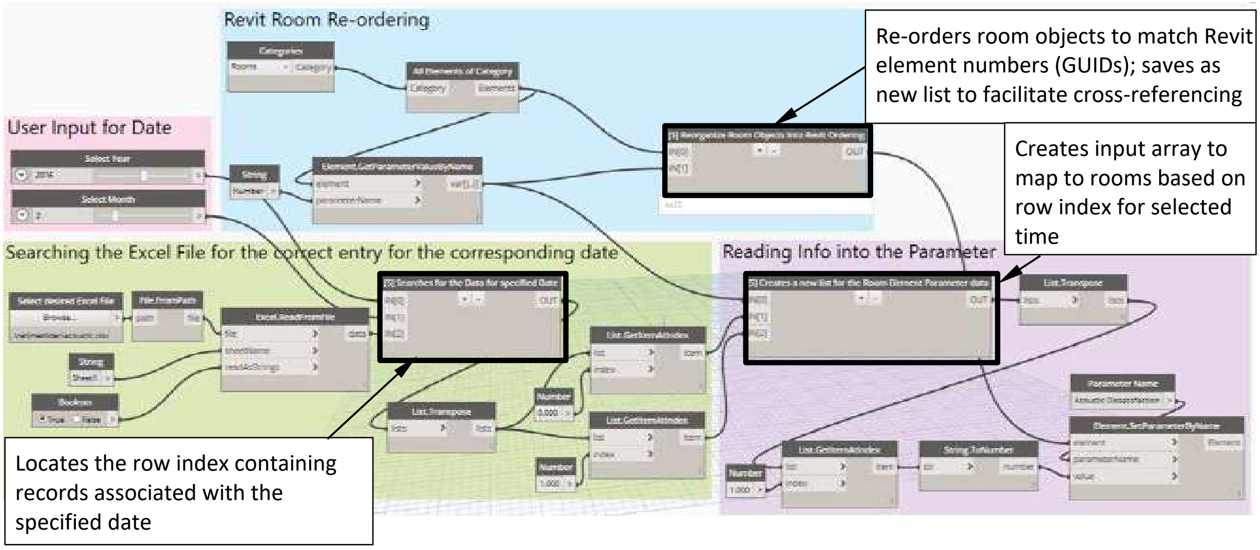

Figure 2. Dynamo script to execute time navigation and supporting code functions

5 Visualization Strategy

There has been significant research within the process control domain to developing effective human machine interfaces (HMIs). To develop the visualization strategy, HMI best practice from both academic literature [25, 29, 30] and industry guidelines [26, 27], including principles of user-centered design, were considered.

5.1 Priority Identification

In order to improve the AAG ability of CAFM systems, the proposed visualization strategy will incorporate a priority identification chart that will map, 1) worst buildings, 2) worst building levels, 3) number of open POE-related complaints for the selected time, and 4) top complaint data categories. The first two comparisons in the priority identification chart use OD (total complaints) metrics to develop these ranks, but individual dissatisfaction metrics can be selected using a toggle function.

5.2 Temporal Analysis

The dashboard will allow the user to select the desired timeframe to show OD and the associated category metrics for the area under consideration. By displaying the current (rolling window) value of these metrics along with average values from a three-year period as illustrated in Figure 3, it is readily apparent to the FM team whether the current frequency of complaints is (a) consistent (b) noticeably above, or (c) noticeably below historic values.

5.3 Spatial Analysis

Where full 3D geometry exists for FM-BIMs, 3D visualizations of the building(s) under consideration provide insight on potential causes. For example, a high window-to-wall ratio could explain significant thermal comfort issues within a particular space. Providing level totals for each of the POE dissatisfaction metrics allows the priority level(s) in a building to be identified quickly.

In all cases, 2D representation (floorplans), color-coded by semantic parameter (nD) data providing POE information are used as the primary navigation interface. Following published guidance [26, 29] a neutral (white) background is used for all floorplans and increasing color saturation – associated with each individual metric – indicates a higher dissatisfaction value.

5.4 Spatio-temporal Representation

Visualization of issue clustering in both space and time provides benefit to the FM team by simultaneously showing clusters of rooms with common issues as well as complaint clusters at individual points in time. The time navigation slider described previously permits near-real-time navigation of historical data. This functionality draws from a data consolidation and mapping architecture developed under a related project [32] to create the necessary time-series arrays for FM-BIM integration.

6 Case Study Implementation

The central theme of user-centered design is to actively engage the end-user, focusing on understanding their needs and priorities, and developing prototypes and mock-ups to gain input at each iteration [25], similar to the Agile [33] process used to develop the FM-BIM at the case study campus [34]. The following priorities were communicated by the Facility Engineers related to prioritization: (1) immediate identification of the most problematic areas; (2) visualization of clusters of issues within buildings and an understanding of these issues over time; and (3) the ability to differentiate between types of issues and their distributions. The support of root cause analysis of these complaints is a long-term goal but is beyond the scope of this study; at this time, this analysis is related to seasonal and other temporal effects.

To address the need to identify priority areas, a hierarchy of views [26] are required: 1) room, 2) level, 3) building, and 4) multi-building comparison (where applicable). Along the top of the screen is the navigation bar to indicate the current scale and permit navigation to other scales. A common conceptual layout is used for each scale. The HMI (Figures 3-5) displays the highest priority areas in the leftmost pane, with a visual of the worst areas based on *OD* (top left), tables listing the OD scores and top complaint types (middle left) and graph indicating breakdown by type of issue (bottom left). The top right pane indicate the current scores by dissatisfaction metric on a gradient metric where the center of the metric (grey) is the baseline value, increasing to red for higher scores and to green for lower scores. The bottom right quadrant shows the navigation through time and permits the user to select a value type (current value, total over range, average over range) and metric for the area selected using the time slider described previously and displays values for each subspace. Increasing color saturation and consistent colors indicate increasing metric scores [26]. At the building cluster level (Fig 3), this is a map showing each building total.

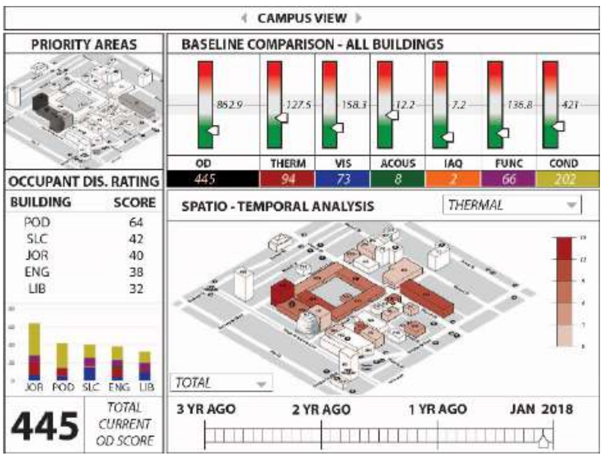

Figure 3. Sample campus-level navigation

This campus-level navigation could support several FM tasks. The top bar provides a real-time summary of campus issues compared to the baseline, allowing the FM team to quickly contextualize the individual results. From the leftmost pane, the FM team can readily identify buildings of concern for further investigation. For example, POEs are being planned for selected buildings across the campus. The campus map illustrated quickly provides a visual indication of the most critical buildings requiring further investigation due to high levels of occupant dissatisfaction. The integration of the time slider extends this visualization into four dimensions, providing insight into seasonal issues and facilitating identification of regular patterns of complaint. Key areas of improvement such as necessary HVAC plant upgrades serving multiple buildings would be informed by patterns of summer overheating and winter undercooling.

Navigating to the building level (Fig 4), the visualization format is retained, however the 2D representation of multiple levels in the building is not immediately user legible, and thus a column graph replaces this visualization. The user can select which metric to display, or whether to display the total OD using a stacked column graph made up of the individual dissatisfaction metrics.

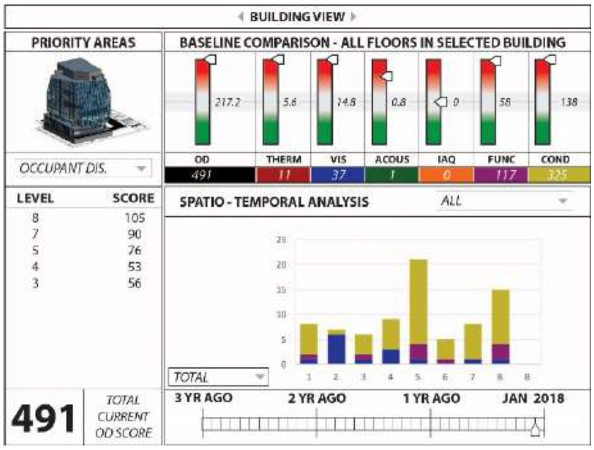

Figure 4. Sample building-level navigation

This view provides the FM team with insight on potential floor-level clustering of complaints. If one floor has a much higher level of dissatisfaction than others, it permits further POE prioritization within a building of concern identified from the campus visualization, and thus enable specific targeting of problem areas. This view also begins to provide insight on large-scale issues causing widespread discomfort or dissatisfaction. For example, high levels of visual discomfort could be caused either by problems with a lighting panel, as these typically serve an entire floor, or due to high levels of solar glare (or low levels of available daylight) in different locations within the building. Thermal and IAQ issues clustered on floors could indicate poor control of zoned equipment, while functionality issues could signal water pressure challenges. Finally, a high condition dissatisfaction score could inform either a custodial services audit to ensure that those floors are being adequately cleaned, or a targeted building condition assessment, depending on the underlying work orders. Given that each work order is flagged to any associated dissatisfaction score(s), queries using these terms would help narrow down underlying causes of clustered complaints.

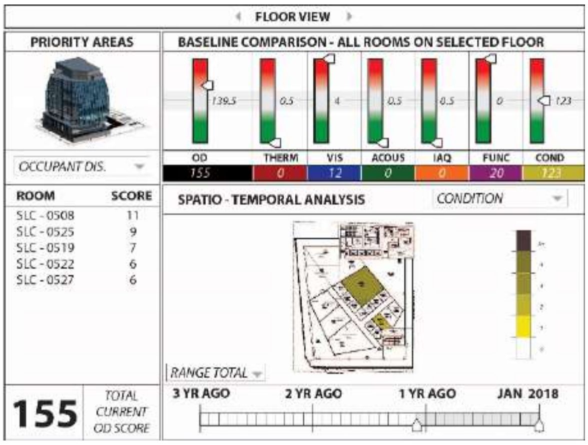

Figure 5. Sample floor-level navigation

The dashboard floor view (Fig. 5) returns to the map view, using the floor plan and colouring data by room, permitting Facility Managers to quickly identify problematic rooms or room clusters within the building. A room-level display has not been created; rather, the FM could refer to the FM-BIM for specific room and local equipment information at this scale. The latter is illustrated in Figure 6, which overlays truncated room and space views for the highlighted room in a real FM-BIM model.

The floorplan view supports similar functionality as the preceding views but with increased granularity. Specific rooms can be identified at this level, permitting a targeted response through reactive maintenance or interaction with the room occupant. The effectiveness of building retrofits or equipment replacement could be assessed by determining whether such action has resulted in a decrease in complaints, or vice versa. Similar conclusions can be drawn regarding the effectiveness of changes in control strategies or maintenance practices. Within the floor, clustering of problems within an area – for example the southwest corner of a building – could indicate faulty equipment, poor building condition in that area, zoning issues, or other underlying causes not evident without this graphical display. Seasonal patterns also become much more visible to FM team with this approach.

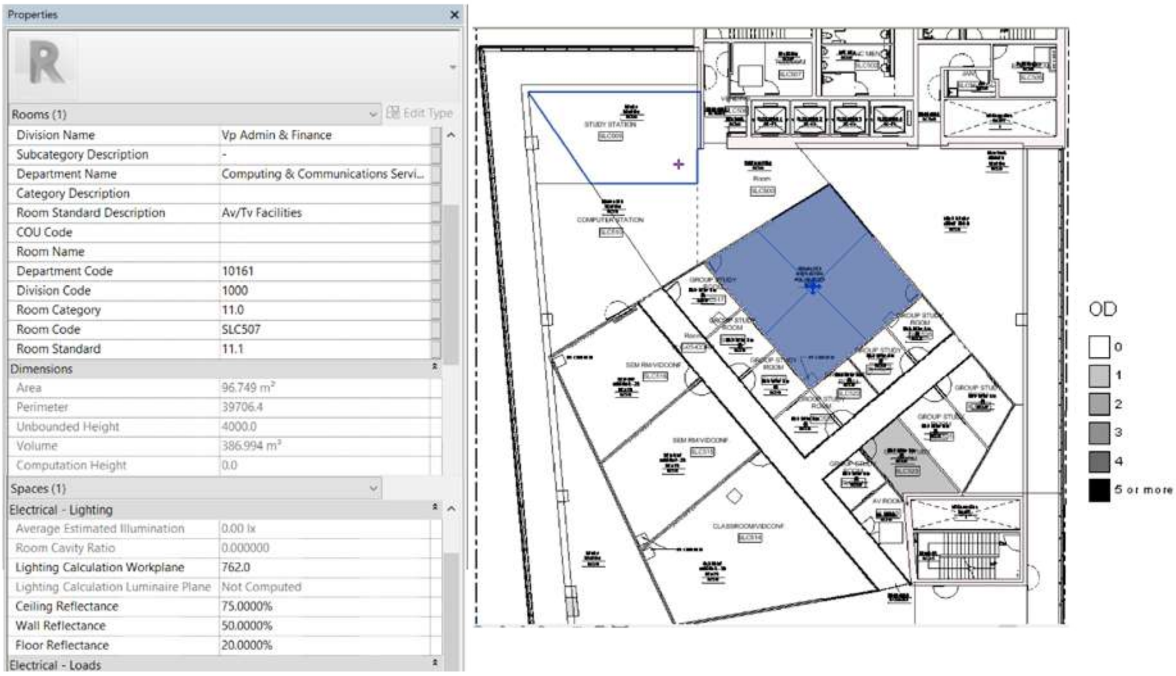

Figure 6. FM-BIM showing room-level information and integration of POE with building automation and other building data

7 Discussion and Conclusions

Given the known impact of the indoor environment on occupant health and productivity, post-occupancy evaluation is a topic of increasing significance.

The case study demonstrates that it is possible to extract relevant data from work orders of relevance to post-occupancy evaluations. Such data indicates the frequency of a high level of dissatisfaction – enough to compel a user to take action and report a complaint – which, in turn, identifies priority areas for intervention and for the deployment of a complete POE study. The data can also support POEs by providing longer-term insight on the frequency and type(s) of complaints reported by space users. By mapping this information into an FM-BIM, it can be readily overlaid with the broader building information, allowing the FM team to understand these complaints in the context of broader building operational parameters, for example current system performance (building automation system point data), equipment condition, and space management.

The conceptual visualizations presented leverage the inherent geometric, time, and semantic data management capability of BIM, and integrate best practices from HMI to provide increasingly detailed navigation through the sample campus and building through a series of dashboards (Fig 3-5).

While the pre-processing logic can be automatically applied to the work order data, this processing occurs in batches in a spreadsheet (Excel); future research will import this algorithm into Dynamo to integrate and fully automate this process. Further, the use of work order categories permits false positive classification and natural language processing algorithms to score dissatisfaction metrics of work orders automatically based on work description text is an avenue of future research to improve the specificity of this mapping and reduce misclassification. Further refinements of the visualizations informed by the test case would include more integration with the BIM and work order system to allow the text of specific work orders (lists at the building, floor, and room levels) to be readily accessed through this interface rather than simple totals. A second refinement would be to allow a side-by-side comparison of different times or ranges of time rather than the single views currently supported.

The single context demonstration is the major limitation of this study. Future research involving new case studies will permit rigorous testing and generalization, while POEs informed by resultant work order visualizations would provide further insight into visualization refinement. The resultant data would support development of a refined work order reporting strategy incorporating POE-supporting questions and mine the data generated to support root case analysis and enhance the decision-making value of this approach.

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Identification of Usage Scenarios for Robotic Exoskeletons in the Context of the Hong Kong Construction Industry

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Abstract –

Exoskeletons can be seen as an archetype of a truly sustainable manufacturing technology since they empower human beings rather than aiming at their substitution. Exoskeletons have been characterized by rapid technological advances in the last decade, as well as an increase of activities attempting to develop feasible usage scenarios for many industries. However, usage concepts for this technology in the construction industry are still rare. This contrasts with the fact that exoskeletons are theoretically ideal for labor intensive industries such as construction. Therefore, in the study presented in this paper, we made a first attempt to conceptually bridge the gap between exoskeleton typologies and construction tasks so as to provide guidance for future target oriented scenarios and technology development. We utilized the Hong Kong housing construction industry as a case study. Consequently, we developed a construction specific classification of exoskeletons and analyzed the suitability and applicability of the resulting exoskeleton types for Hong Kong's housing construction tasks. Our study identified, amongst others, hotspot task areas with high appropriateness for exoskeleton use, task areas with similar needs and usage patterns regarding exoskeletons. Furthermore, our study sheds light on the regimes and rationales behind the identified appropriateness levels. Based on our findings, a set of basic guidelines was developed to support and govern future research and development activities targeting the exoskeleton usage in construction.

Keywords –

Exoskeletons; Classification; Task Analysis; Housing Construction; Hong Kong; Sustainability

1 Introduction

In the study "The Future of Employment", Frey and Osborne [1] argued that in the next decades labor intensive and repetitive jobs such as those in the construction industry will be gradually substituted by automation and robots. On the contrary, recent technological advances indicate that we are able to develop sustainable technological solutions that can literally "bring back humans to work" [2]. According to the authors of this paper, exoskeletons can be seen as an archetype of such solutions, since they empower human beings rather than aiming at their substitution. The term "exoskeletons" (i.e., robotic exoskeletons) refers to a specific branch of wearable devices employing person-external mechanical structures to assist or enhance the physical, motor, and cognitive power of a person [3]. The last decade has witnessed its rapid technological advancement, alongside an increase of projects and activities attempting to develop realistic usage scenarios for many industries (e.g., manufacturing, shipbuilding, agriculture, care, etc.). However, concepts for the usage of this technology in the construction industry are still rare. Exoskeleton technology could provide a couple of performance features such as force augmentation for human beings, high flexibility, the combination of human intelligence with machine capability and improved workplace ergonomics; features ideal for labor intensive and on-product customization focused industries such as construction.

The fundamental motivation to adopt exoskeletons in the construction industry - besides the demands for productivity increase - is to improve the health and safety of workers by enhancing their muscle strength, mobility, and endurance. Construction is a highly physically demanding industry, while musculoskeletal disorders, often caused by overexertion of repetitive works or from heavy lifting or squatting jobs, is one of the leading type of injuries in construction industry [4]. Exoskeleton technologies, therefore, have the potential to dramatically reduce the risk of injuries and illnesses by amplifying the power of construction workers and providing back support. Also, faced by the challenges of an ageing workforce and labour shortages in cities like Hong Kong, exoskeletons and other wearable devices can help to solve the problem by enabling elderly or female workers to perform physically demanding construction tasks in a highly productive manner. Besides, exoskeletons may also be capable of autonomous decision making to achieve certain goals such as being an agent of humans in construction activities [5]. Notwithstanding the tempting potentials, the unstructured and dynamic site environment, combined with the diverse tasks and complicated processes, highly raise the requirements of exoskeleton technologies for construction than traditional military or medical use. To avoid additional risks by wearing exogenous devices, it is of great importance to warrant a high level of portability, flexibility, and coordination with the wearer.

The study presented in this paper attempted to conceptually bridge the gap between existing exoskeleton technologies and construction tasks-based usage scenarios. The Hong Kong construction industry was utilized as a study setting due to its vibrant nature of demands for productivity as well as enhanced health and safety standards. At the same time, some unique characteristics such as Hong Kong's topography and building culture bring forth narrow and cramped sites and floor plans that largely restrict the usage of large machines or robots and demand for small-scale, human-centered approaches. This initial qualitative and exploratory study was conducted in order to pave the ground for larger, qualitative follow up studies involving extensive bottom-up input by relevant stakeholders. This initial study not only identified the relevant domains of knowledge but also combined a comprehensive literature review with a worldwide perspective to the secondary data on exoskeleton technologies by using the Hong Kong housing construction as a case study. The data was collected and developed through the analysis of relevant literature, reports, construction laws and guidelines, construction task descriptions, as well as product leaflets and documents.

The remainder of this paper is structured as follows; first, the background of exoskeletons is introduced, the important development tendencies are characterized, and the diversified technologies are analyzed and categorized. Then, while considering the housing construction practice in Hong Kong, work and labor structures are analyzed and task areas are identified and outlined. Next, usage scenarios that build on the task areas and specific types of exoskeletons to identify the usage scenarios are developed. Finally, a set of basic guidelines derived from the analysis is presented to support and govern future research and development activities targeting exoskeleton usage in construction.

2 Background

2.1 History of Exoskeletons

The development of the exoskeleton can be traced back to the 1960s when the first systems for power augmentation in the context of military applications [6] and physical therapy in medical services were developed [7]. Hardiman, the first full-body powered robotic exoskeleton prototype developed under the U.S. Office of Naval Research, was a heavy (680kg), hydraulically actuated wearable device, with the aim to amplify the muscular capabilities of the wearer [6]. Although its purpose to power up the human was never achieved, critical issues for future development such as power supply and human-machine interfaces were identified [7]. In 1991, the first energetically autonomous exoskeleton, Berkeley Lower Extremity Exoskeleton (BLEEX), powered by bidirectional linear hydraulic actuators, was developed to augment the human strength for material handling [8]. Continuous studies and development have been carried out on BLEEX, triggering out the spin-off company called Berkeley Bionics (now Ekso Bionics) [9]. BLEEX was initially funded by the U.S. Defense Advanced Research Projects Agency (DARPA), which has been regarded as a major impetus to the later development of performance augmenting exoskeletons for soldiers during load-carrying [10]. Medical use cases also played a major role in the evolution of exoskeletons [11] in terms of catalysing the recovery of neurological or orthopaedic patients in physical therapies [12], adding power to help people with muscular weaknesses while walking or stair climbing [13], assisting paralyzed people to regain mobility in daily life [14], etc.

In the recent years, the research and development of exoskeleton technology has prosperously spread in the USA, Japan, Korean, and in Europe. Currently, its applications are broad and vary from military and medical usage to emerging commercial and industrial applications [7, 11]. Although industrial grade exoskeleton usage is still rare in most-non-construction based industries, an enormous amount of research and development activities is currently taking place to crack the code for commercialisation.

2.2 Technological Development Tendencies

Technologically speaking, using exoskeletons as an integration of humans and machines into one system provides new possibilities to create assistive technologies for biomedical, manufacturing and aerospace industries. Even though human muscles have a limitation in power, they naturally use highly specialised control systems to perform complicated tasks. As opposed to humans, robotic manipulators can carry out higher forces on certain tasks, however, their artificial control algorithms compared to humans has less flexibility performance in a wide range of fuzzy conditions. Therefore, combining robotic manipulators directly with humans offers the opportunity to benefit from both sides and use advantages from each branch.

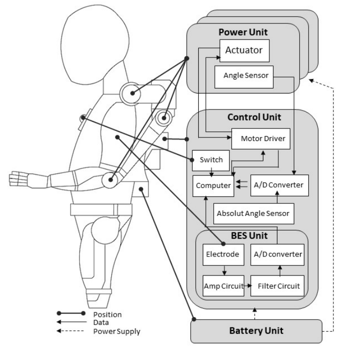


Figure 1. System configuration of the ULSS. All of the power units have the actuator and the angle sensor. The control unit contains the BES unit and the absolute angle sensor, and it controls the whole exoskelton [16].

First generation of exoskeletons used position command from human body to control the exoskeleton. Usually it consists of two layers; a master internal layer providing the position command for the slave and external higher power layer. However, technical problems such as overweight, errors between master and slave layers and poor performance for leg control to achieve the balance for the body movement initially made the achievement of unsupported walking a challenge.

Second generation exoskeletons applied the interface in a dynamic manner; using direct contact force between human and the wearable robot. The measured force is the main signal sent to the exoskeleton. With both the first generation kinematic-position command type and the second generation dynamic-contact force command type, a slight delay to trigger the exoskeleton response by applied action of the wearer [15] represents the challenge with regards to control.

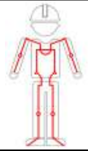
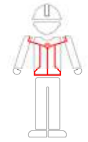
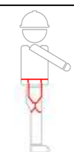
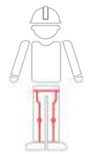
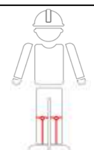
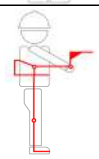
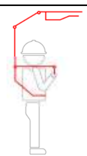
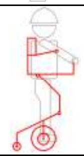
Third generation exoskeletons set the interface at a higher level, i.e., the human neurological system. Likewise, in the human body, a delay is presented between the neurological functions and muscle and body part movements. During this inherent delay, the system gathers information regarding the muscle's neural activation level based on a processed neuromuscular (EMG) signal or even maybe the brain signal, the joint position, and angular velocity, which allow it to estimate the force before the mechanical movement. Thus, the earlier developed dynamic and kinematic feedback types from older generation exoskeleton systems have been integrated and re-combined in the 3rd generation systems. Figure 1 shows exemplarily the system configuration used in upper limb support system (ULSS) [16]. It benefits from using the bioelectrical signal (BES) and automatic changes in the control algorithm. Based on neural network and fuzzy logic, the control algorithms can be developed and designed for specific operators and even specific tasks to fit different physical conditions of the wearers [15, 17] and the requirements of specific work settings and processes. In the development of the fourth generation exoskeletons currently taking place, the key lies in the improvement of technical features such as lower weight, high performance actuators, human–exoskeleton interface, safety, energy efficiency, and lower cost [17].

2.3 Important Definitions

Even though a diversity of definitions exists, the terms "wearable robots" and "exoskeletons" are widely used in the context of wearable robotic technologies. Pons [18] defined a wearable robot as "*a mechatronic system that is designed around the shape and function of the human body, with segments and joints corresponding to those of the person it is externally coupled with*". De Looze, Bosch [3] regarded an exoskeleton as "*an active mechanical device that is essentially anthropomorphic in nature, is worn by an operator and fits closely to his or her body, and works in concert with the operator's movements*". In compliance with definitions used by the International Association of Automation and Robotics in Construction (IAARC) [19], robotic construction technology for on-site construction can be sub-classified into several sub-categories such as; 1) robotised construction machines, 2) single-task construction robots, 3) on-site logistics solutions, 4) Building Information Modelling (BIM), and 5) data acquisition, monitoring, and sensing approaches. Bock and Linner [20] extended this classification by adding amongst others, 6) on-site factory approach, 7) humanoid robot technology, 8) aerial systems, and 9) wearable robot technology. Wearable robot technology can further be sub-classified in approaches such as; a) smart helmets [21], b) smart glasses and virtual reality [22], c) body sensor systems [23], and exoskeletons (which this paper focusses on).

In the study presented in this paper, we principally followed the definitions of Pons and De Loze, by considering "wearable robots" as an umbrella term to describe digital and robotic systems, while defining "exoskeletons" as more specific skeleton applied devices that are worn on the human body to improve or sustain the wearer's ability to perform specific required tasks. In light of our focus on analysing particularly the usage potentials of exoskeletons in Hong Kong's housing construction industry, exoskeletons were further regarded as physico-mechanical support devices that a construction worker can wear to augment or assist his physical abilities, strength, endurance, speed, precision, or general performance on the site.

Table 1 A construction specific sub-classification of exoskeletons.

Main category	Subcategory	Basic kinematic composition	Graphical illustration	Power (type*)	Examples
Full body	Full body	Full body is actuated or powered		Active (*a*) Passive (*b*)	• HULC by Lockheed Martin and Ekso Bionics • Ekso by Ekso Bionics • MAX by SuitX
Upper limb	Shoulder type for back support (without arm)	Provide support to the back		Active (*c*) Passive (*d*)	*upcoming development activity expected* • FLx ErgoSkeleton by StrongArm Technologies
	Shoulder type for arm support	Provide support to the arm		Active (*e*) Passive (*f*)	• Titan Arm by University of Pennsylvania • AIRFRAME by Levitate Technologies
	Elbow	Provide assistive power to elbow joint		Active (*g*) Passive (*h*)	• HAL Single Joint Type by CYBERDYNE • PEX by UC Berkeley
	Hand	Provide assistive power to the wrist or fingers		Active (*i*) Passive (*j*)	• SEM Glove by Bioservo Technologies • Pneumatic Power Assist Glove by Daiya Industries
Lower limb	Hip	Provide support to hip joint or lumber		Active (*k*) Passive (*l*)	• HAL Lumbar Type by CYBERDYNE • AWN-03 by Panasonic ActiveLink • Hip Auxiliary Muscle Suit by Innophys
	Hip-knee-ankle type for leg support	Provide support to the leg and reduce fatigue during squatting, standing or walking		Active (*m*) Passive (*n*)	• Walking Assist Device with Bodyweight Support System by Honda • Chairless Chair Wearable Ergonomic Device by Noonee • Archelis by Wearable Chair
	Knee or ankle	Provide extra force to the knee or ankle to improve walking performance		Active (*o*) Passive (*p*)	• HAL Single Joint Type by CYBERDYNE • Exo-Boot by Carnegie Mellon and North Carolina State
Body extension	Tool holding	With an additional arm to support the holding of a heavy tool, while the weight of the tool is transmitted into the ground		Active (*q*) Passive (*r*)	• Lower Extremity Exoskeleton Robot for Concrete Placing (HEXAR-PL) by Hanyang University • Ekso Works by Ekso Bionics • Fortis by Lockheed Martin
	Extensional / Supernumerary	With two or more extensional arms to perform material handling or other works		Active (*s*) Passive (*t*)	• Exoskeleton for handling heavy steel elements by DSME • Supernumerary Robotics Limbs (SRL) by MIT *upcoming development activity expected*
	Extensional / Wheeled	Extension with wheels or mobile platform which could be further integrated into body parts		Active (*u*) Passive (*v*)	• EXOwheel by Sogang University • iReal by Toyota *upcoming development activity expected*

*letters in brackets are referred to classified types of exoskeletons.

Exoskeletons can themselves be classified based on a variety of viewpoints such as active/passive, the body parts covered, functionality, the types of actuators used, or the types of control and feedback systems used, etc. When considering the power source, there exists mainly the active, or powered exoskeletons using electric, hydraulic or other connections to run sensors and actuators, and passive, or un-powered ones that require no external power but use springs, elastic cords, or other resilient elements to transfer loads to the ground. According to the supporting parts to muscle strength, they can be further categorized into: upper limb, lower limb, and full body [17]. By functionality, they can be considered as power assistance, power augmentation, and cognition and sensing augmentation [20]. Regarding the types of actuators, electric motors and pneumatic systems are mainly used in exoskeleton design. In terms of feedback systems, for example, we can distinguish between a control of the robot based on bio-signals from the wearer or from acceleration forces.

2.4 A Construction Specific Sub-classification of Exoskeletons

In the study presented in this paper, exoskeletons were organized according to their applied body parts and active/passive features, considering that the analysis of the appropriateness of a certain type of exoskeleton for a certain type of construction task can best exploit these two factors. The body parts supported by an exoskeleton give a good hint about the task range and task type that an exoskeleton can cover, and the active/passive view indicates what payloads an exoskeleton can handle. Compared to many other manufacturing industries, building components cover a very wide range of loads and are key factors in deciding which construction processes and tools may be used.

Table 1 outlines the proposed construction tasks oriented classification of exoskeletons with key characteristics and example prototypes (or products) listed for each of the identified categories. The superordinate level of each category was formed by general body parts including full body, upper limb and lower limb, with body extension being considered as a fourth one to cover those with additional arms or support. Then, those four main types were further broken down into detailed body parts and kinematic features. Despite some overlaps, each second level category represents a distinguished body related feature, as manifested in the brief descriptions and graphical illustrations. In addition, the active/passive perspective was employed to determine the construction specific sub-classification of exoskeletons into 22 types, each backed with examples.

3 Housing Construction Tasks

To enable the assessment of the appropriateness of certain types of exoskeletons for specific housing construction tasks, we subdivided housing construction (Level 1) into basic task categories (Level 2) and then further into individual task areas (Level 3), as mapped in Figure 2 (mapping of housing construction tasks in Hong Kong). Relevant documents, like HK Cap. 123B Building (Construction) Regulations [24] and HK Cap. 583 Construction Workers Registration Ordinance [25], were analysed to define and develop the task areas map. On Level 2 the task categories identified are the following: 1) geotechnical and foundation work, 2) site operation, 3) main structure construction, 4) building services, 4) general interior finishing tasks, 5) general exterior finishing tasks, 6) landscaping, 7) ground investigation, site measuring, and monitoring, 8) civil works. Level 3 breaks down this task categories into specific task areas and is used as the basis for the analysis conducted in this paper. A further split down of this task areas as per the task specific execution or assembly process (i.e., sequence of sub-tasks and activities within an individual Level 3 task area; Level 4), would allow a very detailed assessment of the appropriateness of exoskeletons. However, this would require a very detailed decomposition which would go beyond the scope and resources of this initial study. In this study, we generally focussed on assessing the appropriateness of exoskeletons for Level 3 task areas. Our aim was to stimulate through this further research and development by Level 4 domain specific groups and consortia.

4 Analysis of Usage Scenarios

In this chapter, usage scenarios that were developed and built based on those identified in Level 3 task areas are presented. As outlined in Figure 3, we analyzed the previously developed classes of exoskeletons (Table 1) against the Level 3 task areas (outlined in Figure 2) and thus how specific categories and types of exoskeletons can be used within the context of specific task areas. We further identified technology appropriateness through pairwise analysis of task areas and types of exoskeletons (seen in Figure 3).

In general, our analysis revealed the following patterns in the usage of different exoskeletons in housing construction:

1. Active exoskeletons are appropriate in the context of tasks that involve the handling of rather large elements with high payloads (e.g., metal works, dry wall installation, etc.), whereas passive exoskeletons are suitable in the context of tasks that involve the handling of rather small and light components and fine motor skills (painting,

plastering, etc.).

2. Certain task areas show a similarity with regards to the type of exoskeletons used. So, for example, a relative task similarity can be identified within interior and exterior task categories. Also, tasks that involve similar tools and processes or have similar needs in terms of power augmentation, extra support or fatigue prevention (e.g., painting, plastering, etc.) result in similar requirements of exoskeleton use.

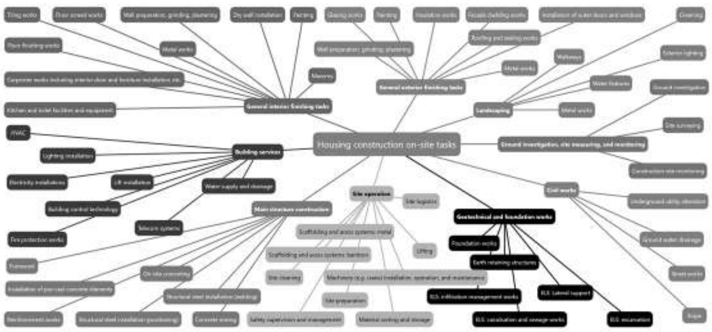


Figure 2. Mapping of housing construction tasks in Hong Kong. The map shows how housing construction (Level 1) can be subdivided into basic task categories (Level 2) and then further into individual task areas (Level 3) based on relevant building construction regulations in Hong Kong.

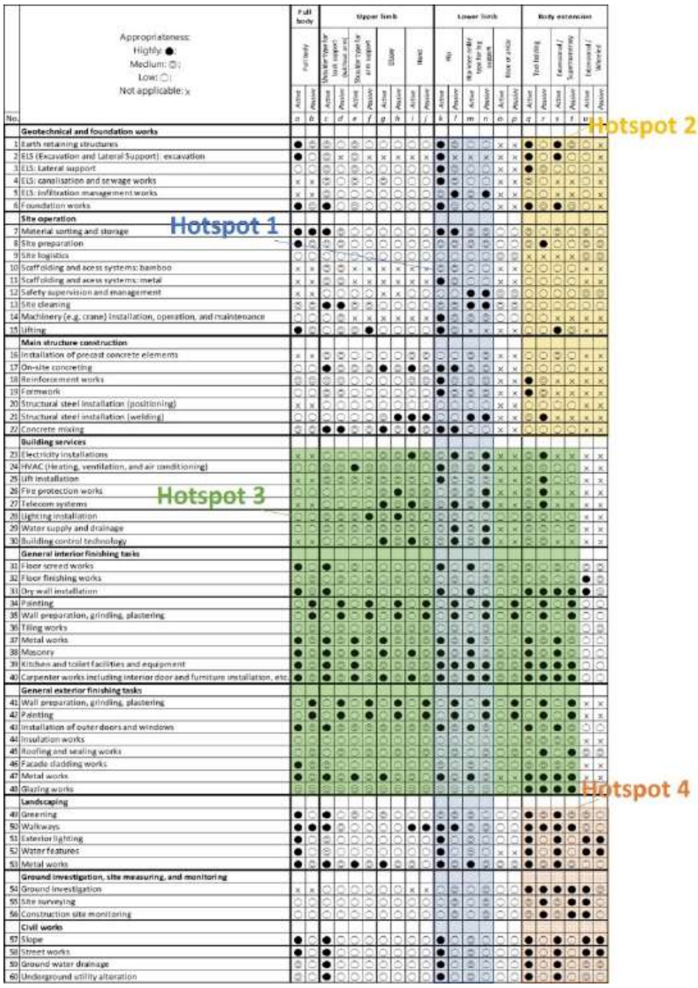


Figure 3. The pairwise analysis of task areas and types of exoskeletons. The previously developed classes of exoskeletons (Table 1) were analyzed against the Level 3 task areas (outlined in Figure 2).

3. Wheeled and full body exoskeletons face challenges in the rather unstructured environments related to geotechnical and foundation works and site operation works. Whilst after the superstructure construction, that the work environments are relatively controllable, the use of such types of exoskeletons is more suitable.
4. In Section 2.4, three exoskeleton types (types *c*, *t*, and *v*) were identified for which at present no developments or approaches are known. Our analysis revealed, in particular for type *c*, that a high appropriateness was identified for a number of tasks and that upcoming development activities for this type of exoskeleton would be justified.
5. Four hotspot areas were identified (see Figure 3):
   a) Hotspot 1: Preferred lower limb exoskeleton usage areas
   b) Hotspot 2: Preferred body extension exoskeleton usage areas
   c) Hotspot 3: Non-preferred body extension exoskeleton usage areas
   d) Hotspot 4: Preferred fully body-upper limb-lower limb usage areas

5 Discussion

The research and development towards exoskeletons usage are manifold, whilst the applications in the construction industry are still limited. Our analysis, with the assignment of appropriate levels for the construction of specific exoskeleton types to the task areas in Hong Kong housing construction, made a first step towards defining and detailing the problem and requirements for exoskeleton use. All in all, the analysis conducted provides guidance for the following follow up activities:

- **Definition of problem**: Once the task areas in which the exoskeleton can be used are defined, the development teams can then focus on creating incremental or breakthrough innovations rather than on basic science. In that context a particular focus could be laid at the sixteen main types of workers highlighted by the Hong Kong Construction Industry Employees General Union [26].
- **Multi-use scenarios:** Using our matrix and the outcomes presented in it (Figure 3), developers can identify task areas with similar or same use patterns for exoskeletons and then attempt to develop one exoskeleton (maybe with slightly adaptable features for each task area) hat can finally be used in a multitude of task areas.
- **Exoskeleton-oriented task and component adaptation:** Existing or efficiently achievable technological systems or breakthroughs shall be exploited in a broader way, developers may also consider changing task and materials/components to make certain types of exoskeletons applicable and suitable.
- **Transform site to be more like a factory:** The unstructured environment of the construction site greatly inhibits the use of certain types of exoskeletons (e.g., fully powered body exoskeletons, wheeled ones, etc.). This circumstance may be equalized through a better structuring of the construction site.
- **Exoskeleton surrounding site infrastructure:** To successfully use the exoskeleton on site, not only must the core tasks be executable but the surrounding tasks and activities have also to be integrated as well. In the context of exoskeleton usage, a key aspect will be how the wearer puts on the exoskeleton. Will there be frames or cabinets available to help the user "slip" into the exoskeleton? Or will there be as in the rehabilitation use, service personnel on the site to support with dressing/un-dressing operations? How will tools or parts be provided to the wearer of the exoskeleton? All these should be considered in the future research.
- **Systematic improvement of exoskeleton key technologies:** As part of a detailed task and applicability analysis, key technologies that require systematic technological improvement such as battery technology and the control interface can be identified (sensors, feedback system, user interfaces, etc.).
- **Identification of new exoskeleton categories:** The analysis shows that all of the existing exoskeletons are not explicitly appropriate for certain tasks, e.g., scaffolding. Consequently, this may lead to the definition of new categories for exoskeletons such as suspended gondola type exoskeletons.
- **Develop exoskeleton complementary technologies:** Complementary technologies (possibly based on BIM, worker guidance systems, new types of Graphical User Interfaces such as smart glasses, etc.) and their usages shall be well-defined and systematically developed towards higher technology readiness levels.
- **Exoskeleton and site usability engineering:** Since the human being is the most important element in the efficient and sustainable use of exoskeletons on the construction site, studies on the short and long-term impact of the use of exoskeletons on human physical conditions, muscles, psychological conditions, and overall health must be conducted and fed back into systems development. Similarly, system features and requirements that enhance motivation to use the equipment and ease of use on the construction site must be identified through user studies.
- **Sustainability:** Exoskeletons can indeed be seen as an archetype of a truly sustainable manufacturing technology since they empower the human being (his capabilities as well as his health at the workplace) rather than aiming at complete substitution of human labor by machine technology and automation.

6 Conclusions

The study presented in this paper examined and explored the usage scenarios of exoskeletons in the construction industry, drawing on the case of the Hong Kong construction industry as an initial use case setting. A construction specific sub-classification of exoskeletons was proposed to support the fundamental understanding of potential usages of exoskeletons for construction. A comprehensive mapping of tasks in Hong Kong housing construction was provided. A pairwise analysis developed usage scenarios for exoskeletons in construction to facilitate future application oriented research and development efforts directed at exoskeleton technologies.

Future work will further split down the identified task areas into sub-tasks (Level 4) to analyze what activities can be carried out by exoskeletons, human beings only, or solely by robots or machines. Also, we plan to analyze in more details the impact of exoskeletons, while being used in specific tasks, on factors such as mental and muscle stress, work organization, and social and legal aspects.

Acknowledgements

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Scaffolding Modelling for Real-Time Monitoring using a Strain Sensing Approach

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Abstract –

Scaffolding structures are important as a temporary structural element that are used to support workers, equipment, and materials during construction activities. Although 65% of construction workers work on scaffolding structures and often are exposed to safety hazards, the current method of monitoring scaffold structures still is premature. As an example of practices set by the U.S. Occupational Safety and Health Administration, a knowledgeable and experienced individual conducts a visual and labor-intensive inspection. However, one difficulty in conducting structural analysis of a scaffolding structure involves its boundary conditions and material design parameters, which vary depending upon loading conditions. This research explored a new method to accurately model the boundary conditions and design parameters of a scaffolding structure in real time by using wireless strain sensors. An Internet of Things (IoT) open-source Arduino module was used to develop wireless strain sensors to acquire strain data directly from a scaffolding structure. The strain data were transmitted to a finite element method (FEM) model, which was used to estimate the real-time structural behavior of a scaffold. A model-updating technique was used to improve the synchronizing accuracy between the FEM model (i.e., the cyber model) and the actual scaffold. The test results indicated that the proposed synchronizing method described the real-time structural behavior of the scaffold accurately, especially for modelling the boundary conditions and design parameters. The outcomes of this paper are expected to foster the use of wireless sensing technology for safety monitoring of temporary structures and to offer the potential of improving construction safety by preventing the collapse of temporary structures.

Keywords –

Temporary structures, monitoring, FEM, scaffold, wireless sensor

1 Introduction

In the construction industry, scaffolding structures have been the most widely used temporary structures; according the U.S. Occupation Safety and Health Administration (OSHA) as many as 2.3 million construction workers work on scaffolds [1]. Thus, proper inspection and the safety conditions of scaffolds are crucial to ensure the safety of construction workers. Currently, the entire structural condition of scaffolds is inspected visually by a knowledgeable and experienced individual [2]; this approach is labor intensive, subjective, and prone to error. However, due to the lack of systematic tools, it is difficult to continuously monitor and inspect multiple scaffolds in a dynamic construction site by using the traditional visual inspection technique.

The real-time monitoring of scaffolds is exacerbated even further by the external work environment, which often occurs under high-pressure conditions; difficulty in identifying defects in scaffolds when at full scale; and simple human errors [3]. As a result, the construction industry has suffered a high number of accidents – 50 deaths and 4,500 injuries (estimated every year) – and has incurred costs exceeding $90 million a year due to improperly managed scaffolds [4]. To improve the effectiveness of monitoring the scaffolds, thus ensuring safety of the scaffolds, there have been efforts to monitor temporary structures automatically with sensors, including load cells, switch sensors, an accelerometer, and a displacement sensor [5]. However, this approach focused only on measurements of the structural responses (e.g., strain, displacement, and load) at a local level without taking into consideration a global structural analysis. In this study, a structural FEM modeling technique was developed for scaffolding monitoring by proposing transforming the boundary conditions of and model updating for a scaffold.

2 Background

OSHA requirements and recommendations for designing, erecting, dismantling, and inspecting scaffolds [2] are the basis for conventional scaffolding inspection in the construction industry. OSHA regulations require inspection of each scaffold before each work shift and after any incident that might have affected its structural integrity as well as safety training programs to educate workers. Despite these efforts to identify and prevent potential safety hazards related to scaffolds, the actual application of this knowledge to a complex construction site still remains challenging.

Thus, researchers have sought more advanced methods to monitor temporary structures. Moon et al. [6] developed a sensing network to collect static structural responses – such as strain, displacements, and loading condtions – and compare them to allowable limits in order to determine structural safety conditions. By analyzing video streams to characterize deformations of targeted temporary structures, Jung [7] developed an image-processing method to automatically identify defects in scaffolding and shoring. Yuan et al. [5] introduced a cyber-physical system that synchronizes a virtual model and a real model of a scaffold with a sensor-based system to monitor its physical status.

However, such past research investigated only element-level behaviors of temporary structures and overlooked integral structural analysis; therefore, the potentially varying boundary conditions of a scaffold were not properly investigated. Since locally stable structures still can be globally unstable, resulting in structural problems, understanding global behaviors should be investigated to ensure the safety of scaffolds in a more comprehensive manner. Hence, there was a need to develop a more reliable scaffolding modelling technique that considers the global behaviors of scaffolding structures to ensure their structural stability as well as the safety of the construction workers and the general public.

3 Objective

The main objective of this study was to improve a structural modeling technique to precisely reflect the actual behaviors of scaffolding structures. In contrast to general structures, such as buildings and bridges, the boundary conditions of temporary structures can be unstable because they often stand on the site without having proper fixtures. To address instability issues in the boundary conditions of a scaffold, our research team developed a technique of a boundary transformation to describe structural behaviors more reliably. In addition, we developed a technique to update design parameter models using the finite element method (FEM). The proposed technique for parameter modelling uses wireless strain sensors to measure the strain data from each of the scaffolding components under given loading. By synchronizing real data with the corresponding data from the FEM model, we updated the model to reflect the actual conditions more accurately of a scaffold. Then, we applied various loading cases to the scaffold model in order to validate the proposed techniques with respect to the boundary conditions and design parameters of the scaffold.

4 Modeling Approach for Monitoring Temporary Structures

4.1 Overview

The overall approach of the proposed methodology was to synchronize the strain data that was collected from the columns of an actual scaffold with that of an FEM model, which represented the behavior of a scaffolding structure by transforming the boundary conditions. To improve accuracy of the FEM model even further, a model-updating procedure was conducted to optimize the material and geometry parameters of the scaffold.

Figure 1 shows an overview of the proposed methodology. The research team developed the wireless strain sensors with the combination of an Arduino Yun board, a strain-gage board, and commercial strain gages (350 Ω and gage factor 2.18). An interface shield provided electrical connections to integrate these three components.

The Arduino Yun board, which is an Internet of Things (IoT) open source hardware, converted an analog signal to a digital signal from the strain gages, and had Wi-Fi communication capability. The strain-gage board managed the measured voltage difference by amplification. The designed wireless strain sensor required 5 V for operation, and the wireless interrogation distance was 30 m of line-of-sight communication. Strain sensing ranged from –1,000 με to 1,000 με, with a resolution of 2 με.

To measure the strain responses, wireless strain sensors were installed on the column components of the scaffold. The wireless sensors measured the strain data for each column of the scaffolding and transferred the strain data to the FEM model. In the FEM model, the boundary conditions were transformed based on loading conditions and amplitudes, as described in Section 4.3. The FEM model sought to optimize the material and geometric parameters of the scaffold, as described in Section 4.4, by processing the model updating until the strain responses from the FEM analysis were close to the measured values.

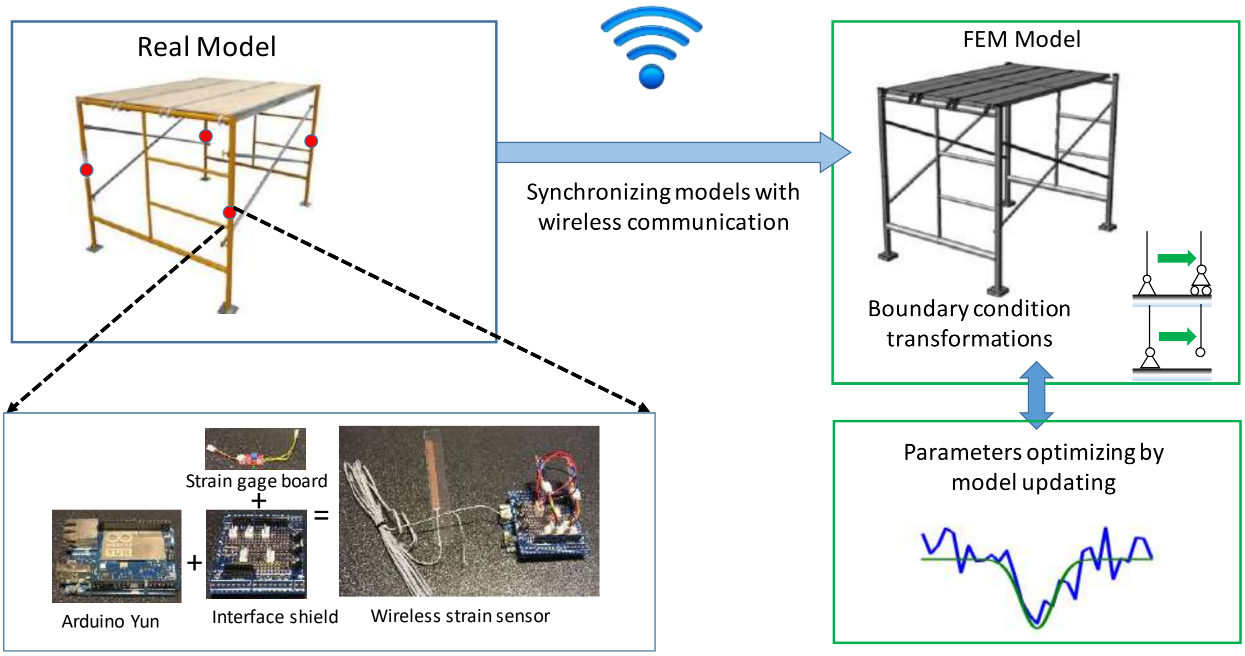
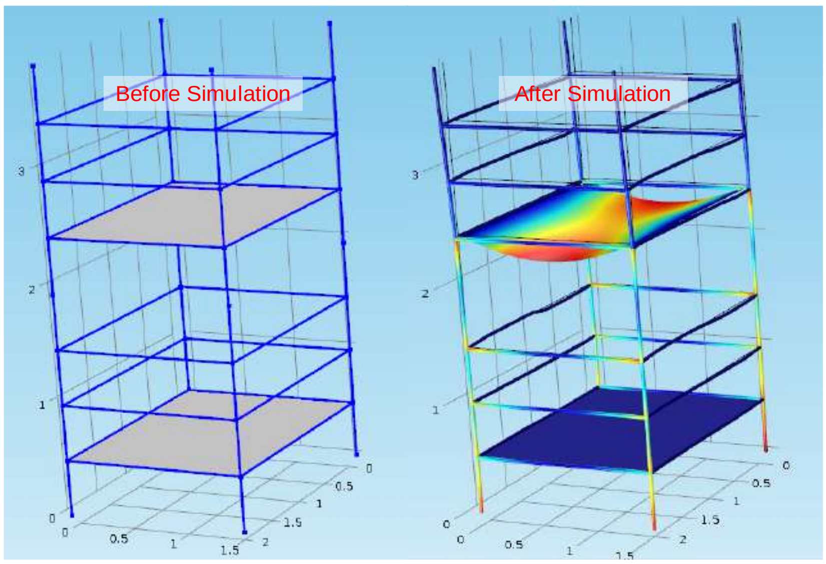


Figure 1 System overview

4.2 Scaffolding Models

For laboratory testing, as shown in Figure 2(a), the research team prepared a one-bay scaffold with two stories; this scaffold consisted of four columns and 24 side frames, with a circular pipe section that was 5-mm in diameter. The dimension of the scaffolding structure was 84 in × 62 in × 152 in (2,133 mm ×1,575 mm ×3,861 mm). Six steel scaffold planks having the dimensions of 84 in. × 10 in. ×0.12 in. (2,133 mm ×254 mm ×3 mm) were placed on each floor.

(a) Actual scaffolding model



(b) FEM model

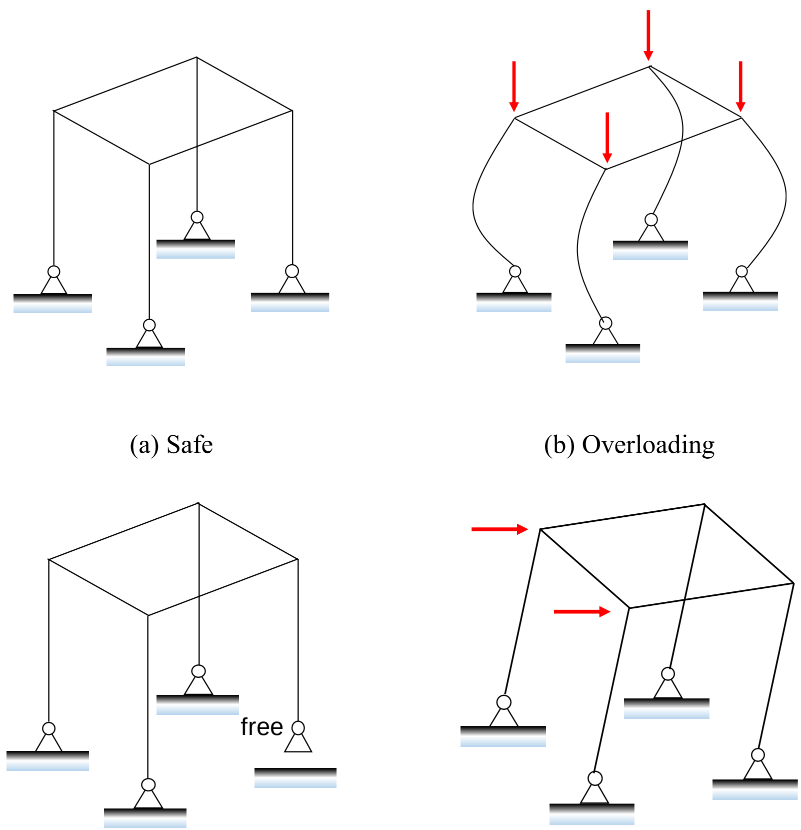
Figure 2 Scaffolding model

The columns of the scaffolding structure stood on wooden foundations; these were not the same type of boundary as conventional boundaries, such as hinges, and fixed boundaries. For convenience, it is a common practice not to attach the columns of a scaffold to the foundation; thus, the boundary conditions of a scaffold might be different from conventional ones. For modelling the scaffold, the research team employed a commercial FEM software package, COMSOL Multiphysics [8]. The frame of the scaffold was modeled by beam-column elements, and shell elements were used to model the scaffold planks.

Figure 2(b) shows the FEM model of the scaffolding structure before and after simulation. The deformed shape shown in Figure 2(b) is an example of a result of structural analysis. In the FEM simulation, each node was formulated with six degrees of freedom due to three-dimensional (3D) analysis.

4.3 Transformation of Boundary Conditions in an FEM Model

As described previously, the columns of the scaffold rested on wooden foundations. From a structural point of view, these boundaries were unstable, and were considered to be a free-boundary condition. While compensating for the boundary conditions of a scaffold, this study proposed a new method for modelling the boundary condition in order to analyze scaffold structures. The structural conditions of a scaffold were classified into four categories: safe, overloading, overturning, and unevenly settled conditions, as shown in Figure 3.



(a) Safe (b) Overloading

(c) Uneven settlement (d) Overturning

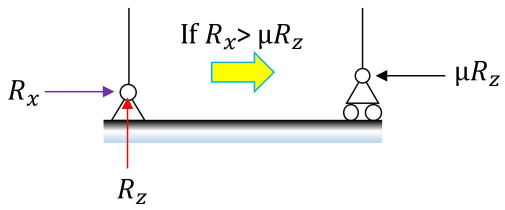
Figure 3 Structural conditions of a scaffold

The boundary conditions were transformed as follows:

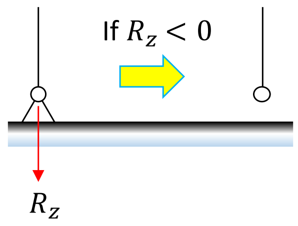
Case I: When lateral forces are greater than the maximum reaction forces of the wooden foundation, the column starts to slip. In other words, when lateral forces (R_x or R_y) are greater than the vertical reaction force (R_z) multiplied by a friction coefficient (μ), a hinge is transformed to a roller boundary with the lateral reaction force of μR_z, as shown in Figure 4(a).

Case II: A reaction force along the *Z* axis is less than zero, which means that the associated columns are unevenly settled or that a full structure is bounded to an overturning condition. Such columns disable to support any reactions. Therefore, the hinge boundary conditions of the columns are transformed to a free condition, as shown in Figure 4(b).

At this point, the FEM simulation performed another analysis on the structure with the transformed boundaries for both Case I and Case II, as shown in Figure 4.



(a) Case I



(b) Case II

Figure 4 Computational modeling for the boundary-conditions transformation

4.4 Model Updating

For structural analysis by means of FEM simulation, nominal parameter values, such as material properties and geometric dimensions were selected. However, these nominal values often are the main factors that lead to a discrepancy between numerical analysis and experimental measurements. To minimize this discrepancy, the research team employed a model-updating technique to extract the precise values of the parameters from experimental data. Upon updating the material parameters and geometric parameters in the model, the FEM model was able to reflect the physical reality of the scaffold more accurately as compared with the initial model, which relied on nominal parameter values. The optimization problem for model updating was formulated as:

$$\begin{aligned} &\underset{\mathbf{x}}{\text{minimize}} \left\| \text{Strain}_{\text{Exp}}(\boldsymbol{P}) - \text{Strain}_{\text{FEM}}(\boldsymbol{P},\mathbf{x}) \right\| \\ &\qquad \text{subject to } \mathbf{x}_{\text{L}} \le \mathbf{x} \le \mathbf{x}_{\text{U}} \end{aligned} \tag{1}$$

where:

$\|\cdot\|$ is the Euclidean norm;

$\boldsymbol{P}$ is a loading vector;

$\mathbf{x}$ is the updating vector parameter, which consists of Young's Modulus *E* and the thickness of a structural pipe *t* ($\mathbf{x} = [E, t]$);

$\text{Strain}_{\text{Exp}}(\boldsymbol{P})$ is a vector function to generate the experimental strain values against loading $\boldsymbol{P}$;

$\text{Strain}_{\text{FEM}}(\boldsymbol{P},\mathbf{x})$ is a vector function to generate simulated strain values with loading $\boldsymbol{P}$;

The updating parameters $\mathbf{x}$, $\mathbf{x}_{\text{L}}$, and $\mathbf{x}_{\text{U}}$ are (element-wise) the lower and upper bounds of the updating vector parameter $\mathbf{x}$.

5 Experimental Validation

To demonstrate the proposed method, three types of structural conditions – overloading, uneven settlement, and overturning conditions – were generated in an extensive experimental validation. Strain gages were installed and connected to the wireless unit for real-time strain measurement from the four columns of the scaffold (C1, C2, C3, and C4), as shown in Figure 5. Then, the strain data were synchronized with the FEM model. For the test of the overloading condition (Case I), the maximum loading capacity of the scaffolding – which as 84 in (213 cm) in width and 62 in (157 cm) in depth – was calculated based on OSHA standards. This specified that the maximum weight exerted on a heavy-duty scaffolding was not to exceed 75 lbs/ft^2, as follows [9]:

$$\begin{aligned} 7\text{ ft } (84\text{ in}) \times 5.16\text{ ft } (62\text{in}) \times 75\frac{\text{lb}}{\text{ft}^2} &= 2{,}709\text{ lb} \\ &= 1{,}229\text{ kg\_force (kgf)} \end{aligned}$$

However, for safety reasons, we limited a loading size up to 400 kgf. We recruited six subjects, and measured their weights prior to the experiment. The subjects stepped on the scaffold one by one until the weight reached near 400 kgf.

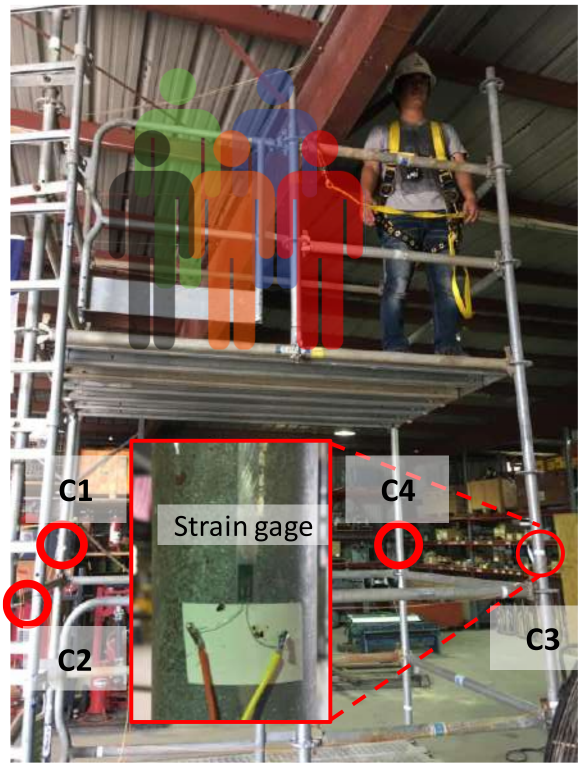


Figure 5 Experimental setup for overloading conditions

In the model updating procedure, initial parameters of vector $\mathbf{x}_0$ were chosen as:

$$\mathbf{x}_0 = [200\times10^9\,\text{Pa}, 3\text{ mm}] \tag{2}$$

The lower and upper bounds were set with a 10% difference from $\mathbf{x}_0$:

$$\mathbf{x}_\text{L} = [200\times10^9\,\text{Pa}, 3\text{ mm}] \times 0.9 \tag{3}$$

$$\mathbf{x}_\text{U} = [200\times10^9\,\text{Pa}, 3\text{ mm}] \times 1.1 \tag{4}$$

During the experiment, the loading step was 100 kgf, which was uniformly distribtied to the second-floor scaffold planks. The loading amplitude increased up to 400 kgf. For benchmark comparisons, the FEM model simulated the structural analysis with the identical loading conditions to obtain analytical strain values. A MATLAB™ optimization toolbox, `MultiStart`, was adopted and integrated with the FEM model to conduct the model-updating procedure. Since this objective function was not convex, we set 1,000 trial starting points for a global search (global optimization). The updating variables ($\mathbf{x} = [E, t]$) for each of the parameters were randomly generated. Starting from each of 1,000 points, the `lsqnonlin` (nonlinear least-squares solver) with the 'trust-region-reflective' algorithm found a local optimum around the point. Among local optimums, the most optimized value was as shown:

$$\mathbf{x}^* = [198.12\times10^9\,\text{Pa},\quad 2.612\text{ mm}] \tag{5}$$

Figure 6 presents the results of model updating. The Y-axis indicates the average strain values from the four columns. This figure reveals an intriguing finding in that the model updated by the proposed method showed more accurate behaviors for the tested scaffold compared to the initial model with nominal parameters. This indicated that the proposed updating technique was superior over the model with the initial parameters.

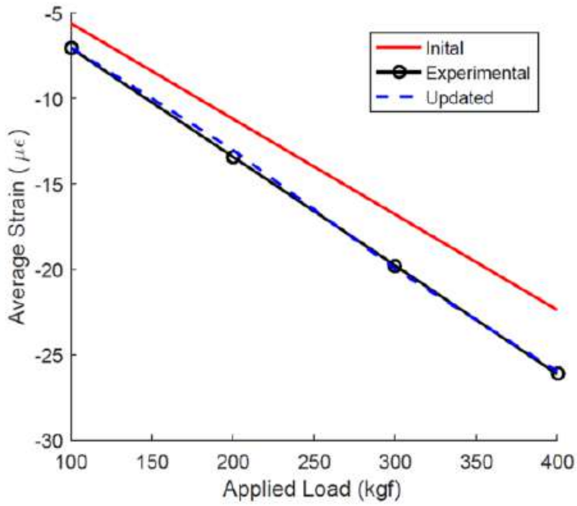


Figure 6 Comparison of strain data of various model updating

To generate unevenly settled (Load Case II) and overturning (Load Case III) conditions, we used a forklift to lift one or two columns, as shown in Figure 7. For safety reasons, the lifting height was limited to 2 in (approximately 5.1 cm). However, this small displacement was enough to emulate unevenly settled and overturning conditions.

Figure 7 Experimental setup for uneven settlement and overturning conditions

Table 1 Test Results shows the results of the experimental validation by comparing the strain data of the FEM simulation and those of the experiments conducted for all three cases to ascertain that the proposed method could perform reliably for various cases. For the overloading condition (Load Case I), the total loads approached near 400 kgf, and strain values were measured from the four columns of the scaffold. The average strain value from both the experiment and simulation indicated –75 με. For uneven settlement (Load Case II), C1 was lifted by the forklift, and its corresponding strain value was close to zero. Strain values from other three columns were from –7με to –8με. For the overturning condition (Load Case III), because C1 and C4 had zero strain, the other two columns needed to support the entire scaffold structure. Strain values from C2 and C3 were approximately –12 με. Thus, both experimental and simulation results were well matched in the three loading conditions.

Table 1 Test Results

Load Case		Strain (με)			
		C1	C2	C3	C4
I	Exp.*	-75.132	-75.142	-75.149	-75.123
	Sim.**	-75.069	-75.027	-75.954	-75.949
II	Exp.	0.013	-7.082	-8.041	-8.071
	Sim.	0.000	-7.004	-8.599	-7.004
III	Exp.	0.001	-12.25	-13.02	0.004
	Sim.	0.000	-12.02	-12.02	0.000

* Experiment, ** Simulation

6 Conclusion

A scaffold plays an essential role as a temporary structure during construction. However, the current approach to monitoring scaffolding structures has focused mainly on local behaviors of a scaffold in spite of the importance of their global behaviors to understand their safety status. This study proposed a modeling technique that could compensate the unstable boundary conditions of a scaffold structure by transforming its boundary conditions based on loading cases. In addition, the model-updating technique improved simulation accuracy to more closely reflect on behaviours of a real scaffold.

For the validation, four structural conditions (safe, overloading, uneven settlement, and overturning conditions) were generated and tested with physical experiments and computational analysis. The results indicated that the proposed method, using boundary transformation and model updating techniques, was reliable for determining real-time structural condition of scaffolds. This result implies that the global behaviours of a scaffold could be modelled and analysed more accurately in an FEM model. In addition, real-time monitoring of a scaffold with rigorous analysis is possible when such an FEM model is synchronized with real-time strain data from an actual scaffold on site. Thus, application of such a technique in the construction industry is expected to significantly improve the safety of the workers at a construction site.

Despite the advancement made in this research, it is limited in the following aspects: it needs model information of a scaffold for initial FEM model development and the following updates. Also, the developed system was a prototype system that was applied to a small scaffolding structure with only four strain sensors applied to each of the four columns. For our findings to be converted to more practical results, the proposed approach should be validated with large systems with more variability.

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Machine Learning for Assessing Real-Time Safety Conditions of Scaffolds

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Abstract –

Researchers have taken advantage of technological advancements to automate construction processes; as a result, significant progress has been made in designing and planning temporary structures. Despite this effort, relatively little attention has been placed on automating the monitoring of safety issues of scaffolding structures, which are one of the major elements used in the construction industry. A need has emerged for a reliable means to assess the safety conditions of scaffoldings. This paper proposes a method of integrating strain-gage sensing with a machine-learning algorithm (support vector machine) to assess the real-time safety conditions of scaffolds. Based on actual strain data of scaffolding members, which were collected using wireless sensors for various loading cases on the scaffolding structure, a support vector machine was applied to differentiate the scaffolding conditions into 'safe', 'overturning', 'uneven settlement', or 'overloading' conditions. Such an automated differentiation of the condition of a scaffold could help to determine whether or not the scaffolding is safe to use without deploying safety inspectors throughout the site. The proposed method was experimentally validated to be successful in estimating the safety condition of a scaffold with an average accuracy of 97.66% for the cases that were tested. The proposed methodology could serve as a real-time monitoring system to determine the status of scaffolding structures. Its application is expected to significantly improve reliability in assessing the safety conditions of scaffolding structures, compared to conventional safety inspections, and to resolve the related safety issues.

Keywords –

Scaffolding, real-time monitoring, strain sensor, machine learning, safety, condition assessment, support vector machine

1 Introduction

Over last several years, interest about information and sensing technologies and their potential in applications has spread across the construction industry, and has resulted in research on automation during various aspects of construction, including design and planning as well as construction operation and management. Researchers [1,2] initiated the Building Information Modelling (BIM) Safety project to uncover potential opportunities using BIM to advance construction safety in planning. In addition, other studies [3,4] have incorporated BIM in scaffolding structures for scheduling and planning purposes [3,4].

While past research has identified new ways to use various resources to plan for safety, in reality, the construction industry still suffers from catastrophic events on a regular basis. To name a few large and deadly accidents, in 2002, the collapse of a scaffold at the Jon Hancock Center in Chicago killed three people and injured a number of people [5]. A recent scaffold collapsed in Houston in 2015, trapping six workers under piles of rubble until they were rescued; in this case, several citations were issued to the associated companies for not properly initiating and maintaining the safety of the scaffolds [6]. Many research articles [7-10] have discussed the problems in using manual inspections, which site managers are required to conduct, including ineffectiveness, unreliability, time consumption, and high cost. Given inadequate practices used currently and the past accidents, it is evident that safety issues of scaffolds during construction activities present challenges to the industry. It also is evident that there is an urgent need for an advanced method for safeguarding scaffolding.

The application of structural analysis in understanding the real time safety condition of a scaffold is an option for safeguarding scaffolding. However, structural analysis requires a full mathematical structural model and actual loading in each of the scaffold members for detailed analysis. However, in real time at construction sites, it is difficult to acquire all this information. Hence, this method may not be suitable for assessing the real-time safety of the scaffold as desired in construction sites. While, with a sufficient number of training data, the implementation of machine learning (ML) can address the limitations found in structural analysis as ML requires only a set of strain data from the strain sensors to predict the real-time stability condition of the scaffold. Thus, a ML approach has been implemented in the proposed methodology. As the structural conditions can be classified to specific categories, we selected SVM as a supervised ML approach.

The objective of this research was to develop an integrated method for assessing the structural safety conditions of a scaffold by using 1) strain sensors to collect real-time strain measurements from scaffolding structures and 2) applying a supervised machine-learning technique (support vector machine) to the strain data in order to analyze the safety conditions automatically of scaffolding structures.

2 Recent Research on Advanced Information and Sensing Technologies

Many researchers explored sensing technologies to assist in construction operation and management. Motion sensors [11,12]; radio-frequency identification (RFID) [13–15]; and ultra-wideband (UWB) [16–19], Bluetooth [20,21], vision [22–24], and laser [25–27] technologies have been studied extensively to discover advanced ways to collect and analyze data. Most of the safety applications from such research, however, are limited to directly using site data from deployed sensors. On-and-off-based violation detection is an example of the direct use of sensory data. Other studies have investigated methods of collecting data on safety issues, but those efforts were limited to handling safety issues directly.

To assist decision making regarding safety, a few researchers [28-30] have integrated sensing technology with machine-learning techniques. This advanced technique allows safety challenges associated with repeated actions to be captured automatically by the system. Researchers have also automated safety monitoring by integrating site information for various construction activities into the construction schedule [31-32]. As far as scaffolding safety is concerned, a minimal level of research has been conducted, with limitations. Moon et al. [33] installed a network of sensors to analyze the condition of a scaffold by using multiple types of sensors, such as an inclinometer as well as ultrasonic and strain gages. Yuan et al. [34] developed a new system, called the Cyber-Physical System (CPS) that links a virtual model of a scaffold with a sensor-based monitoring system. Despite the advancements that these researchers have made, the strain patterns based on structural responses have not been investigated properly, which can offer the potential for rigorous analysis. By applying machine-learning techniques, such patterns could be parameterized and used for analyzing the safety conditions of a structure (e.g., scaffolding).

3 Approach

Figure 1 shows the flowchart of the approach used in this research. It involves six stages, including the construction of a database for structural analysis, process of learning the training data, and the prediction of the conditions of a scaffold. Steps 1-4 pertain to the development of a database system for learning, and Steps 5-6 pertain to the prediction of safety assessments when using real scaffolding structures and strain sensors (CFLA-3-350).

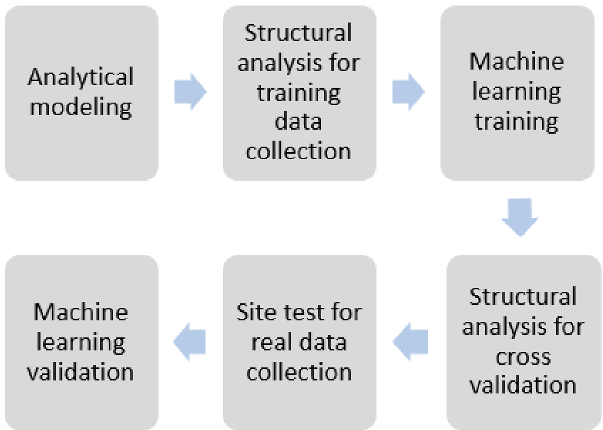

Figure 1 Flowchart of the proposed approach for safety monitoring of a scaffold based on machine learning

To conduct a structural analysis for safety assessment:

Step 1: First, we modelled a scaffolding structure.

Step 2: Then, the constructed structural model was analyzed by using various loading cases.

Step 3: The results of each of the cases were loaded into a database for the learning process.

Step 4: Then, the learning parameters of a machine-learning algorithm, support vector machine (SVM) in this research, were obtained such that the cross-validation produced reliable results, that is, over 95% accuracy.

Step 5: As the real-time strain data were collected, SVM was applied to implement automated analysis by predicting the safety state based on the trained data sets and associated learning parameters

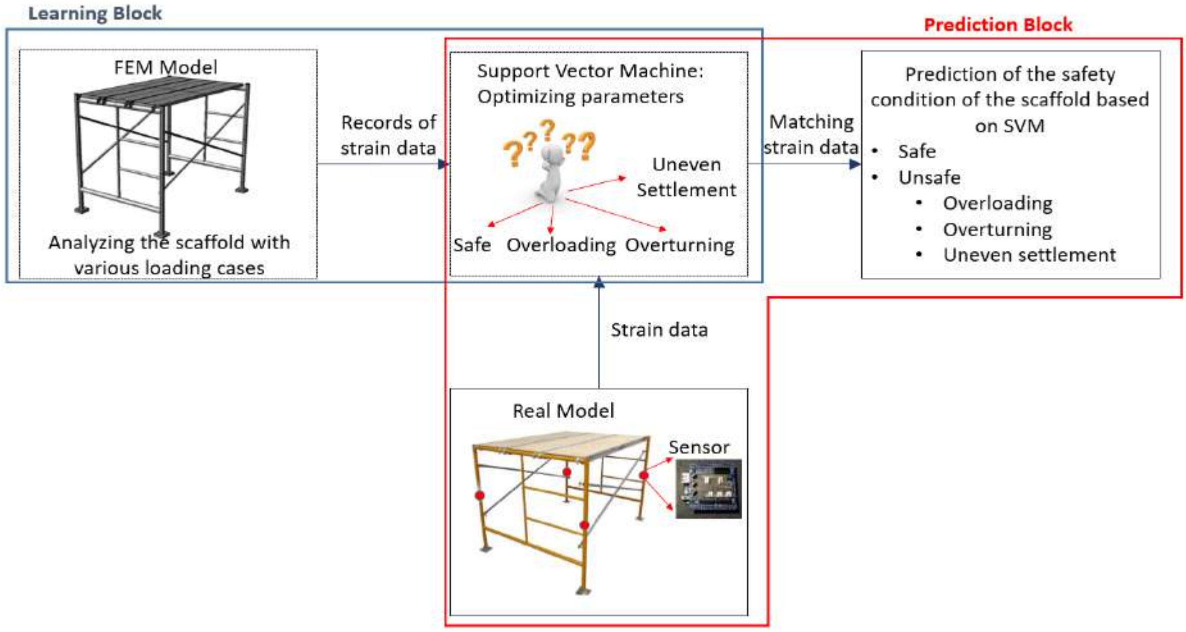

Figure 2 Framework of the approach, with four categories for safety assessment

Figure 2 elaborates the process of the proposed monitoring method and the relationship among the analytical model, analytical data, real model, real data, and encompassing machine-learning algorithm. Figure 2 shows the four categories of safety conditions that were possible as a result of loading conditions on a scaffold; safe, overloading, overturning, and uneven settlement. The SVM-based assessment analyzed the safety conditions of the scaffold with respect to these four categories.

3.1 Learning Part 1: Pre-Processing for the Generation of Training Data

One of the most important steps for machine-learning approaches is the generation of enough numbers for the training data, because the learning algorithms and their optimized parameters heavily rely on the availability of training data on which predictions are based that are used in decision making. Using a finite element model analysis, 300 data sets were generated for each of the four categories (1,200 strain-load data sets). Table 1 shows a sample of the training data sets, with four data sets for each category.

The loading was based on the four safety categories, and the strain data was collected from the four locations shown in Figure 2, based only on the elastic deformation of structure. Due to safety reasons, the tests were controlled to be safe with the following cases:

- Safe: we limited the weight to 400 kgf although the OSHA standard was 1229 kgf for the size of the tested scaffold; a heavy-duty scaffolding should not exceed 75 pounds per square foot applied uniformly over the span area [35].
- Overloading: we considered any weight beyond 400 kgf as overloading
- Overturning: to emulate the effect of overturning, we used a forklift to lift two columns by less than two inches
- Uneven Settle: to emulate the effect of ground settlement, we used a forklift to lift one column by less than two inches

Table 1 Sample of the training data sets

Category	Strain 1 (με)	Strain 2 (με)	Strain 3 (με)	Strain 4 (με)
Safe	-37.69	-48.07	-33.05	-50.81
Safe	-49.26	-54.51	-45.35	-52.28
Safe	-60.46	-54.37	-57.06	-52.07
Safe	-55.40	-42.07	-16.39	-33.73
Overturning	12.29	-5.33	-17.36	0.24
Overturning	1.97	-5.31	-3.01	10.67
Overturning	16.69	6.12	-0.20	14.22
Overturning	1.47	-7.01	2.67	11.78
Overloading	-71.81	-47.46	-47.22	-53.17
Overloading	-59.43	-52.97	-68.76	-54.25
Overloading	-75.59	-62.33	-37.29	-61.37
Overloading	-51.43	-46.94	-62.33	-74.08
Uneven Settle	-17.72	5.91	2.99	-15.95
Uneven Settle	-8.83	0.65	5.57	-9.95
Uneven Settle	-14.98	6.11	0.05	-22.08
Uneven Settle	-24.75	-8.96	8.77	-3.33

The four categories represented different aspects of the structural behavior of a scaffold, and each behavior was indicated by the analyzed strain values corresponding to one of the categories.

3.2 Learning Part 2: Pre-Processing for Training with a Support Vector Machine

This research used one of well-known machine-learning techniques, a support vector machine, to train the data sets that represented the pre-processed load-and-strain values. The load-related strain data (inputs) were processed by SVM to train SVM classifiers (outputs) with the four categories (i.e., safe, overloading, overloading, and uneven settlement). SVM is a binary classification technique that formulates a plane to separate the data into two groups:

$$f^{(i)}(x) = \boldsymbol{\omega}^{\mathrm{T}}\boldsymbol{x}^{(i)} + b = 0, \qquad (1)$$

where $x^{(i)}$ is the feature vector at the i^{th} order, and $\boldsymbol{\omega}$ and b are updating parameters. Then, the classification was made by plugging the function, f(x), into a sigmoid function as shown:

$$h\left(x^{(i)}\right) = g(\boldsymbol{\omega}^{\mathrm{T}}\boldsymbol{x}^{(i)} + b) = \frac{1}{1+e^{-\left(\omega^{\mathrm{T}}x^{(i)}+b\right)}}, \qquad (2)$$

where g is a sigmoid function. Because the outputs of a sigmoid function range from 0 to 1, a classifier function can be applied with two labels (i.e. $\mathrm{y}^{(i)} \in \{1, -1\}$), as shown:

$$\mathrm{y}^{(\mathrm{i})} = \begin{cases} 1 \ \ if\ h\left(x^{(i)}\right) \geq 0.5 \\ -1\ if\ h\left(x^{(i)}\right) < 0.5 \end{cases}, \qquad (3)$$

As the data sets are classified by a plane, each classified set is separated by a margin, and the functional margin is defined as:

$$\mathrm{r}^{(i)} = \mathrm{y}^{(i)}\left(\boldsymbol{\omega}^{\mathrm{T}}\boldsymbol{x}^{(i)} + b\right). \qquad (4)$$

The maximum margin classifier that is the key step for parameter optimization is expressed as:

$$\max_{r,\omega,\mathrm{b}} \frac{r}{\|\omega\|_2} \quad \text{such that } \mathrm{y}^{(i)}\left(\boldsymbol{\omega}^{\mathrm{T}}\boldsymbol{x}^{(i)} + b\right) \geq r,\ for\ all\ data\ sets\ i. \qquad (5)$$

As the value of r can be set to a constant, and because it only scales the values of the updating parameters, Eq. 5 can be simplified further to:

$$\min_{\boldsymbol{\omega},\mathrm{b}} \|\boldsymbol{\omega}\|_2 \quad \text{such that } \mathrm{y}^{(i)}\left(\boldsymbol{\omega}^{\mathrm{T}}\boldsymbol{x}^{(i)} + b\right) \geq 1,\ for\ all\ data\ sets\ i. \qquad (6)$$

For a more sophisticated classification, we used the Gaussian kernel method:

$$K(\boldsymbol{x}^{(i)}, \boldsymbol{x}^{(j)}) = \exp\left(-\frac{\left\|x^{(i)}-x^{(j)}\right\|_2^2}{2\sigma}\right) \qquad (7)$$

The corresponding change in the classification function is:

$$\boldsymbol{\omega}^{\mathrm{T}}\boldsymbol{x}^{(j)} + b = \sum_{all\ i} w_i K\left(x^{(j)}x^{(i)}\right) + \mathrm{b} \qquad (8)$$

Using these equations for a binary classifier, one category can be classified. To further classify more categories (e.g., four categories), the one-versus-all (OVA) method [36] was applied to all the training data sets; accordingly, we extracted the optimized parameters for each of the four categories. Figure 3 illustrates a conceptual example with four classifiers defined by the optimized parameters and four cases classified by the classifiers.

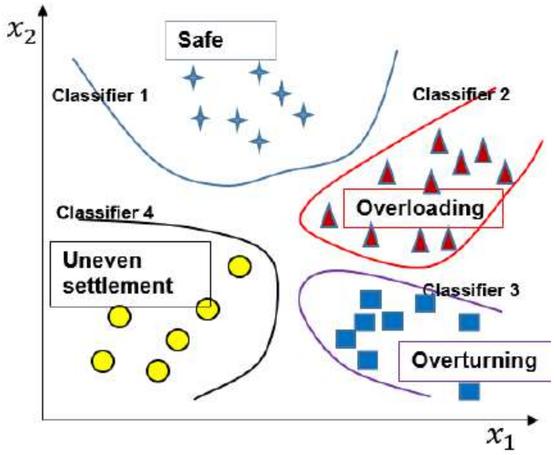

Figure 3 Classification with four classifiers

3.3 Prediction: Real-Time Data Collection and Estimation of the Safety Conditions

As the parameters for the four classifiers became available after the learning step, real-time strain data from an actual scaffold were processed by SVM to predict the safety conditions of a scaffold. To collect such strain data, this research developed customized strain sensors on an Arduino platform and installed them on the four columns of the scaffold being tested. This step was straightforward because the parameters for the classifiers were available from analytical Finite Element Method (FEM) solutions to the load-strain relationship and also because the actual strain data could be collected by strain

Figure 4 Experimental setup with a one-bay scaffold

sensors attached to the scaffold. Actual strain data were validated with respect to the four classifiers for prediction purposes. For statistical assessment of the accuracy of the SVM used in this research, the prediction rate was computed for each of the categories:

$$\text{Accuracy} = \frac{\text{TP} + \text{TN}}{\text{TP} + \text{TN} + \text{FP} + \text{FN}} \times 100 \qquad (9)$$

where:
- TP = true positive
- TN =true negative
- FP = false positive
- FN = false negative

3.4 Experimental Validation

To test the proposed method of real-time assessment of the safety of a scaffolding structure, a one-bay scaffolding structure was set at an indoor site, as shown in Figure 4. The dimension of the scaffold was 213 cm (L) x 158 cm (W) x 386 cm (H); in addition, four strain sensors were attached to the four columns of the scaffold. As soon as strain data were measured and transmitted to a computer equipped with the SVM algorithm, they were analyzed to predict the safety conditions of the scaffold for given loading conditions. We purposely tested 150 cases of each of the unsafe conditions (50 trials x 3 categories), and evaluated the analyzed results compared to the actual safety conditions of the scaffold.

Table 2 shows the results of the three unsafe cases, and Table 3 shows the binary classifications (i.e., TP, TN, FP, and FN) of the predictions and the prediction rates. For the overloading test, the SVM predictions were 100% accurate. However, for the cases regarding the uneven settlement and overturning tests, few cases were encountered where the classifiers were incorrect; yet, the accuracy was 96.5% for both cases. Results for the uneven settlement cases showed that there was one case where the prediction was partially incorrect; this case showed positive results for uneven settlement and overturning, while it should have been positive for uneven settlement only. Due to this redundant classification, the total number of classified cases was 51 (47 + 4), although the number of the corresponding test case was 50. However, the overturning results suffered a different problem in that the classifier was not able to make correct predictions for five trials.

Table 2 Prediction of the Safety Conditions of the Scaffolding Using Real-Time Strain Data and SVM

Actual Conditions	Categories (SVM Outcome)			
	Safe	Overloading	Uneven Settlement	Overturning
Overloading	0	50	0	0
Uneven Settlement	0	0	47	4
Overturning	0	0	2	45

Table 3 Summary of the Binary Classifications and Prediction Rates

Actual condition	Categories (SVM outcome)				Accuracy
	Safe	Overloading	Uneven Settlement	Overturning	
Overloading	TN(50) FN(0)	TP(50) FP(0)	TN(50) FN(0)	TN(50) FN(0)	100.0%
Uneven settlement	TN(50) FN(0)	TN(50) FN(0)	TP(47) FP(3)	TN(46) FN(4)	96.5%
Overturning	TN(50) FN(0)	TN(50) FN(0)	TN(48) FN(2)	TP(45) FP(5)	96.5%

Despite these drawbacks, resulting from the SVM, the accuracy was high at 100%, 96.5%, and 96.5% for the three unsafe test categories in order of overloading, uneven settlement, and overturning. On average, the SVM classifier had 97.66% accuracy.

4 Conclusion

Researchers have used information and sensing technology to advance various aspects of operations related to temporary structures. Such endeavors have resulted in significant progress in safety design and the planning of temporary structures. However, as far as safety monitoring is concerned, the construction industry still relies on human efforts. The limited ability of people doing the safety monitory entails various challenges with respect to sporadic inspections over space and time, inconsistencies, and associated costs.

This research proposed a method to assess the safety conditions of a scaffold in real time by using real-time strain sensors and a machine-learning algorithm. For the machine-learning analysis, the research used a FEM technique to generate training data with respect to four cases (i.e., safe, overloading, overturning, and uneven settlement) and then applied real-time strain measurements from an actual scaffolding structure to the optimized (or learned) machine-learning method in order to predict the safety conditions of the scaffold. Such an automated process to evaluate the safety conditions of a scaffold could help to determine whether or not the scaffolding is safe to use without deploying safety inspectors throughout the site.

The proposed method was validated experimentally to be successful in estimating the safety condition of the scaffold, with an average accuracy of 97.66% for the cases tested. Thus, the proposed methodology demonstrated its ability to serve as a real-time monitoring system for determining the status of scaffolding structures. Its application is expected to significantly improve reliability in the assessment of safety conditions of scaffolding structures, compared to conventional safety inspections, and to resolve the related safety issues.

Although successful, this research identified challenges with using SVM. For example, SVM produced redundant classifications or else did not produce predictions (i.e., when all the classifiers did not generate any positive prediction). For the tested cases, the performance of SVM was acceptable; however, it should be further validated for a larger system, with more various loading cases and a greater number of strain sensors. We suspect that this change may negatively affect the performance of the SVM, as it will introduce more complexity in the optimization of the parameters and thus make prediction more difficult. Additionally, future study should consider more advanced machine-learning algorithms, such as neural network, which are known to manage more complex systems.

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Barriers Analysis to Effective Implementation of BIM in the Construction Industry

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Abstract

Building Information Modeling (BIM) as a new method presents a number of opportunities and challenges for the architectural, engineering and construction (AEC) industry. Obviously, there are many issues in the way of implementing BIM. Some of these issues have been largely eliminated over time and by the advancement of related technologies; however, various issues are emerging when dealing with the details of BIM implementation. Contract and legal barriers, cultural problems, management system, and economic and security issues are the most important challenges against implementing this technology. In order to bridge the gap between researchers and practitioners, this paper aims to summarize available information related to the implementation of BIM in the construction industry (about 47 papers) and its related barriers. This research focuses on the most repetitive challenges and barriers that have been more fundamental than the rest and other related issues have been ignored. Distribution of these barriers and challenges is different from region to region. Finally, challenges, which need to be addressed before we can fully benefit from BIM, are highlighted

Keywords –

Building Information Modeling (BIM); Challenges; Implementation barriers

1 Introduction

Building Information Modeling (BIM) as a new method presents a number of opportunities and challenges for the architectural, engineering and construction (AEC) industry. BIM is an evolution of the computer-aided design (CAD) system, which provides more intelligence and interoperable information and is named as project modeling, virtual building, virtual design, construction and finally nD modeling [1]. BIM is also unequivocally a tool of collaboration. Collaboration in the design and construction decreases design mistakes and increases the productivity of the construction industry [2].

Contract and legal barriers, cultural problems, management system, and economic and security issues are the most important challenges toward implementing BIM. Understanding the challenges ahead in implementing BIM is the first step in finding a solution for them [3]. Therefore, this article attempts to present a statistical report of worldwide problems and obstacles that have been linked to the implementation of BIM by studying the articles published in the past decade, and then presents the most important challenges..

Obviously, there are many issues in the way of implementing BIM. Some of these issues have been largely eliminated over time and by the advancement of related technologies whereas various other issues are emerging when dealing with the details of implementing BIM. The focus of this research is on the most repetitive challenges and barriers that have been more fundamental than the rest, and other related issues have been ignored.

2 BIM History

The early concept of BIM dates back to the 1970s and 1980s when the computer-aided design (CAD) was introduced [4]. The creation of the ArchiCAD software in Hungary in 1982 is the real beginning of BIM, and Revit software in 2000 is considered a major turning point in the implementation of BIM [5]. Given that about two decades have passed since the advent of BIM, its implementation in the construction industry has been relatively slow in comparison to other industries, such as manufacturing and engineering industries [6]. However, in the last few years, there has been a lot of advancement in the technology and implementation of BIM, and the construction industry has realized that it can take advantage of using this technology. A brief history of BIM is given in Fig. 1.

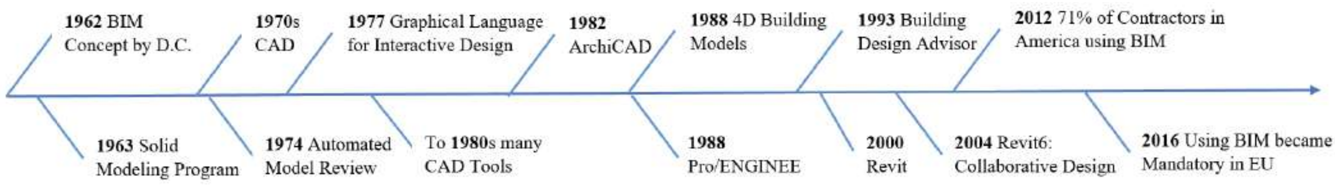

Figure 1.The History line of BIM

Many studies have been conducted to examine BIM implementation issues, which often emphasize the positive impacts of its implementation on the construction industry. Research has shown that major changes have taken place since the launch of BIM, and in recent years, the use of BIM has increased dramatically. In North America, the use of BIM by contractors has increased from about 28% in 2007 to more than 70% in 2012 [7]

Recent surveys also show that BIM implementation is accelerating in leading countries such as the United States and the United Kingdom, as well as in new adapter countries such as Brazil and Australia; more government and private owners want to recognize its benefits [1].

The EU made an important decision in 2014. Accordingly, 28 EU Member States may encourage, specify or mandate the use of BIM in public projects from 2016 onwards [8]. Until now, the United Kingdom, Denmark, Netherlands, Norway and Finland considered it necessary to use BIM in publicly funded projects. The first step in achieving the BIM utopia is to recognize the barriers and challenges of implementing it [1].

3 BIM Implementation Challenges

Despite the great benefits of BIM, there is still no clear strategy for its widespread use in the future. [9]. There exist vast variety of classifications in different studies with regard to barriers against implementing BIM .

After reviewing over 100 studies and selecting 47 final papers that were more related to this subject, five major problems in BIM implementation are divided by location listed in Fig. 2.

The USA with 19 papers and the UK with nine papers are the top countries working on issues related to BIM implementation. The map point of origins of the articles is shown in Fig. 3. Accordingly, 62% of the articles are from journals and 38% are collected from conference proceedings. Fig. 4 shows the distribution of the reviewed articles by year of publication.

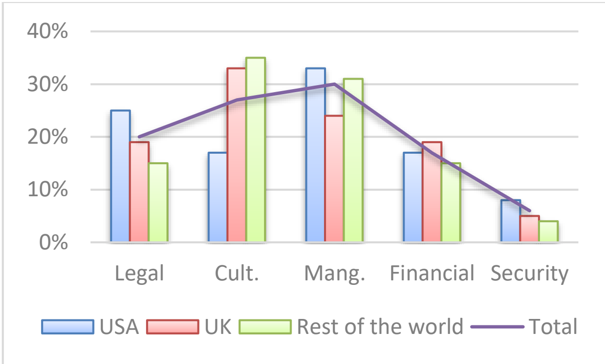

Figure 2. Distribution of BIM implementation Challenges

Figure 3. Map point: origins of reviewed articles

Figure 4. Distribution of reviewed articles by year of publication

Major issues according to the author's opinions and frequency of appearances on articles are management (30%), cultural (27%), legal (20%), financial (17%) and security issues (6%).

However, in the USA, arrange of barriers is slightly different from the world. Accordingly, issues related to management are first, but legal issues are more important than cultural and financial aspects of BIM implementation..

The UK is known as the leader of implementing BIM in the world. The most common problem in the UK is cultural-related issues, followed by the management, legal and financial problems.

If we ignore the papers from the USA and the UK, in the rest of the world, main barriers are related to cultural, management, financial, legal and security issues. Problems related to security appear only in a few articles; however, authors believe that this challenge is one of the major challenges in the future. The second point from this chart is that the order of problems is similar to that in the UK.

A short review of five more important issues is collected. Order of subjects is according to authors' opinions on the importance of subjects and different from the frequency of appearances on the articles.

Table 1. Literature on BIM implementation barriers

Challenges	Articles
Legal	[1],[10],[11],[12],[13],[14],[7],[15],[16],[17],[18],[19],[20],[21]
Cultural	[22],[23],[2],[24],[10],[11],[12],[13],[25],[8],[16],[26],[17],[27],[28],[29],[30]
Management	[31],[1],[32],[12],[33],[15],[34],[35],[36],[17],[37],[38],[39],[40],[41]
Financial	[22],[11],[12],[13],[42],[25],[38],[19], [43],[44],[41],[45],[20],[46]
Security	[22],[9],[7],[44],[18]

3.1 Legal and Contractual Issues

Despite the fact that BIM technical issues have been highly considered in recent years and considerable energy has been spent on these areas, “maturity of the legal body of BIM as well as its contractual configuration is more unsophisticated than its technical aspects. [18]” This weakness has a special effect on contractual terms and there is a challenge that limits the responsibilities of legal issues related to BIM implementation. Therefore, an appropriate substrate for implementing BIM in contract clauses of projects should be created or added.

3.1.1 Legal issues

In addition to technical barriers, resistance to changes in employment patterns and the need for education and training on the path toward implementing BIM in the industry, legal issues are the most neglected challenges against BIM implementation. These legal problems are generally due to:

1. Liability issues: Legal liabilities are due to the multiple number of stakeholders contributing to the model and/or dependent on the precision and quality of the data in the model [1]. Moreover, fraction of sufficient legal structure for managing owners’ comment in design, construction and installation is one of them [11].
2. The need for regulations: Executive regulations in this regard and their coordination at international level to create a common language, reduce conflicts and create a clear path to resolving the dispute are essential.
3. Intellectual property rights: Because BIM models can be easily extracted and copied, intellectual property rights are determinative in BIM implementation [18]. For example, a BIM protocol may need a higher price intellectual property licensing than that procured under traditional contracts [9] For intellectual property rights in contracts, these provisions are important: model ownership, copyrights, authorized and unauthorized uses of models and e-documents, and the level of exposure of the special trade information.

3.1.2 Contractual Issues

Poor contractual agreements in addition to failing to implement BIM may pose a significant risk to the success of the entire project. BIM contractual language must deal with two important risk categories, including:

1. BIM behavioural risks: Which may include collaboration issues, efficiency level of coordination, and collaborative information development..
2. Issues in BIM technological aspects: Arise in forms of information reliability, model accuracy, model management and maintenance, and model ownership.

BIM contractual provisions refer to levels of BIM maturity, which, in higher maturity level contract, should address more issues and more details on BIM implementation. This is because responsibilities, relationships, interactions, and technologies are different at each maturity level [18].

Thus, to avoid arguments concerning BIM responsibilities, limitations and liabilities, a new form of contract/amendment should be implemented. This would cover all the parties directly involved or any other party that may be affected by BIM working method. On the other hand, BIM protocols should be developed by taking into account legal issues, which could be used as an emendation to the main contract to make it adequate for BIM [9].

A recent survey in the AEC industry revealed that approximately 40% of the professional BIM users are unaware of BIM standard forms of contract. This shows that many projects have incorporated custom manuscripts in their contracts [18].

In addition to the amendments, which are intended as a text to improve and correct the main agreement, an addendum is an informational or explanatory note of the requirements of the parties concerned, which has not been specified in the main contract document. Thus, BIM has entered into some of the contracts that have been produced in recent years in format of specific BIM addenda to contracts. Those addenda have the purpose of defining the scope of BIM for facilities designed and constructed for each owner. Owners such as the United States Army Corps of Engineers (USACE), Pennsylvania State University, and the United States Air Force Centre for Engineering and the Environment have developed their own BIM addenda, some of which are used with a whole package of other documents aiming to optimize and ensure the successful implementation of BIM. Those efforts subscribe to the goal of overcoming the challenges that have accompanied BIM use.

In addition to the owners mentioned above, two industry leaders, AIA and AGC, have developed BIM contracting standard forms to address BIM contracting requirements. These include Consensus DOCS 301: BIM Addendum: Building Information Modeling Protocol Exhibit [18].

3.2 Cultural Issues

In general, about 30% of the total number of articles studied in this project referred to cultural problems. Cultural problems are the background of other problems and by solving them, a great step can be taken to solve the problems of implementing BIM.

Cultural problems include many aspects and the most important ones are resistance to change, lack of cooperation between project stakeholders, and the absence of the real BIM-based sample.

3.2.1 Resistance to Change

Actually, only small fractions of companies are aware of BIM and are using this technology to benefit their own projects. While other companies do not have experience in this field and carry out their own projects traditionally as they are unwilling to use BIM technology. These companies believe that BIM is an underdeveloped technology with limited capabilities; they also feel that using BIM is very complicated and thus it is best to do their own projects using non-BIM tools.

The lack of knowledge and education is another factor; engineers and companies are doubtful about learning BIMs concept and they believe that it is costly to train their employees in this regard.

In addition, the lack of knowledge and trained staff as well as inability to persuade other stakeholders to handle BIM implementation costs is among other issues that makes it difficult for individuals to carry out their projects using non-traditional methods.

3.2.2 Lack of Cooperation between Project Elements

In the success of BIM-based projects, there are many people involved; the collaboration and reflection of the project team can help ensure the success of the project, rather than discussing the goals that contribute to the success of the project. Lack of cooperation from any of the stakeholders can cause serious damage to the entire project. In general, BIM implementation in construction projects requires more collaborative and integrated delivery of the project.

3.2.3 Absence of a Real-World BIM-Based Sample

Another approach to persuading stakeholders to use BIM technology is the availability of run-time examples of projects implemented using BIM technology. If project stakeholders and companies visit a real sample of BIM-based project, they are more willing to do their projects using BIM technology.

By organizing several meeting sessions with activists in the AEC and introducing BIM technology and its benefits along with showing a real BIM-based sample, they can be familiar with BIM concept and its advantages. To this end, catalogues that briefly introduce BIM and its benefits are published and presented in the building industry exhibitions; moreover, experts are invited to these exhibitions to provide explanations and answers to questions. It is also possible to add a course to the university curriculum and invite BIM experts to train students in BIM area and related software. Companies and organizations can also arrange classes for their employees to become familiar with BIM technology. Moreover, BIM experts could be asked to prepare educational videos for teaching BIM software. Because BIM-based projects require teamwork, before the start of the project, it is necessary for one of the specialties to be selected as the head of the group and clearly describes the responsibilities and duties of all the team members. It is also necessary to control the work of all the members to guarantee a collaborative work.

3.3 Management

There is much debate on the benefits of implementing BIM. This improvement surely will make the project managers more likely to be happy since BIM helps managers reduce their concerns in the following areas:

1. “Complexity of infrastructure development projects needs strong project management for (a) a multidisciplinary management system (s) to support decision making and (b) to motivate many practitioners involved in the design process” [47].
2. The role of information in the management of the design phase workflow [47].
3. Knowledge management for better risk management: One of the principles of risk management in the project is that all the team members must contribute to the risk database in different phases of the project. It is complicated to manage these databases with traditional methods [41].
4. Based on the main failures identified, and compared to international standards, cost management is one of the main categories, arising as the most recurrent issue [41].

In addition to the above, there are plenty of other things that cannot be considered here. With BIM, project management is better to be performed in these areas, and its quality becomes better through using less energy. However, to reach this point, the project manager should face the following challenge:

1. Need to upgrade the communication platform: Vital communication is more than ever before; it puts new risks on the project.
2. The complexity of team building in this new environment: The performance of virtual teams requires their own techniques, which usually require managers to master their skills. It should be recalled that in the last 40 years, the productivity of human resource in the construction industry has been less than productivity in the non-farm industry. Therefore, the use of experiences and other techniques of the basins (e.g., IT) is remarkable in this regard. The third party as BIM implementation manager can help in this category, since specific professions will have synergy with the project team members [26].
3. Challenges are caused by longer project engineering time, especially in EPC projects, where its nature is the integration of the stages of engineering and construction. Justifying the expectation of completing the model and engineering will be to some extent difficult.
4. Considering the production of the visual model: Stakeholders seem to be more willing to comment. Since prioritization is different from each stakeholder’s point of view, their summing up in stakeholder management processes sometimes will be more challenging.

However, due to the benefits and facilities BIM provides for project managers, it is justifiable to spend energy on overcoming the above problems. However, overcoming the above problems and other challenges mentioned in this article, especially EEFs, In practice, the implementation of BIM in projects has encountered obstacles. What is certain is that after the transition period has passed and BIM has been stabilized in future projects, one of the most beneficial stakeholders in this implementation will be project managers.

3.4 Financial Issues

Financial and investment issues are the determining factors in any project. These issues become more important during emerging BIM technology. As mentioned in the "cultural" section, the lack of a real and complete implementation of the model creates many doubts for investors and stakeholders. There are two main questions in this area, which will be answered in this section: 1- Is it reasonable to have a high initial investment to equip the company with BIM technology? 2- What is the rate of return on investment?

Implementing any new technology requires an initial investment. Most of the investment required to implement BIM is spent on purchasing software, hardware, personnel training, and recruiting specialized staff. The main challenge is to justify and explain these costs to project stakeholders. In 2012, equipping each workstation with BIM technology costed about 10,000 pounds. One point to note is whether this cost is estimated at project cost or considered as part of a larger process. These costs are only seen as purchases of software and personnel training, or as part of a business change process. The answer to these questions can greatly justify the initial investment [25].

The return on investment (ROI) is one of the main concerns of investors. Analysis of the ROI is one of the ways to evaluate the investment; ROI = earning/cost. According to the survey, 48% revealed average or higher ROI. In one study, BIM ROI was measured in 10 different projects, varying from 140% up to 39900%. An average of 1630% for all projects and 640% for projects without a value analysis phase were obtained. Although ROI values are very different and the way to calculate the savings is different for each project, it is shown that implementing BIM has a large impact on reducing costs . The actual BIM ROI can also be much larger than reported [19].

3.5 Security

Reputable organizations in the world predict that in 2019, cybercrime and information theft will cost $ 2 trillion to the world economy. This figure has been rising for years to come and will be up to $ 6 trillion by 2021. The goals of a cyber-war are not limited to military complexes and installations and public and private financial and economic activities are also important goals.

The lack of proper civil law for cybercrime results in the ineffectiveness of international law in this area. Among the examples of these weaknesses, one can disrupt the electricity grid of Ukraine, hack the National Committee of the Democratic Party and the NSA, hack Taiwan and Philippines Government Networks, and attack on Russian banks, which is worth mentioning.

Cyber threats are not just about governments; individuals and companies are also threatened by these attacks. Since BIM is a shared knowledge centre for information about a facility creating an important basis for decisions during its product life cycle" [7]. Therefore, the feature of its being shared in the network context has led to security risks have been taken into account since the beginning of research on BIM implementation [44].

Now it can be even said that one of the main challenges facing the BIM adoption and implementation is the security challenge. Because parties' agreement on model access, software, security, information, archiving, transmitting, etc., is different, the safety of the model has always been and will be sensitive [9]. These security challenges arise from the following:

Intellectual property [9]- Since models can be easily transmitted, extracted, and reused (in whole or in parts) [18].

Cyber security of BIM tool outcomes As information sharing makes project data accessible to team members, cyber security is a concern due to the possibility of online unauthorized access and copyright infringement [9]. Data security is essential to avoid snooping, theft, virus and worms, and hacking [18]. One of the major challenges in BIM implementation at the AEC industry in the UK is security issues [22].

Clearly, solving this issue is beyond BIM control. As stated above, cyber security is a global challenge; however, it should be considered as one of the main challenges facing the implementation of BIM. Since there are fewer projects, all stakeholders do not have the same sensitivity to the information leakage. Therefore, solving the cyber security problem is crucial for the development of BIM implementation.

4 Discussion

In the previous section, we were acquainted with BIM implementation problems. This familiarization helps to better understand the subject and find the right path and think of the necessary arrangements for implementing BIM. The five categories of problems identified in the section 3 are fundamental issues, today. However, familiarity with problems that have been solved over time or problems that will arise in the future will be needed to implement BIM.

4.1 Challenges Resolved over Time

It seems that problems related to the software issues were largely resolved. In the early papers (early 2010), widespread mention was made of technical problems, especially software problems; Problems such as the lack of single software, lack of coordination between the software used in different sectors, and lack of a single standard for software output. However, today, with the advances in software, the standard definition of the unit and the acceptable coordination between different softwares have been largely resolved.

4.2 Future Challenges

Problems that will emerge in the future on BIM implementation path will be mainly contractual and security issues. Both the issues have been discussed in detail in Section 3. However, in short, the successful implementation of BIM requires new contractual types. IPD contracts may be a way out of this turbulent path.

Making secure information in BIM also requires defining a new protocol security. Defining and limiting access to various levels of software and clouds is an interdisciplinary field that requires more research.

5 Conclusion

This article introduces BIM implementation issues. Five fundamental issues including managerial, cultural, financial, legal, and security issues were fully introduced in this paper. By knowing more about the issues of the day, better solutions could be found. In general, from the discussed issues, it can be concluded that many problems would be resolved over time by providing more real world examples. In addition, project stakeholders will invest on BIM with low risk. In addition, the support and guidance of governments as well as the mandatory use of BIM in specific projects will increase the speed of BIM implementation. Although software problems have been largely resolved, there is still a need for more secure software. The reason is that the construction industry compared to other industries is less advanced in the automation sector. However, the need to use modern tools like BIM is increasingly understood. The path to outdo other competitors in this competitive market is BIM implementation.

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Automatic Generation of the Consumption for Temporary Construction Structures Using BIM: Applications to Formwork

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Abstract –

Temporary construction structures (TCSs), such as formwork and scaffolding, attract a lot of attention due to their impact on the schedule and cost of construction projects. In many cases, the determination of the consumption (i.e., labor, materials, and equipment) of TCSs is a complex process subject to errors. This paper presents a general framework to automatically generate the consumption of TCSs based on the geometry and quantification of building elements in the BIM model, coupled with applicable building codes and industry standards. The framework has been implemented to automatically generate the consumption required for the formwork in a BIM test model. The findings show that the framework provides an efficient way to determine the consumption requirements for formwork. Compared to the current consumption estimating tools for TCSs typically used, this BIM-based tool improves efficiency, allowing the project participants to account for TCSs during the preparation of the project schedules and cost estimates during the early phases of a project. With small modifications, the proposed framework could be applied to other TCSs.

Keywords –

BIM; Temporary construction structures; Formwork; Consumption; Quantity take-off

1 Introduction

As an indispensable part of construction resources, temporary construction structures (TCSs), such as formwork and scaffolding, play a significant role in the proper planning and smooth progress of construction projects. They are large in quantity and numerous in category, and due to their complex construction process, can take a long time to be built as well as take considerable amounts of labor and equipment [1]. According to Ko et al. [2], formwork alone, generally accounts for approximately 15% of the total construction cost. Therefore, the consumption of TCSs (i.e., the quantity and cost of the TCSs, as well as their accessories, and associated labor and equipment required) is a critical factor in project profitability [2][3]. In the construction industry, there are applicable building codes and industry standards (i.e., consumption standards), such as *RSMeans Building Construction Cost Data* [4] and *Standard for the Consumption of Construction Engineering in Hunan Province of China* [5], that are used to estimate the consumption of TCSs. For example, the consumption standard [5] specifies the consumption of formwork based on the area and type of formwork used, as well as the type and height of the corresponding building elements. Similarly, the consumption of scaffolding depends on the structure type (e.g., frame structure and shear wall structure), as well as on the building height and area. The information required includes the characteristics and dimensions of the building, the characteristics and quantity of the TCSs, and the type and height of each building element. The collection of this information is a tedious and error-prone process, which becomes difficult in large and complex projects.

Traditional 2D estimating tools were developed to assist estimators in the preparation of quantity take-offs by having a visual representation of the materials to be quantify [6]. This quantification could then be used to determine their consumption. Nevertheless, the main challenge remains when quantifying TCSs as they are not shown in the drawings (or models) from the designers. In recent years, with the advancements in 3D technology, the tools have shifted toward 3D-based estimate as they result in reduced errors and time when compared to 2D-based estimate [7]. But they still have a few disadvantages [8][10]. For example, some tools cannot be used with the building information modeling (BIM) model so its industry foundation classes (IFC) file has to be exported to the new platform to recreate the 3D model for further use. This causes unnecessary duplication of work and the loss of model information because many of the features of the original model are lost due to software compatibility issues (i.e., interoperability problems), and creates problems when changes are made at different project phases. In addition, some tools require to manually selecting the items of the consumption standards to connect quantity take-offs, which can easily lead to errors due to the estimators' interpretation of the consumption standards. Currently, BIM technology based on parametric modeling and three-dimensional digital representation has been widely applied to extract information needed to support project management [8]. Users can expediently obtain the information generated through the creation of building elements automatically. For instance, Kim et al. [11] used information such as location, geometry and quantity of building elements stored in the BIM model to automate the generation of construction schedules. Wang et al. [12] proposed the use of building elements to integrate schedule and cost to establish a cost-based progress curve used to control construction project schedules by extracting the quantities of cost items associated with each activity. In order to make BIM models effective, more and more projects strengthen the collaboration amongst participants, and the BIM models provided by the designers are used by the general contractors to support project management [8][9]. However, except for a few proprietary BIM tools, general BIM authoring tools do not have the ability to work with TCSs, including formwork and scaffolding, in the model [1] [6] [13][14][14]. Although it is possible to create TCSs utilizing the functions used when creating building elements, this process is time consuming and inefficient. The study by Monteiro and Martins [14] has shown that the modeling time would double when considering the creation of formwork.

Some researchers have made beneficial efforts to improve the automation level in generating information for TCSs based on BIM. For example, Kim and Teizer [1] developed a rule-based system that automatically plans scaffolding systems in BIM, which can recognize geometric and non-geometric conditions in building models and estimate the required materials for scaffolding. Monteiro and Martins [14] explored the possibility to develop a tool for ArchiCAD that would automatically provide a formwork model based on the building elements. Users could determine the building elements through a selection of Types, IDs and Layers, and then define the formwork parameters, such as thickness and material type. The formwork quantity would be obtained from the formwork model created automatically. Le [15] presented an algorithm to quickly calculate the quantity of formwork using the application programming interface (API) provided by Autodesk Revit. The algorithm accounted for the areas of intersecting faces. Wei et al. [16] proposed a BIM-based method for the calculation and management of temporary materials. They calculated the formwork quantity taking into account the thickness of formwork when different building elements intersect. Kim et al. [17] developed a semi-automated system to select the correct scaffolding. It included a feature lexicon to formalize the representation of factors essential to scaffolding planning. Singh et al. [18] used BIM data as input to compute the quantity of formwork and generate the visualizations and the schedule of quantities for formwork. Formwork elements were developed as parametrically constrained objects, and by using dimensional parameters, their size, number of sub-elements, and alignment can be adjusted. In previous studies, there are two main types of methods to automatically generate TCSs information. One is to create TCSs elements through a developed BIM-based tool, and the other one is to generate TCSs information directly based on building elements in the BIM model. For the estimate of the consumption of TCSs, the characteristics and quantity of TCSs needs to be determined [5]. Therefore, the latter method is better suited to obtain the information from the TCSs required by the consumption standards while minimizing unnecessary manual operations to generate it.

To address the shortcomings of current estimating tools, this paper presents a general framework that integrates BIM and consumption standards to automatically generate the consumption of TCSs. The framework uses the generation of the consumption required for formwork based on the geometry and quantification of building elements in the BIM model as an example. Compared to previous related studies, this study accounts for the location relationship of different categories of building elements, making the generation results of the formwork more accurate, and the generation process more efficient. A Revit-based tool to generate the consumption required for the formwork is developed and tested by a BIM structural model. By using Revit API [19] and MySQL [20], the whole generation process reaches a high level of automation.

2 General Framework

This section presents a general framework for integrating BIM and consumption standards to automatically generate the consumption of TCSs, which consists of four parts (Figure 1), and uses formwork as an example for its implementation.

The first part is to obtain a BIM design model. The

Table 1. Formwork consumption according to [5]

			Item		
			A 13-20	A 13-21	A 13-22
			Rectangular Column	Special-Shaped Column	Column Height Exceeds 3.6 m
			Bamboo Plywood Formwork		Excess Part is Within 3 m
			Steel Shoring		
Category		Unit	Usage Amount (Per 100 m² Formwork Area)		
Labor	General Labor	Man-day	34.8	51.64	9.42
Material	Sporadic Fixture	kg	-	27.94	-
	Steel Pipe and Coupler	kg	45.94	59.53	10.11
	…	…	…	…	…
Equipment	Truck Crane (5 Tons of Loading Capacity)	Machine-team	0.18	0.18	0.012
	Truck (6 Tons of Loading Capacity)	Machine-team	0.28	0.28	0.03
	…	…	…	…	…

model should include basic building elements such as columns, walls, beams, slabs and stairs, without creating temporary construction structures directly. In addition, the naming of the same type of building elements should be distinguished from other types, so that the consumption of different types of building elements can be calculated according to the corresponding rules of the consumption standards. For example, the consumption standard [5] classifies structural columns into rectangular columns and special-shaped columns in the section of formwork consumption, so different naming is needed to distinguish between these two types.

The second part is to extract and integrate building information required by the consumption standards. As previously indicated, the information required by the consumption calculation of different TCSs is not the same, and specific information needs to be extracted according to the corresponding requirements. For instance, the consumption of formwork is determined by the area and type of formwork used, as well as the type and height of the corresponding building elements [5]. Therefore, this information should be extracted and integrated. It is worth noting that information that is not automatically generated in the BIM model requires additional provisions. In this instance, the area and type of formwork is not readily available, so they need to be determined in this part so that they can be stored in the database for further use, as explained in the next section.

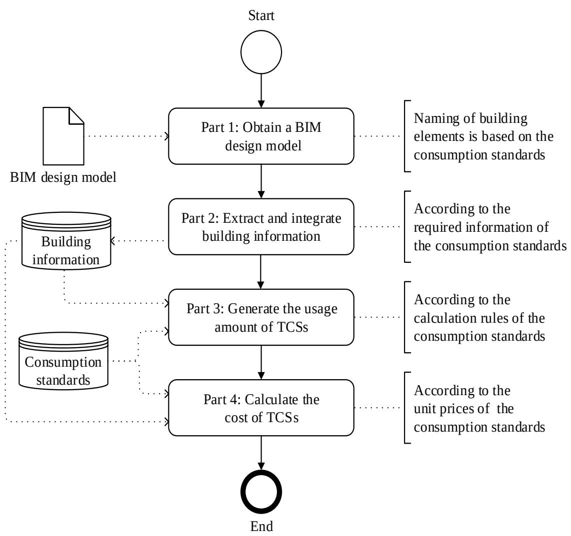

Figure 1. General framework

The third part is to generate the usage amount of TCSs according to the calculation rules provided by the consumption standards, including their quantity, as well as their accessories, how much labor is needed, and which and how much equipment is required. The associated consumptions are coded for a given work and they are accounted in the consumption standards into different items. The applicable items are used based on the information provided in part 2. For example, according to [5], for a rectangular column using bamboo plywood formwork with steel shoring, the usage amount of formwork is defined in item “A13-20” (Table 1). Similarly, for a special-shaped column using bamboo plywood formwork with steel shoring, the usage amount of formwork is defined in item “A13-21” (Table 1).

The fourth part is to calculate the cost of TCSs based on their unit price. With the generated usage amount of TCSs from part 3 and the unit price provided by the consumption standards, the cost of TCSs, including labor, materials, and equipment, can be calculated.

3 Adaptation of the General Framework: Using Formwork as an Example

This section shows the process to automatically generate the consumption of formwork using the general framework presented in Section 2. The process is shown in Figure 2.

In part 1, building elements of every type for which its material is cast-in-place concrete is classified (i.e., giving a specific name) during the modeling to identify the applicable items in part 3. The classification of the types of building elements such as columns, walls, beams, slabs and stairs should be done in accordance with the requirements of the consumption standards.

Part 2 determines the formwork area of the building elements, the projected area of the stair elements, and the formwork type required by the consumption standard [5]. First, the formwork area of the building elements with a material classified as cast-in-place concrete is calculated without considering intersection among building elements. The calculation rules are different based on the real construction situation. For example, the formwork area of columns and walls only calculates the side areas of the building elements, while that of beams, floors and stairs includes the bottom and side areas. The direction of the element surface can be judged by obtaining the vector of the max point of the bounding box of each surface in the elemental solid. If the vector is (0, 0, 1) and (0, 0, -1), it is shown that the surface is the top and bottom of the element. Then obtain the bounding boxes of the solids from the building elements and the midpoint of their surfaces, and convert bounding boxes into new outlines. Two building elements intersect when the midpoint of the surface of a building element is contained within the outline of another building element (to within a predefined tolerance). The tolerance depends on the thickness of the formwork used. The area of the intersecting surface is deducted from the formwork area of the building element.

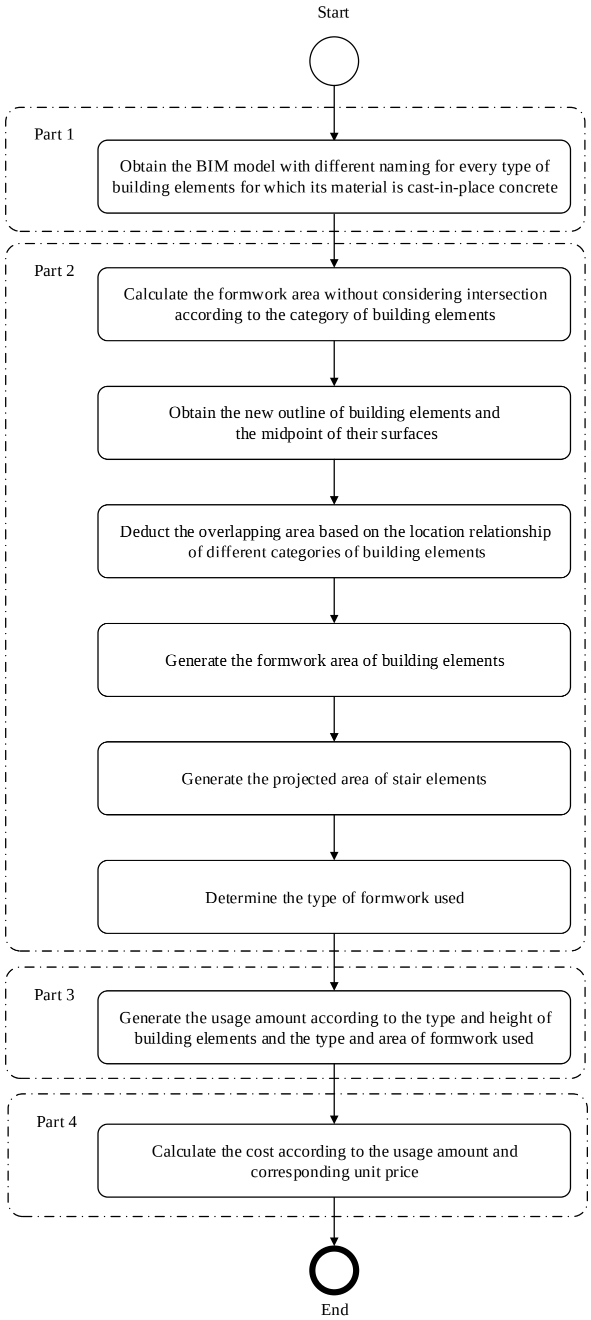

Figure 2. Process to automatically generate the consumption required for formwork

According to the location relationship of different categories of building elements, it is not necessary to judge whether a building element intersects all the other building elements of the BIM model, and it can be summed up as three types of rules. Firstly, intersection is only carried out in building elements including columns, walls, beams and slabs of the same floor. Stairs are the exception because they connect adjacent floors. Secondly, a certain category of building element would selectively judge the intersection with other types of building elements. For example, when a column intersects a beam, the intersection rule is required. On the other hand, when a column intersects a slab, no intersection rule is required because the top and bottom of the column have been previously deducted. Thirdly, a certain category of building elements has a specific intersection judgement process when it intersects with different categories of building elements. For instance, when judging whether a column intersects with a wall, the midpoint of the column surface and the outline of the wall would be retrieved; however, when judging whether a column intersects with a beam, the outline of the column and the midpoint of the beam surface would be retrieved. Through the selective intersection rule based on the consideration of the location relationship of different categories of building elements, the calculation results of formwork area would be more accurate and the calculation would be more efficient. Once the building elements are calculated in accordance with the above rules, the formwork area of those building elements is generated. The consumption of stairs depends on their projected area, and the projected area is generated based on the area of surfaces with vectors that are (0, 0, 1) from stair element. After that, the type of formwork, including material and its shoring (according to the actual situation), is determined.

The last two parts are to generate the consumption of formwork, which represents the usage amount and cost of labor, materials, and equipment that need to be consumed to complete the work content of the formwork including production, installation, maintenance, demolition, stacking and transportation. The consumption value depends on the type and height of the building elements, and the area and type, including material and shoring, of the formwork [5]. For example, a rectangular column using 100 m^2 of bamboo plywood formwork with steel shoring requires 34.8 man-days, 45.94 kg of steel pipes and couplers, and 0.28 machine-team of a truck with a loading capacity of 6 tons (Table 1). When the height of the column exceeds 3.6 m and the excess part is within 3 m, then the excess part requires 9.42 man-days, 10.11 kg of steel pipes and couplers, and 0.03 machine-team of a truck with a loading capacity of 6 tons (Table 1). The type and height of the building element can be obtained from the BIM model, and the area and type of the formwork has been determined in part 2.

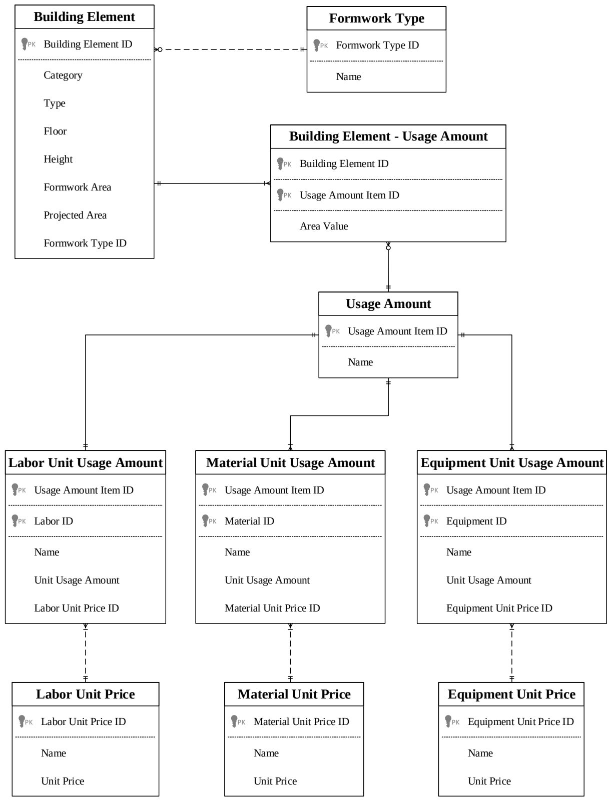

Figure 3. Entity relationship diagram of database structure

To store and manage data efficiently, a database structure containing 10 tables was designed to be used by the BIM-based tool (Figure 3). Using the reference IDs, the tool could parse attribute information from tables by following the paths from the reference IDs to the attributes. Thus, the consumption of formwork can be generated.

4 Case Study

Based on the presented framework, a Revit-based tool was developed to automatically generate the consumption required for the formwork, and was tested using the BIM model of a four-story cast-in-place concrete frame structure. The structure is 17.1 m high and has a building area of 5,028 m^2, which includes concrete columns, concrete walls, concrete beams, concrete slabs and concrete stairs (Figure 4).

All building elements have been named separately according to the classification of the consumption standard [5]. For example, rectangular columns are named “RC”, when the developed tool searches for the building elements with this name, only the consumption of rectangular columns is used.

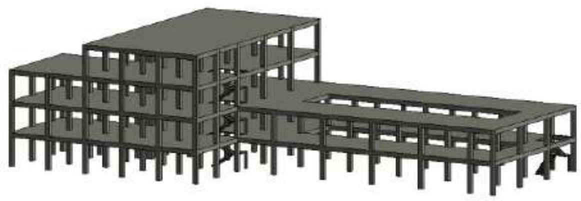

Figure 4. A BIM structural model

The formwork area of each building elements has been calculated using the adapted framework shown in Section 3, the output is shown in Figure 5. The total area calculated for the formwork is 8,436.46 m^2. The type of formwork is selected as the bamboo plywood formwork with steel shoring in the user interface (Figure 5).

After generating the formwork area of the building elements and the projected area of the stair elements, and determining the formwork type, the tool generates the usage amount and cost of labor, materials, and equipment. An example of the output is shown in Figure 6, Figure 7, and Figure 8. Figure 6 and Figure 7 show for each floor the labor usage amount, and cost and their percentage respectively. From the first floor to the fourth floor, it takes 1,509, 1,481, 800 and 623 man-days respectively. The cost per floor is 105,600, 103,659, 55,998 and 43,631 Chinese Yuan (1 CNY = 0.15 USD), also shown as a percentage of the selected cost for each floor; in this case 34.19%, 33.56%, 18.13%, and 14.13%. It can be clearly seen that the first and second floors have the highest labor consumption, while the fourth floor has the lowest. Different categories of total cost and their percentage are shown in Figure 8. The labor cost amounts to 308,888 CNY, which accounts for 64.41%, almost two-thirds of the total cost; while the cost of materials and equipment amounts to 142,470 and 28,222 CNY, or 29.71% and 5.88% of the total cost respectively.

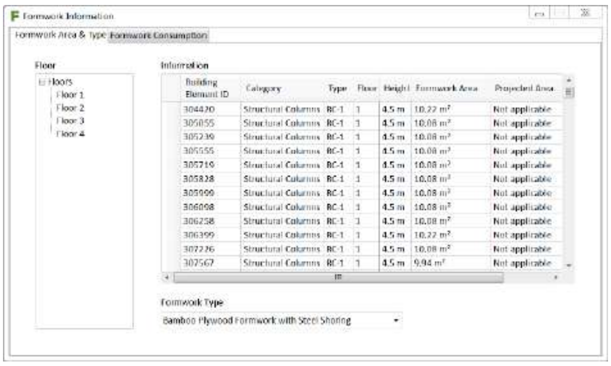

Figure 5. Generation of formwork area and determination of formwork type

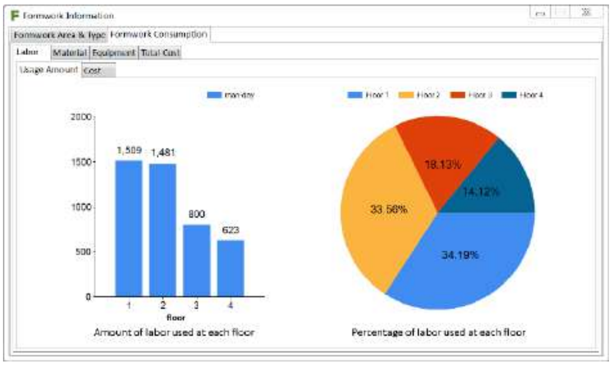

Figure 6. Amount (man-days) and percentage of labor used at each floor

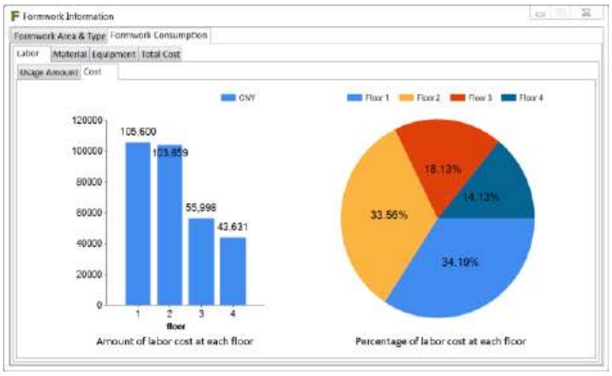

Figure 7. Labor cost (CNY) and percentage at each floor

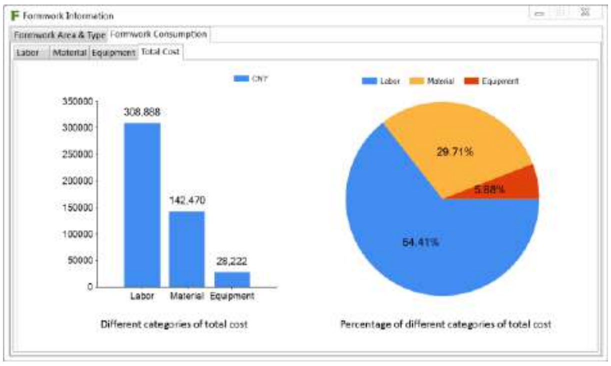

Figure 8. Different categories of total cost (CNY) and their percentage

5 Discussion

The current 3D estimating tools for TCSs typically used in construction projects have a few disadvantages (e.g., some tools cannot be used with the BIM model and/or require to manually selecting the items of the consumption standards to connect quantity take-offs). The framework proposed in this paper only needs the

Table 2. Scaffolding consumption according to [5]

			Frame and shear wall structures	
			24 m < BH* ≤ 30 m	30 m < BH ≤ 50 m
			A 12-12	A 12-13
Category		Unit	Usage Amount (Per 100 m^2 Building Area)	
Labor	General Labor	Man-Day	22.06	17.78
Material	Bamboo Scaffold Floor	m^2	19.56	18.38
	Steel Pipe (Ø 48*3.5)	kg	144.16	149.71
	Sleeve Coupler (1.4 kg)	-	3.87	4.9
	Right Angle Coupler (1.4 kg)	-	19.58	21.96
	Protective Net	m^2	45.01	45.01
	Base (1.71kg)	-	0.43	0.46
	Rotary Coupler (1.4 kg)	-	6.54	6.03
Equipment	Truck (6 Tons of Loading Capacity)	Machine-Team	0.32	0.24

**BH: Building height*

BIM model provided by the designer to automatically generate the consumption of TCSs, which improves efficiency. Although this study adopted proprietary API for Revit, this limitation can be removed by using the IFC compliant BIM model. When comparing the total area of formwork calculated by the presented algorithm to the one calculated by hand, it was found that the difference was negligible (about 0.02% difference). The algorithm considers the general sense of the location relationship of different categories of building elements, though it is not absolute accuracy to every project, it provides a sufficiently accurate way to estimate the formwork area at the early stage of the project. The calculation time using the proposed framework is less than one minute, far less than the time of the hand calculation. In addition, when changes are made to the building elements (i.e., new building elements are added, existing building elements are reduced or the dimensions of the building elements are modified), the TCSs could be recalculated effortlessly using the proposed algorithm.

The presented general framework has lots of potential with respect to other types of temporary construction structures such as scaffolding, which has some differences from the formwork. Fox example, in part 1, the BIM design model should include the area elements in addition to the basic building elements (e.g., columns, walls, beams, slabs and stairs). The consumption of general scaffolding is determined by the structure type (e.g., frame structure and shear wall structure), height and building area [5], therefore, part 2 should extract and integrate the values of the level elements and the area elements, and determine the structure type of the building.

In addition, there is also different in the classification criteria for items. For a building with a frame structure and a total height of 30 m, the usage amount of general scaffolding is defined in item "A12-12" (Table 2). Similarly, for a building with a shear wall structure and a total height of 50 m, the usage amount of general scaffolding is defined in item "A12-13" (Table 2).

6 Conclusions

TCSs is not only critical for the successful completion of construction projects, but is also one of the most significant cost factors in the construction projects. This paper presents a general framework to automatically generate the consumption of TCSs integrating BIM and consumption standards and shows an application to determine the consumption of formwork in a sample project. Information about the amount of resources needed, as well as the cost breakdown, was generated in an efficient manner. The output of the presented framework includes the usage amount and cost of labor, materials, and equipment that need to be consumed to complete the work content of the TCSs. The information provided allows project participants to focus on planning and logistics of the procurement of TCSs as well as having reliable information about their consumption to be accounted during the preparation of the construction schedule and cost estimates during the early phases of a project, rather than spending valuable time in their quantification. Future research will combine schedule information with the consumption, making it a more beneficial tool to the project management team, and more sophisticated algorithms should be developed to provide more accurate results in a more efficient way.

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Project production flows in off-site prefabrication: BIM-enabled railway infrastructure

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Abstract – Railway infrastructure projects provide required physical and organizational facilities for transportation networks. Production flows in railway construction are complex especially when a hybrid of on-site and off-site processes is in progress. With railway projects still experiencing budget and time overruns, there is need to re-examine production flows. Towards this aim, a framework to investigate production flows in railway infrastructure projects is presented and discussed. A three-dimensional view of construction production including portfolio, process and operation aspects is found capable of improving performance measures in both design and construction. Such improvements include minimized rework and re-entrant flows, flexible prefabrication, enhanced multidisciplinary collaborations, and efficient planning of temporary works. This research contributes to the construction body of knowledge by examining production flows in a complex infrastructure setting. Construction managers would benefit from the presented model of production flows and its customization in the context of their projects to improve productivity and performance.

Keywords –

Building Information Modeling, Construction Management, Design Complexity, Infrastructure Project Management, Reentrant Flows, Rework Minimization, Robotics, Shop drawings, Three dimensional models (3D), Uncertainty in Decision Making

1 Introduction

Dynamics of workflow have been explored in the construction management literature [1-4]. However, there is need to investigate production flows in complex environments of infrastructure projects [5, 6]. Management of production flow in construction of railway, utility and energy projects is more challenging than residential and commercial construction [7, 8]. Among others, challenges are caused by involvement of many collaborating teams [9], lack of established frameworks for managing project production flows [10], and large numbers of stakeholders [11]. Recently, mainstream research in construction has been focused on Building Information Modeling (BIM) as a facilitator to support production flows in construction [12, 13]. Although useful, there are sparse studies aimed at improving the construction understanding of project production flows [14].

Off-site production, which is a hybrid of construction and manufacturing, has the potential to improve production flows in infrastructure projects [15], and increase flexibility in processes and operations [16]. The challenge, however, is the complexity of production flows within infrastructure project settings [17]. Not much research has been conducted to investigate project production flow dynamics in complex infrastructure construction where prefabrication is a major player [18].

The current study aims to bridge this gap by analyzing railway infrastructure projects within the framework of the production flow model developed by Sacks [19]. Towards this aim and in a similar approach to Liu, et al. [20], a case study approach was adopted as it is capable of responding to "how" and "why" types of research questions and allows retaining a holistic approach towards the research problem at hand [21]. Selected railway projects in Australia were deemed suitable to analyze production flows within infrastructure project settings. A purposeful selection of case studies targeted maximum level of complexity in project production flows. Main factors contributing to project complexity included the hybrid production mode (on-site and off-site), the concurrency of construction and train operations, numerous engineering scenarios and production alternatives, collaboration of many multidisciplinary teams, and complicated design and construction processes across several project modules.

To streamline complex production flows, railway infrastructure projects are often broken down to smaller manageable zones (modules). Geographic proximity and similarity of construction methods mainly drive the exercise of project modularization. The purpose-built production flow model in projects should realizes three dimensions of project portfolio (module), process and operations. The production flow model in infrastructure projects aims to maximize flow continuity for design and construction of on-site assembly and off-site prefabrication. This paper analyzes and discusses four major improvements resulting from the three-dimensional flow model in the following order. After describing the base model, most important improvements in terms of minimization of rework and reentrant flows are discussed. This is followed by series of performance enhancements including flexible prefabrication, improved multidisciplinary collaborations, and efficient planning of temporary works. Finally, conclusions are presented followed by discussion of limitations and opportunities for future research.

2 Design and construction complexity-implications for production flows

In the context of infrastructure construction, project teams need to frequently evaluate and compare different engineering solutions to optimize performance measures [22-24]. In the case projects, an elevated rail solution was selected over a rail-under alternative. Elevated railways minimize construction impacts on local utilities and major gas, water and electricity transmissions across the rail corridor [25, 26]. Furthermore, risks of flooding and manipulation of water tables are minimized by using this engineering solution [27, 28]. Finally, elevated rail projects require lower amount of land acquisition as opposed to traditional open cut trench solutions [29, 30].

Design in infrastructure projects is more complex than other project types in which respective processes are often entirely completed before commencement of construction [31, 32]. In order to address complexity in railway infrastructure projects, design processes are split into different packages. The interdisciplinary design teams comprise architects, engineers, scientists and consultants. Detailed design drawings that are produced by design teams are reviewed by major stakeholders including local councils, road authority, electricity and gas distributors, public transport network, and government agencies. Considering the projects is a challenging task.

Production flows in large infrastructure projects are complex to manage with high levels of variability in both design and construction. For an effective management of production flows in railway infrastructure projects, a three-dimensional view of production, proposed by Sacks [19], is adopted. In this flow model, processes and operations of multiple project zones are managed in a three-dimensional (3D) space. The model has been customized to reflect the dynamism involved in design and construction of prefabricated elements in railway infrastructure projects. As can be seen in Figure 1, inclusion of the project portfolio (module) axis reflects the simultaneous occurrence of design and construction across several project modules. The model's objective is to achieve maximum production flow continuity at the project level.

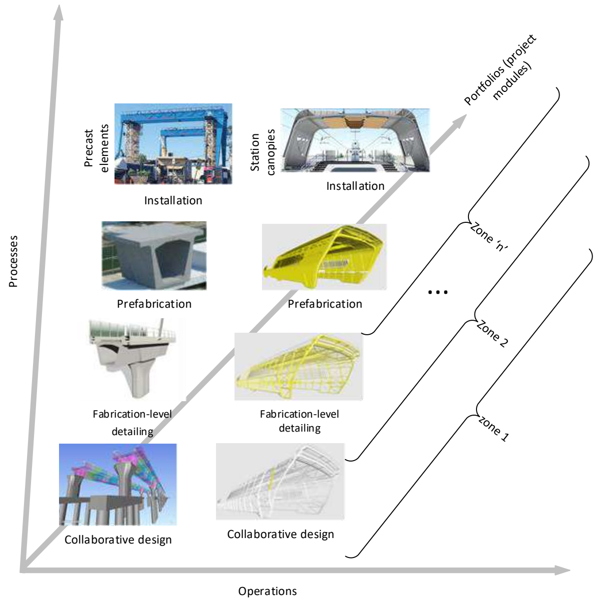

Figure 1. Three dimensional view of production flows in infrastructure projects

3 Robustness of the 3D view of project production flows

The balancing of production flows across different project modules results in several improvements that are discussed in the following sections. Improvements in the context of infrastructure projects include but are not limited to minimization of rework and re-entrant flows, maximization of flexibility in prefabrication, improvements in multidisciplinary collaborations, and efficient planning of temporary works.

3.1 Minimization of rework and re-entrant flows

In complex environments of infrastructure projects, resources often have to return to work locations more than once to complete processes. This creates reentrant flows resulting in delays and discontinuity of work [33, 34]. One contributor to reentrant flow is planning and management of process and operations without considering the production flow continuity at the project level [35]. For example, installation processes of station canopies in the investigated railway projects require teams to return to same work locations several times to complete assembly of canopy elements that have complex geometries and connections. Adoption of the customized 3D flow model resulted in real-time prioritization of installation processes across different project modules and minimization of reentrant flows.

The second contributor to project reentrant flow is defective work and resultant rework [36, 37]. After identification of defects by successor trades or inspectors, responsible resources are called back to undertake rework in respective work locations [38]. Defects in construction are caused by inaccurate design and/or errors in completing the work [39]. Both issues in the analyzed railway projects were managed by using the 3D project production model. This along with the use of building information models facilitated collaborations in detecting design faults and clashes ahead of fabrication-level detailing. Furthermore, the model created continuous production flows for off-site manufacturers and on-site installation teams. As an example, collaborative review of initial design across project modules revealed several inconsistencies in the design of station canopies. Furthermore, frequent comparisons of planned and actual construction, resulted in early detection of errors in column locations for elevator shafts in railway stations.

Reduction of rework and reentrant flows by using the portfolio- process- operations model of production flows improves performance measures at the project level. This is due to the fact that reentrant flows often pass through bottleneck resources and cause further delays in completing activities on the project critical path [40, 41].

3.2 Flexible decision making for prefabrication

Implementation of the 3D model of project production facilitated the postponement of differentiation points in manufacturing of prefabricated elements such as viaduct segments, super T beams, precast piers, and elevated station canopies. The portfolio dimension facilitates continuity of process and operation flows at the project level and in accordance to unique requirements in each and every project module [42, 43]. Furthermore, the production flow structure provides required interfaces between preliminary design, prefabrication and on-site assembly. This allows completion of more design iterations before fabrication-level detailing and prototyping prior to mass manufacturing of non-standard elements.

The extraction of component data for fabrication can be deferred to optimize production of elements for different project modules. As an example, complex hyperboloid geometries and novel fabrication procedures to construct station canopies were developed by postponing decision making and achieving the maximum possible level of design maturity.

Furthermore, the production flow model allows temporal flexibility for consecutive design stages. As can be seen in Figure 2, preliminary design of the steel structure for station canopies significantly improved during detailed design stages and fabrication-level detailing. The final structure is lighter by removing excessive horizontal members and more stable because of increased number of braces.

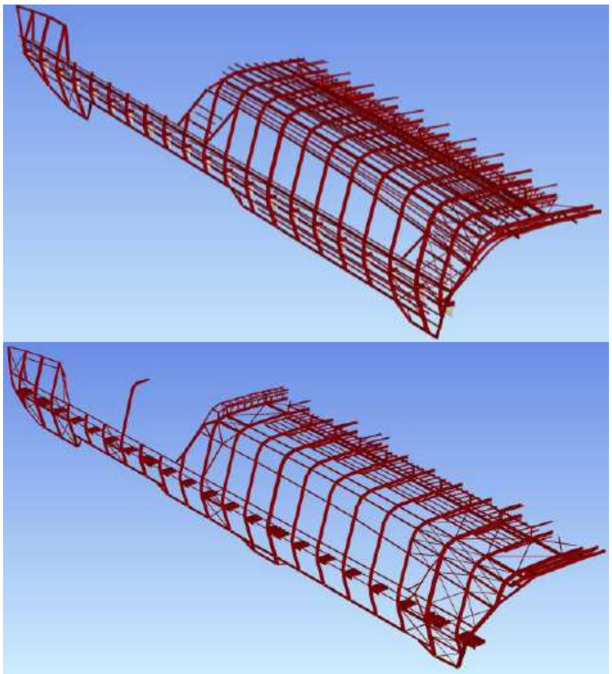

Figure 2. Flexible decision making- Initial design of canopy structure (top) and final design (down)

The continuity of production flow at the project level is maintained by considering the three dimensions of project portfolio, process and operations [44]. The modularity of project production in the railway case facilitated collaboration and information transfer amongst project teams. This is in line with findings of Williams, et al. [45] and confirms that a robust production flow structure should cover all project dimensions from design to fabrication to assembly. This holistic view maximizes temporal flexibility in decision making on downstream project processes that are often dependent to upstream work.

3.3 Improvements in multidisciplinary collaborations

Continuity of production flows across different project modules can only be achieved by efficient collaboration of multidisciplinary teams [46, 47]. This collaboration is essential for each and every project process including development of shop drawings. These drawings provide fabrication-level details of different structural and non-structural project elements. In the traditional approach to review and finalization of shop drawings, 2D documents sequentially pass through different discipline teams and necessary corrections are made [48]. This time consuming and error-prone process causes prolonged delays in downstream processes related to prefabrication and on-site installation [49, 50].

Departing from a file-based mode of reviewing and finalizing shop drawings, a cloud-based approach was used in the investigated infrastructure projects. Multidisciplinary collaborations were enhanced by the parallel use of commercial packages such as BIM360 Glue and Navisworks to facilitate reviewing fabrication-level details by collaborating multidisciplinary teams. As an example, in prefabrication of steel structures, comments from architecture, engineering and manufacturing teams were collaboratively addressed to finalize shop drawings.

The portfolio- process- operations view of production flows (Figure 1), provides a collaborative platform for exchanging fabrication-level information across different disciplines such as architecture, civil, rail and services. Modularity of the production flow structure and existence of the portfolio dimension (project modules) resulted in prefabrication of bespoke elements across different project modules.

3.4 Efficient planning of temporary works and structures

Temporary structures and works such as hoardings and scaffolding support construction of projects [51, 52]. Decision making on temporary structures and works requires consideration of both temporal and spatial limitations [53, 54]. Traditionally the decision making has been based on experience of design and construction teams, often causing delays and time-space conflicts [55, 56]. The portfolio- process- operations flow model facilitates decision making on temporary structures and works by considering multidisciplinary requirements across different project modules.

Temporary works are of great importance to the investigated project cases because of simultaneous operation of trains and construction. Hoardings next to rail tracks were designed considering safety of train users and construction crews, spatial limitations on worksites, duration of use, and possible workspace conflicts. After multidisciplinary analysis of optimum distance from hoardings to center of nearest tracks, project teams agreed on 2.1 meters to satisfy constraints. Understandably, this base distance is re-examined in different production scenarios to evaluate suitability to each project module.

Scenario analysis and evaluation of alternatives to temporary works often result in minimizing cost and maximizing performance measures at the project level [57]. For example, alternative use of scaffolding and scissor lifts as the work platform in the assembly process of elevated stations was deemed suitable in different project zones.

The portfolio-process-operation model of production flow facilitates consideration of multidisciplinary constraints in planning and design of temporary works with the aim of maintaining flow continuity at the project level.

4 Conclusions

Previous research has realized the complexity of managing production flows in large construction projects [58, 59]. However, studies that take holistic approaches to manage process and operations across different modules of infrastructure projects are sparse [60]. To bridge this gap, the current research analyzes railway infrastructure projects to evaluate the three-dimensional production flow model developed by Sacks [19].

The findings present significant improvements in terms of production flow continuity at the project level. Adopting the portfolio- process- operation view of project production resulted in minimization of rework and reentrant flows, flexible prefabrication, enhanced multidisciplinary collaborations, and efficient planning of temporary works. Results of the current analysis are in line with those of Mullens [61] and Sacks, et al. [62], confirming that all dimensions of production flow need to be holistically considered in order to maintain flow continuity at the project level.

This work contributes to the literature by analyzing dynamics of production flow in complex infrastructure projects where a hybrid of on-site and off-site processes across several project modules are in progress. Furthermore, the paper’s approach to customize production flow model is of practical use to those planning and managing infrastructure construction. Early adoption of production flow model facilitates creation of a holistic approach to manage process and operations across different project modules.

5 Research limitations and further opportunities

Investigation of production flows in the current study is limited to infrastructure cases in the railway context. Future research would benefit from investigating other types of infrastructure projects to test the generalizability of findings. Furthermore, the results of this study are limited to four aspects of re-entrant flow, decision flexibility, collaboration and temporary works. With a more in-depth analysis of production data, there will be opportunities to investigate other production aspects.

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Automated Localization of UAVs in GPS-Denied Indoor Construction Environments Using Fiducial Markers

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Abstract

Unmanned Aerial Vehicles (UAVs) have opened a wide range of opportunities and applications in different sectors including construction. Such applications include: 3D mapping from 2D images and video footage, automated site inspection, and performance monitoring. All of the above-mentioned applications perform well outdoors where GPS is quite reliable for localization and navigation of UAV's. Indoor localization and consequently indoor navigation have remained relatively untapped, because GPS is not sufficiently reliable and accurate in indoor environments. This paper presents a method for localization of aerial vehicles in GPS-denied indoor construction environments. The proposed method employs AprilTags that are linked to previously known coordinates in the 3D building information model (BIM). Using cameras on-board the UAV and extracting the transformation from the tag to the camera's frame, the UAV can be localized on the site. It can then use the previously computed information for navigation between critical locations on construction sites. We use an experimental setup to verify and validate the proposed method by comparing with an indoor localization system as the ground truth. Results show that the proposed method is sufficiently accurate to perform indoor navigation. Moreover, the method does not intensify the complexity of the construction execution as the tags are simply printed and placed on available surfaces at the construction site.

Keywords –

Indoor localization; construction performance monitoring; Building Information Model (BIM); AprilTags; Automated monitoring; Facility Management;

1 Introduction

Unmanned aerial vehicles (UAVs), also known as drones, have recently attracted attention from various industries including construction. Employing UAVs equipped with visual sensors for construction site monitoring is beneficial due to the vehicles' maneuverability and rotary features. UAVs can access points that are inaccessible or unsafe to be reached by humans. UAVs may also be equipped with other devices such as a laser scanner, thermal sensors, or hyperspectral/multispectral sensors that can be used for acquiring further insights and then generating very informative analytics about the status of the construction component being monitored. Specific applications in the construction industry include 3D mapping for dimensional measurement of construction components [1], visual progress monitoring, and visual inspection [2].

The key capability of UAVs that makes them useful in so many industries is their ability to be programmed to perform tasks autonomously. One critical module of such autonomous robots for automated task performance is the localization system. For outdoor environments, autonomous flight planning is less challenging, because the localization module is based on global positioning systems (GPS), which is accurate and reliable. Localization results are then fed to the control systems as the state sensing component (feedback loop). Navigation and path planning can then be performed based on the accurate and reliable localization results obtained in outdoor environments. However, indoor localization using GPS is not sufficiently reliable because of the weak signal and other interferences present in indoor environments such as walls and other interior components under-construction.

Using reliable indoor localization systems that already exist commercially, such as wireless networks, UWB, or vision-based positioning cameras (e.g. Vicon system) intensifies the complexity of construction sites and, indeed, requires additional costs for deployment. This paper investigates the use and employment of fiducial markers (AprilTags, in particular) for potential deployment in GPS-denied indoor construction environments. The 3D coordinates of fiducial markers are hardcoded into 3D CAD drawings integrated with the building information models (BIM). Camera-equipped UAVs can identify their relative pose to the tags and then calculate their location in the global coordinate frame give the tag's location.

2 Background

The related background information is investigated from three different perspectives: (1) indoor localization state-of-the-art, (2) fiducial markers for indoor localization, and (3) localization of construction equipment and materials. These areas are extensively discussed in the following sections.

2.1 Indoor localization state-of-the-art

Indoor localization and the related research area is used when objects are to be detected in a location where a global localization signal such as GPS is not reliable [3,4]. According to Ibrahim and Moselhi (2016) [5], indoor localization techniques can be divided into three major categories:

- Wave characteristics and propagation: various ultrasonic and sound waves and receivers such as radio frequency (RF), ultra-wideband (UWB), and wireless local area network (WLAN) are used for indoor localization [3,6,7]. Indoor localization using ultrasound waves may result in 9 cm accuracy, however, it requires direct and interference-free access to the objects. Other techniques such as UWB and RFID have reported accuracy of 5-9 m, which is insufficient for high accuracy applications and analyses. Localization systems with such low accuracies are used for sensing and roughly locating materials in warehouses and other indoor environments.
- Image-based/vision-based localization: image-based localization uses computer vison to identify the location of objects in the global coordinate system. Image-based localization has been categorized in two major groups: (1) global feature detection, identification and localization such as edge and corner detection, and (2) local feature detection such as fiducial tag and marker detection and localization. Image-based localization requires line-of-sight to extract features; therefore, it is significantly impacted in dynamically changing environments and also by markers' deterioration throughout the project lifecycle. Recently, simultaneous localization and mapping (SLAM) has been found to be capable and reliable for indoor localization and mapping [8]. The method proposed in this paper belongs to this category and aims to investigate and overcome some of the existing challenges using fiducial markers.

- Inertial navigation systems: indoor localization can be performed, given an initial location and navigating using on-board accelerometers, inertia measurement units (IMU's), and other motion sensors. Inertial navigation and IMU-based indoor localization drifts from actual measurements as movement progresses, if motion components are not appropriately updated. Ibrahim and Moselhi [5] developed an IMU-based localization technique combined with a Kalman filter, which was found to be more accurate compared to the wave-based method. However, relying on IMU for UAV navigation is very risky and may lead to serious hazards such as loss of control and subsequent collision with objects in the environment. SLAM [8] may also be used with inertia measurement units (IMU's) or some other motion sensors for facilitating the localization. In such cases, processing is less computationally demanding and therefore closer to real-time.

2.2 Fiducial markers for indoor localization

Visual tags are designed to be easily detectable by camera systems. If a camera system is well calibrated, the relative pose of the camera with respect to a tag can be calculated, and therefore the camera system can be localized with respect to the tag's coordinate frame. Challenges for employing and implementing fiducial markers include: (1) the processing cost for decoding the tags, and (2) the difficulty of generating template tags that are orthogonal with each other [9].

Among fiducial markers, AR Tags were found to be very easily detectable and quickly decodable. AprilTag Tags were then introduced to overcome the inadequacies of AR Tags, which included the accumulated error when distancing from the target [10]. AprilTag Tags were proved to be more robust for indoor localization, and, since then, they have been used for many applications such as robot localization and navigation. AprilTag Tags are used in this study to investigate the localization of UAVs using their on-board camera systems [11].

2.3 Localization of construction equipment and materials

The previously explained techniques and technologies have been used for locating construction equipment and materials on site. Razavi and Haas [12] presented a method for localizing construction equipment and materials using RFID tags. In another study, indoor localization was tested using passive RFID tags for sensing. Song et al [13] used RFID tags for automating the task of tracking the delivery of materials on construction sites. As reviewed in the literature, localization frameworks are either performed outdoors or only for the purpose of sensing if performed indoors. This study aims to test and assess the performance of AprilTags for indoor localization of UAVs.

3 Methodology

For the purpose of localizing UAVs used for indoor task performance, on-board cameras are employed to detect AprilTag Tags with known locations in the world coordinate frame, and therefore linked to the building information model. On-board cameras are first calibrated to identify the physical and intrinsic parameters required for pose identification. An overview of the proposed framework is illustrated in Figure 1.

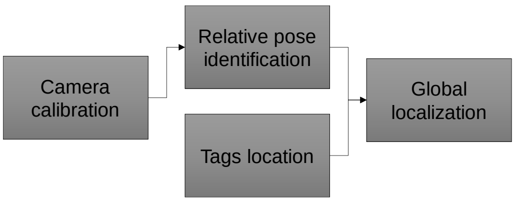

Figure 1: Overview of the proposed framework for indoor localization

3.1 Camera Calibration

Camera calibration is required to estimate the parameters of a lens and image sensor of an imaging system. Camera calibration parameters are thus required for accurately measuring distances to perceived objects. The Robotics operating System (ROS) package for camera calibration is used to estimate the camera parameters using a large checkerboard (8×6) with known dimensions (108 *mm*) for camera calibration.

3.2 Tags location

UAVs are going to be employed for indoor monitoring of construction elements. To identify the critical elements to be monitored, different filters can be applied on the building information model to extract the world coordinates and assign them to the tags used for localization. For example, a filter can be applied on object types, in case a specific type of object, such as drywalls or electrical outlets, is to be monitored. The construction of some objects may become behind schedule; they are the purpose of task monitoring using UAVs. In that case, a filter on object status can be applied to the BIM objects to extract the critical locations in the world coordinate system. Moreover, project managers might be interested in tracking and monitoring the tasks performed by specific subcontractors or vendors.

In summary, filters can be applied based on the search criteria in order to extract critical locations to be monitored by the UAVs employed in indoor environments. Extracted coordinates are assigned to tags, which are then employed for the localization of UAVs. Tags link the UAV's location to the world coordinate system as explained in the following section.

3.3 Relative pose identification

Once the on-board camera on the UAV is calibrated and tags locations are identified, UAVs can be localized with respect to the tags placed on construction sites. The relative pose is reported as a relative translational vector (x, y, z) and a rotational vector $(roll, pitch, yaw)$. These two vectors are reported as a relative transformation denoted as T_t^l, which relates the position of the UAV measured locally and in the tag's local coordinate system. Given the transformation that relates the position of the tags in the global coordinate system T_g^t, the UAV can then be localized globally. The required transformation for localizing the UAV in the global coordinate system T_g^l is calculated as: $T_g^l = T_t^l \times T_g^t$.

4 Design of experiments and results

An experimental setup is designed to collect the required data for verifying the accuracy of UAVs under various circumstances. A Parrot Bebop 2 equipped with a camera and on-board accelerometers is used as the UAVin this study. Detailed specification of the vehicle is provided in Table 1. AprilTags of type *36h11* printed at two different sizes are used to identify the impact of the tag's size on the accuracy of detection and pose identification. For integrating the on-board sensors of the UAV used in this set of experiments, a ROS driver for the Bebop device is used [14].

Table 1: Parrot Bebop 2 technical specifications

Feature	Specifications
Video resolution	14 MP
Image resolution	1920×1080 pixels, 30 frames/sec
Flight time	~ 25 min
Networking	Wi-Fi Dual Band 2.4 & 5GHz
Weight	500 g
Operation range	Up to 2km (Wi-Fi controller)

4.1 Effective variants

Four parameters are investigated to identify the accuracy of the proposed indoor localization framework:

1. Tags' placement orientation: construction sites and environments are dynamically changing during the projects' lifecycle. If the tags are planned to be placed on vertical walls, there might be a delay on the deployment of tags when a new floor is being inspected. On the other hand, tags placed on floors may be covered by building materials and elements. Both situations are tested to better understand the limitations.
2. Tags' size: the accuracy of the detection and pose identification with respect to the size of the tags is investigated. Larger sizes are more visible and therefore their detection accuracy is expected to be higher; however, smaller sizes are more practical to implement and deploy on construction sites.
3. Distance from tags: the UAV must see at least one tag at all times during the flight. This is crucial because if no tag is, the navigation control switches to on-board odometry which is neither reliable nor safe. The reason is that the UAV may lose its pose and location in the world coordinate system. In order to identify the threshold distance at which the UAV has a sufficiently accurate level of pose identification with respect to the tags, the impact of distance on localization should be investigated. The results can then be considered as a constraint in optimizing the tag placement plan on a building map.
4. Angle of view: similar to the previous variant, the angle of view is also of crucial importance in pose identification. The threshold angle value for which UAVs are localized with sufficient accuracy should be identified and considered in the tag placement optimization plan.

4.2 Experimental setup

An experimental setup is designed to measure the accuracy of the tag-based localization system. Tags are placed at previously known locations linked to the world coordinate system in the BIM. Figure 2 illustrates how world coordinates are calculated using the tag locations and how they are measured with the ground truth indoor localization system (Vicon cameras).

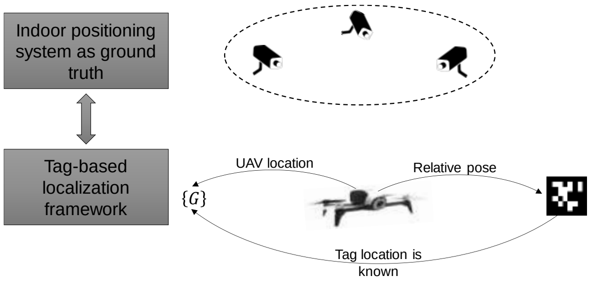

Figure 2: Tag-based indoor localization. For verification and validation of the calculated location, the results are compared with ground truth indoor positioning system. Tag-based localization results are compared with the Vicon system used as the ground truth (Section 4.3).

4.3 Ground truth indoor positioning system

An overhead camera system is used to assess the accuracy of the proposed tag-based localization framework. The overhead camera system detects markers that uniquely identify various objects. Once markers are detected, the position of the object is estimated as the ground truth. In the laboratory setup, the Vicon system is integrated with the ROS and the localization results are reported in a *rostopic* recorded for further result analyses.

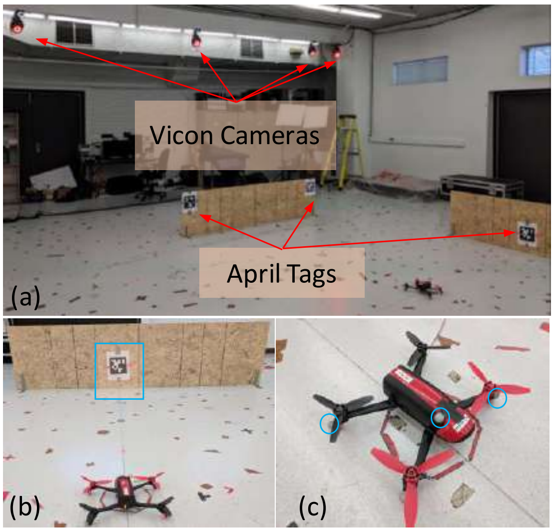

Figure 3: Experimental setup for testing the accuracy of the proposed indoor localization framework. (a) Ground truth system (Vicon cameras) are shown within the laboratory. AprilTags are also placed at various locations. (b) Take-off position where the UAV is faced to Tag-id=0 to be initially localized. (c) Markers are put in a specific pattern on the UAV, so as to be recognizable by the ground truth indoor localization system.

5 Results

In order to investigate the impact of the effective variants, the localization results are compared with the ground truth system under various scenarios. Each scenario is designed to capture the effective variant being investigated.

First, the effect of the orientation of the tags is investigated. For this purpose, localization results for vertical tags placed on walls and horizontal tags placed on the floor are compared with the ground truth system (see Figure 4). Figure 5 illustrates the accuracy of the localization system as the angle from the tag chages for horizontal tags.

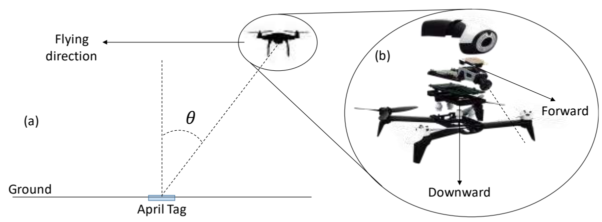

Figure 4: Side view of the experimental setup. (a) Auto-flight plan for calculating the localization accuracy when tags are placed horizontally on the ground. (b) Configuration of the on-board camera of the UAV used in this study. Figure is from Bebop forum [15].

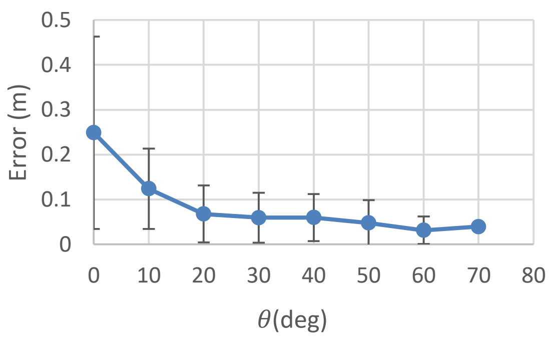

Figure 5: Localization error for horizontal tags placed on the ground. The UAV flight height is fixed at 2 m. Camera angle (θ) with respect to the tag is variable.

As seen in Figure 5, the accuracy of the localization increases as the angle increases. Moreover, the standard deviations (error bars) decrease as the angle increases, which implies more stability in the localization system as the angle increases. This is due to the orientation of the on-board camera used in the experiments. As shown, the camera is angled between forward and downward directions, as shown schematically in Figure 4-(b).

To understand the effect of distance from tags, the UAV is programmed to fly at different distances perpendicular to the tag's plane. Figure 6 schematically shows the automated flight plan programmed to investigate the effect of distance on the localization results. Figure 7 shows how accuracy changes while the UAV is flying at various distances with respect to an AprilTag.

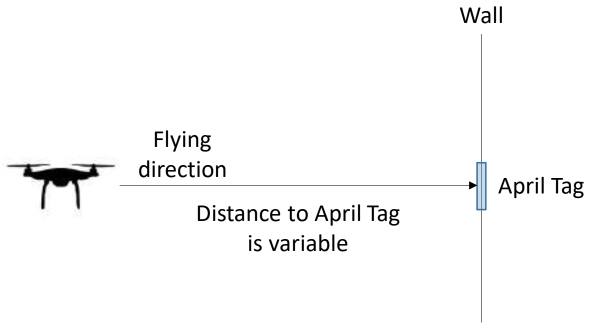

Figure 6: Automated flight plan for investigating the effect of distance to an AprilTag on the localization results

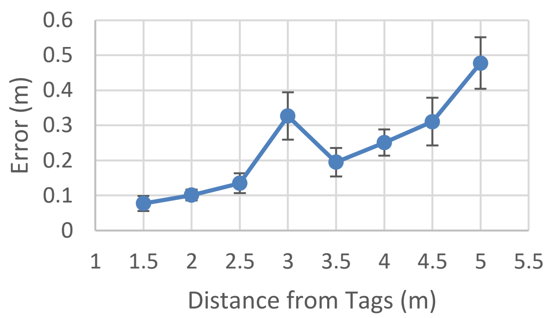

Figure 7: Localization error at different distances from tags. The on-board UAV's camera is facing perpendicular to tag's plane.

As seen in Figure 7, localization accuracy decreases as the UAV gets further from the AprilTag. The discrepancy at 3 m distance is due to the take-off position. Although, a tag is visible even before taking off, the localization is not sufficiently accurate and robust while the UAV is moving. It is expected that the graph monotonically increases if the data associated with take-off is filtered out from the results. Another observation is that the standard deviation increases as the UAV gets further from the AprilTag. This implies that the localization is more robust at closer distances.

Finally, the yaw angle of the UAV at a fixed distance (2 m) from an AprilTag is investigated to quantify the localization accuracy at various view angles. An automated flight plan (depicted in Figure 8) is implemented and the localization error is reported (in Figure 9) at various yaw angles (ψ).

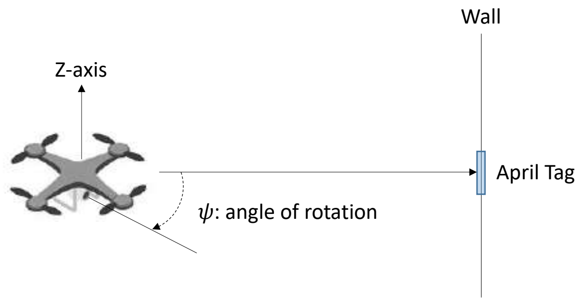

Figure 8: Automated flight plan to quantify the effect of yaw angle (ψ) on the localization accuracy

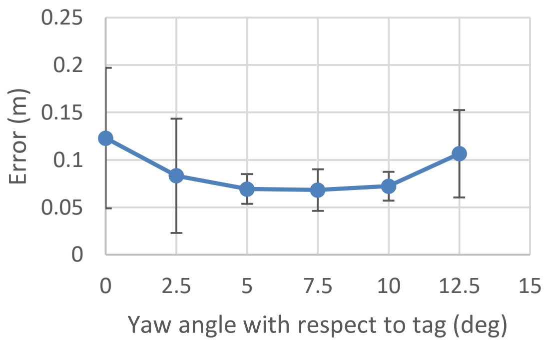

Figure 9: Localization error at different yaw angles. The UAV is flying *2 m* away from the tag and the yaw is variable.

As seen in Figure 9, the localization is robust and the accuracy is very stable for the yaw angles investigated. The large discrepancy at $\psi = 0$ is due to the take-off position, and if the data associated with the take-off is eliminated, the graph becomes even more stable and robust. Comparatively, the standard deviation is expected to be as low as the same values reported for $\psi = (5, 7.5, 10)$; however, the take-off localization inaccuracy is affecting the standard deviations as well. It should be noted, that the further the UAV is from an AprilTag, the lower the expected maximum yaw angle because of the line of sight and angle of view.

6 Conclusions

An indoor localization system using fiducial markers was developed in this study. AprilTags were used to globally localize flying UAVs in indoor construction environments. UAVs will then be used to capture some critical information about building components under-construction. Such information is then linked with a global system like BIM in order to measure the actual construction performance metrics with designed values to update plans accordingly. Progress of construction components can, for example, be measured at different locations in order to update the schedule accordingly. A robust indoor localization framework will provide an opportunity to fly autonomously and perform the whole process automatically. In order to verify and validate the performance of the proposed framework, an experimental study was designed. Some key findings are summarized as follows:

- Localization error decreases as the angle of view to horizontally placed tags on the grounds aligns with the on-board camera orientation. As the angle of view becomes steeper with respect to the camera orientation, the error increases.
- As expected, localization error increases as flying vehicles get further from AprilTags. The localization error will be higher than 30 cm if the UAV is flying further than 3.5 m from an AprilTag.
- Localization accuracy is very robust and stable for the yaw angles at which an AprilTag is visible by the UAV's camera.

For all cases, localization during take-off and landing is not sufficiently accurate to be reliable. Hence, the data associated with those situations must be filtered out for more accurate analyses. Future work includes incorporating the findings with automated flight plans on real construction sites. Threshold values are going to be extracted as constraints for distance and view angles to optimally place the tags on a construction site to be monitored.

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Reasoning on Human Experiences of Indoor Environments using Semantic Web Technologies

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Abstract -

The Indoor Environmental Quality (IEQ) in a building affects occupants' well-being and productivity. Traditionally, models are developed to predict IEQ satisfaction from physical measurements. These approaches work fine in a laboratory environment but tend to fail in real-world applications. Recent work focuses on collecting direct human feedback on IEQ. However, existing approaches either lack the ability to capture the multiple dimensions of IEQ or the integration with other domain knowledge, e.g. from building information modeling or building automation systems. To tackle this problem, we have developed a novel approach based on Semantic Web Technologies (SWT) which enable interoperability and reasoning. In this paper, the HBC (Human Comfort in Building) ontology is presented, which formally specifies the domain of IEQ in multiple dimensions and relates it to adjacent domains. An online survey is designed in order to specify ontology requirements and collect human feedbacks for evaluating the ontology. We evaluate the use of the HBC ontology in two use cases in an office building: recommendation of spaces based on IEQ factors and recommendation of settings for technical equipment from collected feedbacks.

Keywords -

Human Experiences; Indoor Environmental Quality; Semantic Web Technologies; Ontology; Office Buildings

1 Introduction

In modern life, people spend between 80% and 90% of their time indoors [1]. Recent studies have shown that Indoor Environmental Quality (IEQ) not only can affect occupants' well-being, but also their productivity [2]. Dimensions, or factors, of IEQ are amongst others indoor air quality (IAQ), thermal comfort, visual comfort and acoustic comfort. In the past, researchers have identified a number of physical measurements which correlate with IEQ. In experiments, human satisfaction is determined from questionnaires while measuring physical quantities identified to correlate with IEQ (e.g. [3]). From the results, models have been developed to predict IEQ satisfaction from measurements.

However, since standards have often been found to be at odds with the requirements of occupants [4], recent work focuses on using direct human observations on IEQ with the aim to improve IEQ satisfaction of users [5, 6].

In the current state of art, several studies and tools exist to capture occupant experiences in buildings: Comfy [7], TherMOOstat [8], CrowdComfort [9], CBE Occupant Feedback Toolkit [10] and MYBUILDINGMESSAGE [11].

Comfy, TherMOOstat and CrowdComfort share a common downside: the inability to capture other IEQ factors besides thermal comfort. For CBE Occupant Feedback Toolkit and MYBUILDINGMESSAGE, although they can capture various IEQ dimensions, they lack the ability to integrate the occupants' experiences automatically with information from adjacent domains, e.g. Building Information Modeling (BIM).

There are also projects which try to capture occupants' experiences while integrating with adjacent domains. For instance, Twitter surveys have been used to integrate occupants' thermal comfort experiences [12]. YouSense is a web-based application which can capture human observations of spaces. It is built on the expressiveness of the EXPERIENCE vocabulary—a lightweight vocabulary for describing human experiences [6]. The authors argue that it is usable for linked data applications via collecting human experiences. However, it is notable that EXPERIENCE has a more general scope beyond IEQ factors.

To address these limitations of existing approaches, we developed an ontology that formally specifies human experiences on the several dimensions of IEQ in spaces. The ontology is aimed to derive a better understanding of perceived comfort, spaces, and relations between them. Further on, this ontology-based approach allows to infer new information given rules and linkages to information modeled according to BIM and BAS. We also designed a survey for collecting experimental data. The process of ontology development follows a well-known approach called METHONTOLOGY [13]. Semantic Web Technologies are used for ontology implementation, such as

OWL DL and SWRL rules. The ontology is populated based experimental data using OWL API. We evaluated the ontology by means of SPARQL queries with regard to the targeted scenarios.

The rest of this paper is organized as follows. Section 2 describes the designed online human experience survey. Section 3 presents the HBC ontology and the development process of HBC. Section 4 shows the application of evaluation of HBC ontology in two use-cases. Section 5 discusses the limitation and future work. Section 6 provides the concluding remarks.

2 Online Human Experience Survey

We designed a human experience survey using an online questionnaire tool in order to gather data as an input for ontology development and validation.

There are thirteen questions that are about location (question 1), IEQ (question 2-5) and settings of building objects (question 6-13). Questions related to IEQ are the core parts. Apart from reviewing literature, we interviewed domain experts on common terms used. We designed questions and possible answers for assessing the IEQ aspects of human experiences.

Occupants can assess the quality of a certain IEQ as positive, neutral and negative. For instance, according to a person's experience, the thermal comfort can be assessed as positive. However, it is unknown whether the positiveness of thermal comfort is caused by feeling warm or cold. People can feel warm positively, or on the other hand cold positively due to differences in their age, culture or psychological factors. Therefore, we not only capture thermal comfort by quality, but also thermal sensation. In this way, thermal comfort can be assessed by the combination of them. Similar design choices were made for questions about acoustic comfort and visual comfort.

However, there is no duality for IAQ. Since, normally, people have a positive feeling when the air is fresh; when the air is stuffy, the quality assessment is negative.

The last part of the survey is about the settings of building objects. After finishing the questions about IEQ assessments, occupants have to report settings of building objects at that moment.

3 Human Comfort in Buildings (HBC) Ontology

3.1 Ontology Engineering Methodology

METHONTOLOGY [13] is an ontology engineering method we adopted for building the HBC ontology. It is widely used as it provides sufficient descriptions and allows ontology reuse [14]. It is an iterative process along with knowledge acquisition and evaluation as supporting activities. In this section we provide an overview of the steps of METHONTOLOGY.

3.2 Specification

The *Specification* stage consists of domain analysis and knowledge acquisition in the course of expert interviews and literature reviews. While designing the survey questions, the requirements of the ontology are identified which include the scenarios in which the ontology is used. Also a set of terms along with their characteristics are identified.

The HBC ontology models the scenario that an occupant describes about his/her experience at certain times in a space. Conceptually, the HBC ontology is divided into three modules: Hex ontology, bim4Hex ontology and Time ontology (see Figure 1). The module of Time describes necessary time concepts for the Hex ontology. Modularizing the HBC ontology is good for (1) reusing ontologies, (2) maintaining and extending ontologies.

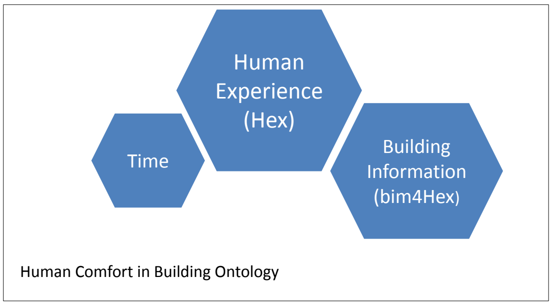

Figure 1. Modules of HBC ontology

Competency questions are the set of the questions that the ontology should be able to answer (See Table 1). These competency question are evaluated via specific use-cases.

3.3 Conceptualization

As proposed in METHONTOLOGY [13], the domain knowledge is conceptualized into a model that satisfies the ontology requirements in the *Conceptualization* activity. It is worth mentioning that there is no single correct way to model the domain of interest. There are always alternative design choices.

Figure 2 shows the overall conceptualization of the HBC ontology. This graphical representation has been created using the *Graffoo* method [15].

3.3.1 Hex Module

The concept classification of IEQ factor is shown in Figure 2. Thermal comfort, visual comfort, acoustic comfort and IAQ are the factors considered for IEQ factors, which makes them subclasses of *IEQFactor*. Also, they

Table 1. Basic (1-9) and complex (10-11) competency questions.

Competency Questions
1. What are the spaces where people experienced positive thermal/visual/acoustic comfort and air quality?
2. What are the spaces where people experienced negative thermal/visual/acoustic comfort and air quality?
3. What are the spaces where people experienced neutral thermal/visual/acoustic comfort and air quality?
4. What are the spaces where good/bad/neutral experiences?
5. What are the spaces where people experienced as a quiet space?
6. What are the spaces where people experienced dim light?
7. When do people usually have good experience of space?
8. When do people usually experience positive visual comfort?
9. When do people experience quietness?
10. What are the equipment settings when people feel cold and report negative thermal comfort?
11. What could be the adjustment of shading device settings when people report negative visual comfort in a certain space?

are primitive classes. Furthermore, *IEQFactor* can be decomposed into *PostitiveIEQFacotr*, *NegativeIEQFactor* and *NeutralIEQFactor* based on the value of *Quality* that it connects to via object property *hasQuality*. Hence, these three subclasses are defined classes.

Figure 3 shows the concept classification tree of sensation. The modeling corresponds to the design of questions in the human experience survey.

The core concept in the Hex module is *Experience* (see Figure 2). It connects to *IEQFactor* by object property *isAbout*. *Experience* is also a bridge linking the Time module (via *hasTime*), and the bim4Hex module (via *withObjectSetting* and *hasLocation*) with the Hex module.

3.3.2 bim4Hex Module

The bim4Hex ontology contains all concepts, properties and axioms related to building information in HBC. According to ontology requirements, window, air terminal, shading device and space heater are the types of building objects considered in the domain, but can be extended when required.

Figure 4 shows the concept classification tree of `BuildingSpace`. Spaces are defined based on whether they contain certain types of building objects or not, and they are all subclasses of `BuildingSpace`. For example, the concept definitions of `SpaceWithHeater` and `SpaceWithoutHeater` are presented in listing 1 and they are written in Manchester OWL syntax [16]. The rest of the subclasses are defined in the same fashion.

Listing 1. The concept definitions of `SpaceWithHeater` and `SpaceWithoutHeater`.

```
Class: SpaceWithHeater
    EquivalentTo:
        BuildingSpace some SpaceHeater
    DisjointWith:
      SpaceWithoutHeater

Class: SpaceWithoutHeater
    EquivalentTo:
        BuildingSpace and (contains only
                        (not SpaceHeater))
    DisjointWith:
      SpaceWithHeater
```

Rules are used to infer rooms that are similar to each other in terms of building objects (see Listing 2). There are nine rules in total. Six rules are omitted here for simplicity, since they are defined in the same fashion as the first two rules. For each type of building objects, there are two rules defined in order to formally specify similar spaces in terms of that specific type. For instance, if two instances are members of class `:SpaceHeater`, then they are in the relation of `:isSimilarSpaceHeaterTo`. Similarly, if two instances are members of class `:SpaceWithoutHeater`, then they are also in the relation of `:isSimilarSpaceHeaterTo`.

The last rule is defined for inferring spaces that are similar to each other taking all types of building objects into account.

Listing 2. Rules defined for inferring similar rooms in terms of building objects

```
SpaceHeater(x),SpaceHeater(y)
              ->isSimilarSpaceHeaterTo(x,y)
SpaceWithoutHeater(x),SpaceWithoutHeater(y)
              ->isSimilarSpaceHeaterTo(x,y)
...
isSimilarWindowTo(x,y),isSimilarSpaceHeate-
rTo(x,y),isSimilarShadingDeviceTo(x,y),isS-
imilarAirTerminalTo(x,y)
                    ->isSimilarObjectTo(x,y)
```

3.4 Integration

3.4.1 Reusing Existing Ontologies in the Field

One of the principles for designing an ontology is to reuse ontologies whenever it is possible—this idea has served as our guide here as well.

According to the requirements of the ontology and the human experience survey, we identified three areas where

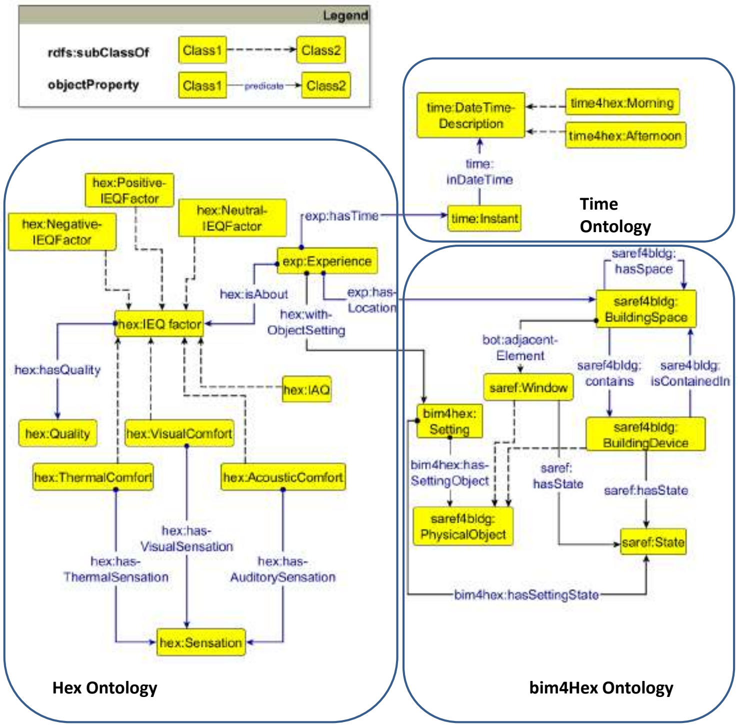

Figure 2. The overview of HBC ontology and its submodules.

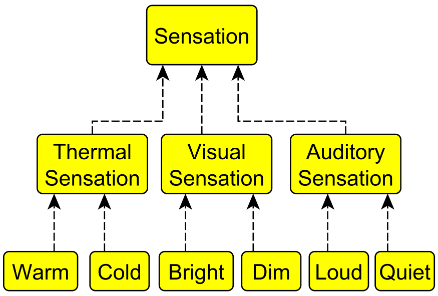

Figure 3. Concept classification tree of Sensation.

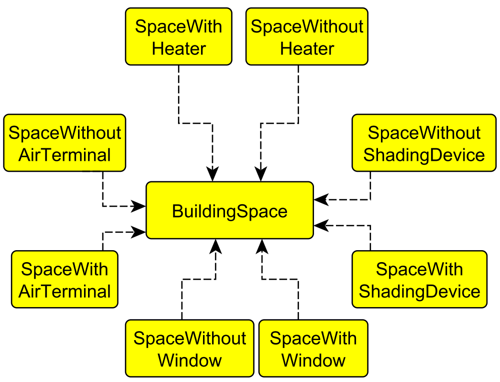

Figure 4. Concept classification tree of BuildingSpace.

existing ontologies may be reused. These areas are experiences, building information and time. The Linked Open Vocabularies repository (`lov.okfn.org`) is used to search desired vocabularies. A brief summery of selected ontologies of the current research domain is presented below:

- Experience Vocabulary [6] is used to describe experiences;
- The *SAREF* (Smart Appliances REFerence) [17] ontology is used for specifying the devices in a space where experiences are provided;
- The *S4BLDG* ontology [18] is an extension of the SAREF ontology. It is created based on the Industry Foundation Classes (IFC) standard for building information. In our approach, it is used for specifying the building information about a space that experiences are about;
- The *BOT* (Building Topology Ontology) is an ontology "covering only the core concepts of a building" [19]. It provides extra vocabularies for describing the building elements which are not included in the *S4BLDG* ontology, for example the vocabulary describing the relation between windows and building spaces;

- *OWL-Time* [20] specifies temporal properties and it is a W3C candidate recommendation. Currently, although this is a draft version and may be updated in future, the main concepts and properties are likely to remain unchanged;

For this article we surveyed also other ontologies about building information, such as ThinkHome [21], DogOnt ontology [22], ifcOWL ontology [23] and Brick schema [24]. However, in terms of the coverage of concepts based on ontology requirements, *S4BLDG* ontology contains major elements that we needed to for the work reported in this paper.

3.4.2 Reused Ontology Fragments

We reuse fragments from the mentioned ontologies as follows. From the *Experience* vocabulary, we use the concept `:Experience` and the object properties `:hasTime` and `:hasLocation`. From the *S4BLDG* ontology, we use the concepts `:BuildingSpace`, `:PhysicalObject`, `:BuildingDevice`, `:SpaceHeater`, `:ShadingDevice` and the object properties `:contains` and `:hasSpace`. Furthermore, after the evaluation of the reusable ontologies, some of the terms used in the human experience survey are replaced by corresponding terms in existing ontologies. `:AirTerminal` is defined in the *ifcOWL* ontology [23].

We reuse from the *SAREF* ontology the concepts `:Window`, `:State`, `:OnOffState`, `:OpenCloseState`, `:ShadingDevice` and the object properties `:hasState` and `:hasSpace`. We make also use of `:adjacentElement` from the *BOT* ontology and `:DateTimeDescription`, `:Instant` and the object properties `:inDateTime` from the *OWL-Time* ontology. Moreover, the data properties `:year`,`:month`,`:day`,`:hour` and `:minute` are also reused.

3.5 Implementation

The ontology was developed using the Protégé editor 5.2. Protégé is extensible and provides a plug-and-play environment. Its editor supports editing SWRL rules and importing ontologies. HermiT [25] supports reasoning with SWRL rules and it is available as a Protégé plug-in. The implementation of the HBC ontology followed a practical guide presented in [26]. Furthermore, we have taken into account the common errors for modeling with OWL DL pointed out by [27].

The collected data of the human experience survey and building information data is converted into OWL from CSV using OWL API. The ontology is published online[1].

[1]https://github.com/TechnicalBuildingSystems/Ontologies/tree/master/hbc

3.6 Evaluation

Our leading principle has been that the evaluation is not only done at the very end of the process of the development. Rather, it is performed in each phase and between activities of the life cycle. If any mismatch is found, the activities of conceptualization, integration, implementation and evaluation will be performed once more.

In this section we evaluate the correctness of `:isSimilarObjectTo` object property defined using SWRL rules with sample data presented in Table 2.

Table 2. Sample data to evaluate similar rooms (R) in terms of their equipment.

Room Name	Air Terminal	Space Heater	Shading Device	Window
R16.2.28	X			
R16.3.29	X			
R16.2.05	X	X		
R16.3.05	X	X		
R16.2.11		X	X	X
R16.3.11		X	X	X
R16.2.10	X	X	X	X
R16.3.32	X	X	X	X

Figure 5 shows the obtained results after executing the SWRL rules. Among all inference results the reasoner correctly inferred that `:Room16.2.05` is similar to itself and `:Room16.3.05` in terms of building objects.

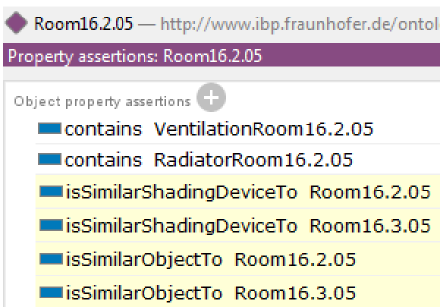

Figure 5. The results after executing the SWRL rules in Protégé.

4 Use-Case

We evaluate the ontology by means of answering all of the competency questions (see Table 1). Essentially, those questions can be categorized into two use cases: *Space recommendation* (1-6) and *Setting recommendation* (10-11). Question 7-9 are about the time feature of experience which further specifies both of the use cases. Hence, all the competency questions are covered by these two use cases. In this section, we describe the use case scenarios, the related queries and results.

4.1 Space Recommendation

4.1.1 Scenario

Often in our daily life we would like to find a certain kind of a space to meet the situation at hand. For example, for studying a textbook,say, in the morning, one might prefer a quiet space. In order to address this need the straightforward question one might ask is, ”which spaces are quiet in the morning?"

4.1.2 Query and Result

In order to retrieve answers to the question of finding a quiet space, we envision a SPARQL query depicted in Listing 3. `?QuietPercent` is the percentage of experiences about acoustic comfort assessed as quiet.

Listing 3. SPARQL query for recommending quiet spaces in the morning.

```
select ?location (count(*) as ?NrOfAC)
       ?NrOfQuietAC
       (?NrOfQuietAC*100/?NrOfAC
       as ?QuietPercent)
where{
     ?exp1 hex:isAbout ?AC;
          exp:hasLocation ?location.
     ?AC rdf:type hex:AcousticComfort.
     {select ?location (count(*) as
             ?NrOfQuietAC)
      where{
          ?exp hex:isAbout ?quietAC;
              exp:hasLocation ?location;
              exp:hasTime ?datetime.
          ?quietAC rdf:type
              hex:QuietAcousticComfort.
          ?datetime time:inDateTime ?time.
          ?time rdf:type time4hex:Morning.
        }
       group by ?location
     }
}
group by ?location ?NrOfQuietAC
order by  desc (?QuietPercent)
```

Figure 6 shows the result of the above query with the experimental data obtained through a survey conducted in an office building. According to the chart, `Room16.2.20` is the space that receives the highest percentage of experience feedbacks about quiet acoustic comfort in the morning. Consequently, this room seems to be recommendable in a first attempt.

The competency questions 1-6 can be verified by similar SPARQL queries. It is only necessary to replace the type of `?quietAC`, `?AC` and `?time` by changing the part after `rdf:type`.

4.2 Setting Recommendation

4.2.1 Scenario

Equipment settings can be recommended to occupants depending on their comfort requests, if the system that exploits the Hex ontology is integrated with a building control system. For example, if an occupant experiences that the light is too bright in a certain space and requests for a dim light, then the system can recommend settings for the controllable devices in order to provide better visual comfort. The query corresponding to this example is ”what kind of shading device settings can be applied for providing positively dim light in a space?”.

4.2.2 Query and Result

The query shown in Listing 4 is about obtaining the objects and their related states when the occupants report their positive visual comfort with dim visual sensation. The rooms which are similar to each other in terms of objects can be retrieved by property `:isSimilarObjectTo`—inferred using the mentioned SWRL rules. Figure 7 shows the result of this query.

Listing 4. SPARQL query for recommending settings of dim visual comfort in the morning.

```
select  ?location ?object ?state
        (count(*) as ?NrOfSetting)
where{
     bim4hexAbox:Room16.3.12
     bim4hex:isSimilarObjectTo ?location.
         ?exp hex:isAbout ?com;
          exp:hasTime ?time;
          exp:hasLocation ?location;
          hex:withObjectSetting ?setting.
     ?time time:inDateTime ?datetime.
     ?datetime rdf:type time4hex:Morning.
     ?com rdf:type hex:PositiveIEQFactor,
                   hex:DimVisualComfort.
     ?setting rdf:type
              bim4hex:ShadingDeviceSetting;
              bim4hex:hasSettingObject
                              ?object;
              bim4hex:hasSettingState
                              ?state.
    FILTER (?location !=
             bim4hexAbox:Room16.3.12)
}
group by ?location ?object ?state
order by  desc (?NrOfSetting)
```

The presented query corresponds to the competency question 11. Similarly, the query can be designed for question 10 by changing the types of `?com` and `?setting`. The query and result for competency question 10 are omitted here.

5 Discussion

We evaluated the ontology in two use cases by means of SPARQL queries. As we reported the results are promising.

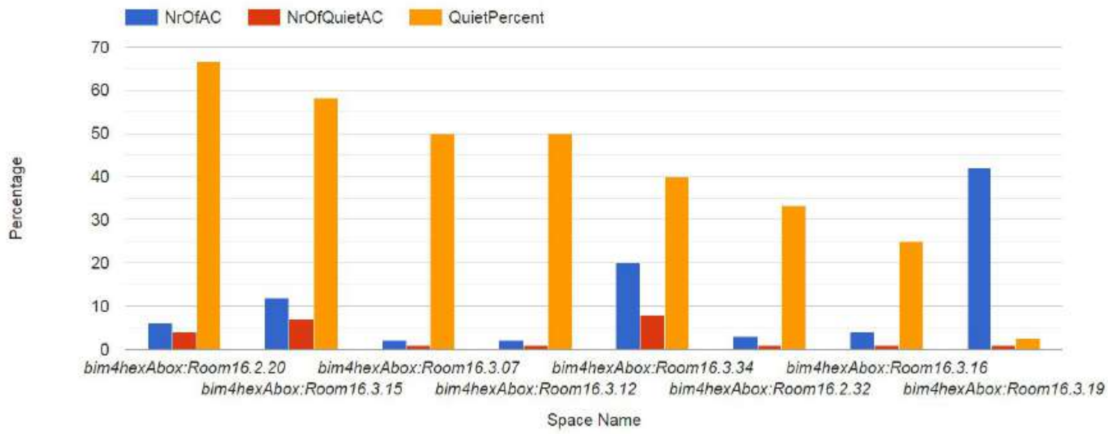

Figure 6. Quiet spaces in the morning.

Location	Object	State	NrOfSetting
R16.3.15	WindShutR16.3.15	PartlyDeployedStateInst	3
R16.3.19	WindShutR16.3.19	FullyDeployedStateInst	2
R16.3.19	WindShutR16.3.19	PartlyDeployedStateInst	2
R16.3.15	WindShutR16.3.15	FullyDeployedStateInst	1
R16.3.16	WindShutR16.3.16	FullyDeployedStateInst	1
R16.3.22	WindShutR16.3.22	NotDeployedStateInst	1

Figure 7. Ordered recommended settings for positively dim light.

However, we have identified some limitations. First of all, ontology serves merely as an aid for the initial step for analyzing data. Further on, data analysis techniques are required when one desires more profound and rigid results. This is in particular the case when evaluating quantitative or time-encoded data. For instance, an experience about a room from one day ago should in an extended analysis treaded differently than an experience from last year (see the first use-case).

Furthermore, although human experiences can reveal some facts of the reality, it is not sufficient to utilize human experiences alone in an objective way. The great strength comes from combining human experiences within the context of more objective information, such as sensor observations, weather information and so on.

6 Conclusion

Understanding human experiences of Indoor Environmental Quality (IEQ) has potential benefits including reducing energy demand and enhancing occupants' comfort. We provide an ontology for capturing human experiences about the several dimensions of IEQ in spaces by means of which we confirm the following hypotheses:

- Human experiences about IEQ factors can provide insights about their spaces;
- Human experiences about IEQ factors can inform building settings.

The ontology consists of three modules: Hex, bim4Hex and Time. It formally defines the domains of IEQ, experiences and their relationship to Building Information Modelling (BIM) and time.

In order to evaluate the HBC ontology, we collected data through designed human experience survey and converted them into the Resource Description Format (RDF) compliant with HBC ontology. With the help of reasoning, all desired implicit data were obtained. SPARQL queries were designed for answering questions based on two identified use cases corresponding the hypotheses. The queries performed over the gathered data are able to provide expected results. This supports a conclusion that HBC has the ability to leverage the Semantic Technologies to provide insights of spaces and inform building settings.

With large sources of human experiences, such as hotel reviews written in text, the system can provide the advanced searching options based on IEQ, e.g. quiet rooms or rooms with good visual comfort. In addition, the ability to predict human IEQ could assist towards more informative control decisions in specific Building Management Systems.

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PIECE 3D: Portable Interactive Education for Construction Engineering in 3D

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Abstract -

Everything starts from a piece. Bits and pieces are collected to form an entire structure. PIECE 3D is a framework for developing 3D education for the construction engineering field. Construction processes are dynamic and complicated. There are many components, and some processes are hard to understand from 2D pictures or even clips/videos. Thus, to improve the education system, this paper presents a portable interactive 3D education framework. As a case study, we developed rebar work process and measured students' performance and satisfaction. Compared to existing BIM education model, PIECE3D outperformed in portability, conveying educational objectives in 3D, enhancing understanding the processes of rebar, and triggering the interest of students.

Keywords -

3D education; Virtual Reality; BIM; Portable

1 Introduction

Building Information Modeling (BIM) has various features such as integrating and managing the information, illustrating the progress of work and visualizing finished models. Recently, BIM has been used as an educational tool because of its 3D visualization feature. However, education and training are not BIM's main objectives; thus it cannot serve well as an educational tool due to its functional constraints.

Education needs adequate scenarios with objectives and methodologies. For some fields like art and music, creativity should be emphasized without fixed direction. However, when it comes to engineering knowledge transfer, there are terms and processes which are worth remembering. This holds true with construction engineering education. Terms and processes of work need to be taught with objectives and a specific scenario so that students can grasp the concepts quickly, and those concepts become embedded in long-term memory. The delivery method needs to be intuitive and convenient.

For delivery, we decided to use a smartphone-based platform as most people possess smartphones these days and carry them wherever they go. Thus, we concluded that users can review the learning materials whenever and wherever they want with smartphones. Smartphones also have the advantage of possessing touchscreens rather than mouses or keyboards. Touchscreens can aid intuitive understanding of 3D models due to their gestural interfaces.

Considering both software and hardware, this study designed a framework for 'Portable Interactive Education for Construction Engineering in 3D (PIECE 3D).' In order to do so, we first analyzed needs and determined the work types to develop a model. Then, a 3D model was designed, an interactive scenario was constructed, and an interactive scenario-based 3D model was programmed. Once the model was developed, an experiment was conducted to measure students' learning performance and satisfaction with and without PIECE 3D in a controlled experiment. Control material was built on BIM-based learning, and experimental material was built on PIECE 3D. Finally, the difference between the experimental and control groups was evaluated with the t-test.

2 Literature Review

Three dimensional technologies have been used creatively to create different course materials. Ku and Mahabaleshwarkar proposed a new concept of Building interactive Modeling which augments the concept of Building Information Modeling to facilitate interaction [1]. They focused on safety training and equipment operation training. Irizarry et al. introduced layers that bring up exterior walls or even a house in order to execute structural analysis between formwork and loads [2]. They compared 2D and 3D views of rebar and recorded answers from students. Kim focused on teaching construction details and material quantity take-offs and assessed the effectiveness of BIM [3]. However, these BIM-based studies are not portable nor scenario-based as compared to the approach suggested in our paper.

Virtual Reality (VR) has been applied to general education with positive effects. Construction engineering educators have adopted VR to increase understanding and immersiveness through visualization and interaction. Messner et al. programmed cave-shaped IPD (Immersive Projection Display) to allow students to interactively develop a sequence of arrangements for a room [4]. The room consisted of 'air handling units', 'off-module platform', 'fire protection valve station' and so on. Sampaio and Henriques programmed a 3D exterior wall and bridge [5]. For instance, in rebar work, the components are grouped into 'footing', 'column', 'wall', and 'beam'. Sampaio et al. separated construction engineering education based on life-cycle and provided a 3D VR education model in each section [6]. Sampaio and Martins compared two different construction engineering methods for bridge construction [7]. Park et al. suggested IBAM (Interactive Building Anatomy Modeling) for experiential education [8]. They focused on assembly & disassembly of the building elements in terms of anatomical breakdown. However, as they created the materials based on a finished model, the compositions of building components were limited to components that remain in the finished model. For instance, components that are used temporarily such as forms and scaffolding were not considered.

The history of traditional education based on paper and pencil is far longer than that for any other tools. Paper and pencil allow writing, drawing and modification to be easy and quick. However, paper has some limitations. It is demanding to retrieve paper documents as they take physical space. It is also difficult to manage and classify the large amount of papers when accumulated. The advent of computers overcame the limitations of paper. However, though computers have many advantages, there are limitations to using them in a lecture. First, computers are difficult to configure for each student in each class. Also, they are relatively heavy to carry. Thus, portable devices such as laptop and pocket PC were devised and applied in construction engineering education.

More recently, smart devices such as smartphones and tablets influenced not only the social atmosphere but construction engineering education. Smart devices are handy as they are portable and touch-based. While there are many construction engineering education studies based on computers, there are few based on smart devices. Pedro et al. tried smartphone-based education [9]. However, the content was in 2D rather than in 3D and was limited to finding safety issues between two similar pictures. Nevertheless, because of the numerous advantages that smartphones have, such as communication, search and entertainment, we developed a smartphone-based platform.

3 The Framework of Portable Interactive Education for Construction Engineering in 3D (PIECE 3D)

3.1 Need Analysis & Work Type Selection

In order to discover the needs of PIECE 3D, a survey of 31 practitioners was conducted. Participants' work experiences and positions varied. Participants consisted of 20 practitioners with less than 5 year experience, 4 practitioners with more than 5 years and less than 10 years, and 7 practitioners with more than 10 years. The participants' main duties varied as well: 11 construction workers, 7 office workers, 4 managers, 4 researchers, and others. Five questions were asked in this survey.

Experienced tools during construction engineering education

Perception towards current education system

Applicability for 3D (VR) learning

Selection of topics to develop in 3D

Possible limitations

The results indicated that educational institutions mainly use textbooks (33.8%), handouts (29.9%), site visits (18.2%) and videos (13.0%). Concerning the current education system, 12 respondents were positive, 13 were neutral, and 6 were negative. This number indicates that the current education system is helpful to many, yet has gaps to be improved. Based on the survey, we concluded that PIECE 3D should neither exclude nor neglect current education paradigms. Rather, the new model should be an additive one that could improve the existing ones.

Although some (22.5%) of the respondents had a negative opinion of VR due to the ambiguity of VR's role and the time and cost it will take to build the model, most (77.4%) of the respondents agreed that virtual reality-based content will be effective when applied to construction engineering education.

3.2 Scenario Setup

A generalized method for learning module development that we also followed for our own module development is described in this section. Based on the survey, needs were identified. A scenario for the contents could be developed either from scratch by receiving advice from practitioners, or it could be excerpted from existing content sources such as textbooks. For this study, we used both methodologies. We used textbooks for terms and visited experts to learn how the processes work in the site. We created a representative scenario for a typical case for a given topic.

3.3 Model Development

To design the components in 3D, it was reasonable to acquire an existing BIM model. We acquired an existing model from 'Tekla', and imported it to 'Revit' to modify or remove some components. Then, to build a scenario with interactions, 'Unity' was used.

3.4 Model Validation

To validate the suggested model as an integrated learning tool for effective teaching in construction engineering education, a series of assessments were conducted in undergraduate-level courses before actually implementing in traditional lectures.

4 Case Study: Reinforcement Bar Work

4.1 Need Analysis & Work Type Selection

Based on 'Korean Standard Specification for Building Construction (2013),' 20 out of 28 major work types and 51 out of 203 detailed work types were selected. These topics were chosen considering complexity, importance and 3D visualization potential. The survey ranked construction work types that could be visualized in interactive 3D.

According to the survey, steel work should have been selected for the case study (Figure 1). However, after consideration, rebar work was selected, because respondents with less than 5 years experience strongly insisted on the importance of rebar work. As less experienced practitioners tend to rely more on knowledge and experience from the universities or other institutes, their needs were considered to be more critical than the overall needs of the respondents.

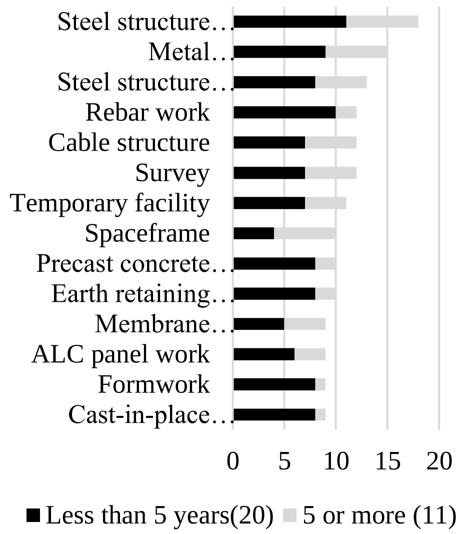


Figure 1. Survey results for work type preferred to be developed in 3D

4.2 Scenario Setup

We set up an example scenario. Actual processes can be flexible. The process sequences from foundation, column, wall, beam to slab were designed. The sequences are illustrated in Figure 2. Before any footing or foundation is built, the elevator pit is constructed in order to dewater the excavation volume. To construct the elevator pit, bottom bars, rebar supports, top bars, vertical bars and horizontal bars are built in that order. Rebar supports exist to support top bars. Vertical bars should be placed before horizontal bars as horizontal bars cannot stand alone in the air. Mostly, internal bars are constructed before external for the convenience.

Once the elevator pit is constructed, types of footings or foundations are selected. Single footings support one column while strip footings support multiple columns in a row. Mat foundations also support multiple columns but in multiple rows. They contain rebar supports between bottom and top bars.

In order to connect footings/foundations and columns, dowel bars are planted. Then, main bars are connected to the dowel bars in the vertical direction followed by tie bars in the horizontal direction. Walls are constructed with the same principle.

Beams have a special process. For beam, top bars are separated into two parts: (1) the edge and (2) the rest. Two top bars on the edge are placed on the wedge to carry the stirrups. The workflow of the beam is top bars (edge), stirrups, bottom bars, top bars (rest) and the cover bars.

Lastly, for the slab, the end parts of the bars go before bent bars. The middle part goes after bent bars. It is due to the shape of the bent bars, which adds tensile force of the rebar. Main and sub bars refer to the position of the rebar.

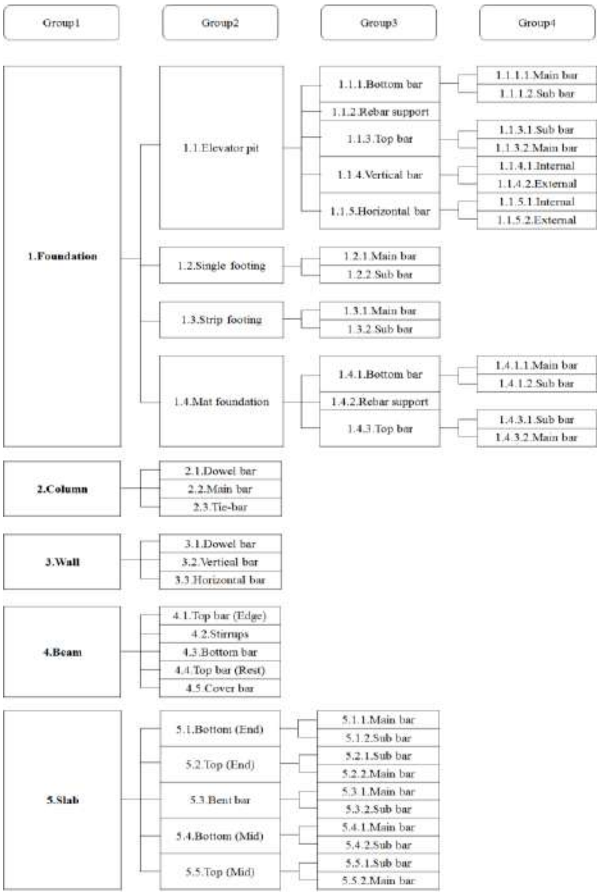


Figure 2. Summary of rebar work processes

4.3 Model Development

PIECE 3D was developed in three steps. The first step was to design the components in 3D. As we acquired an existing building model from 'Tekla', and imported to 'Revit,' (Figure 3) it was not difficult to dissect some components. Once the main components, such as foundation, column, wall and slab were ready (Figure 4), we saved the files respectively. These were used in a "hint" level to demonstrate finished shape as a reference and line silhouette in level 1. Then, components were dissected once again as subcomponents, subsubcomponents and so on. Subcomponents and subsubcomponents were used in level 0, level 1 and level 2.

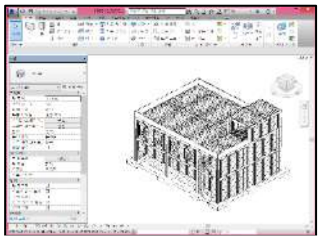


Figure 3. Entire BIM model

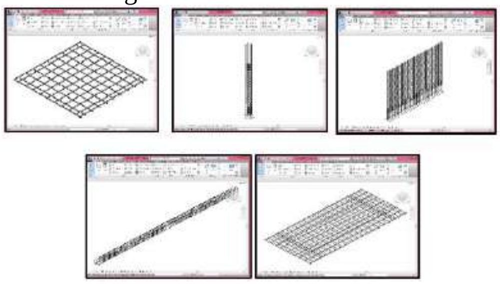


Figure 4. BIM model components (Foundation, Column, Wall, Beam, Slab)

The second step was to create a scenario (Figure 5). From level 0, students can learn the terms of rebar components not only top or bottom rebar but specific terms such as support rebar, stirrup and dowel bar. Students can zoom, move and rotate the components in any direction. In this level, students can also learn the process of rebar work as it is arranged in sequences. From hint level, students can view the finished design before moving on to next level. Level 1 shows line silhouette in green. Students can zoom, move and rotate the given components in order. From level 1, students can review the process and learn the right positions of rebar components. Finally in level 2, students are required to perform their learning experience from previous levels. A black space is given, and students can assemble the components in the right sequence at the right position. The labeling is not in order but is in random to check student's understanding of the processes. Screenshots of each level are illustrated in Figure 6.

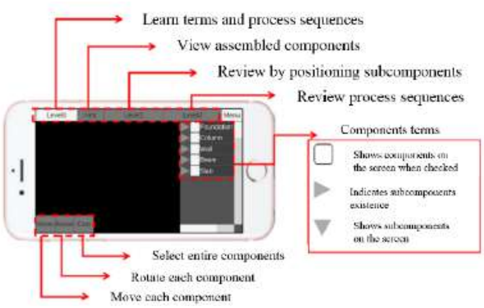


Figure 5. Roles of different levels and buttons

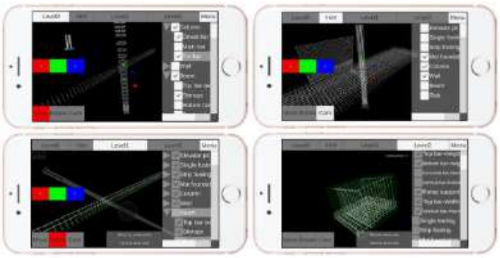


Figure 6. Screenshots of each level

The third step was to create interactions. There are unique features in PIECE 3D. Because the model is based on smartphone, it is touchscreen-based. In this case, it is complicated to move or rotate in 3D as the smartphone can only recognize two fingerprints at once. To overcome such barrier, we decided to integrate a feature called 'Gizmo,' which allows user to view in 3D directions.

4.4 Model Validation

To evaluate the usefulness of PIECE 3D as an integrated learning tool for an effective teaching approach in construction engineering education, we conducted a series of assessments in an undergraduate-level course, 'Building Systems' in the Department of Civil, Environmental and Architectural Engineering at Korea University. The experiments compared the effectiveness of PIECE 3D for learning with that of a tabletop computer. The course is a three-credit course for second year or higher grade students. Every year, 50-80 students take this course as a prerequisite for 'Building Construction' so that consistency in prior knowledge is maintained. 'Building System' introduces various kinds of wooden, reinforced concrete and/or steel buildings. 'Building Construction' investigates deeper the processes and methods of building construction.

The experiment was designed to meet two objectives: 1) learn the terms of rebar and 2) learn rebar fabrication processes. We believed students taking 'Building System' were suitable for this experiment, as they have learned the basic concepts and characteristics of rebar. This experiment would facilitate overall and detailed understanding of rebar work before taking 'Building Construction' and would also engage the students' interest in learning by doing.

Out of 29 students who participated this experiment, 26 students were taking Building Systems in Spring 2016. All 29 students were in department of Civil, Environmental and Architecture Engineering. Participants consisted of 11 second year students, 16 third year students and 2 fourth year students. Students were asked to come to the office (Engineering Building 351) individually or in pairs. A laptop and a smartphone were prepared in the office.

The operating system of the laptop was Microsoft© Windows© 8.1K (64 bit version) and it contained 8GB RAM. The BIM program used for the experiment was Autodesk Revit 2015.

The operating system of the PIECE 3D was Microsoft© Windows© 10Pro. The virtual reality engine used for this smartphone-based program was Unity 5.3.1f, and the IDE (Integrated Development Environment) was Visual Studio 2015. The language was C# and the test phone was a Samsung Galaxy Alpha.

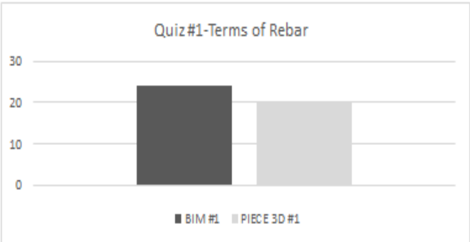
It took 40 min to an hour for students to complete the experiment. Students were first asked to keep the objectives in mind. Then, the instructor explained how to view 3D models from a BIM program embedded in the laptop. By using keyboard (shift) and mouse (scroll wheel), students were able to zoom, move and rotate each and overall components. With the 'view cube' that assists visualization in Revit, students were able to view from the direction they wanted. Students could see eight components: elevator pit, single footing, strip footing, mat foundation, column, wall, beam and slab. Students were asked to pay attention to terms and processes. Students were allowed to ask questions to the instructor freely so that interactive atmosphere could be created. The instructor kindly explained basic principles of processes so that students can infer the sequences. For instance, the instructor gave hints such as 'top bar' is built after 'bottom bar,' 'internal bar' is built before 'External bar,' and as horizontal bar cannot stand alone in the air, 'vertical bar' is placed before 'horizontal bar'. After viewing all eight components, students were asked to answer three questions in a quiz including terms and processes of rebar work. Question 1 was to recognize 'column' components terms, and questions 2 and 3 were asked to measure the understanding of the sequences of 'mat foundation' and 'beam.'

Then, students were told to control smartphone-based model. The instructor showed how to check/uncheck the checkbox, how to zoom and move and rotate the components. Students went through all four levels (level 0, hint level, level 1, level 2) and were asked in another quiz to answer three different questions. Question 1 was recognizing 'elevator pit' components terms, question 2 and 3 were asked to measure the understanding of the sequences of 'wall' and 'slab.'

Finally, based on students' experiences, they were asked to evaluate BIM model and PIECE 3D. The survey included 15 criteria and they are assorted into four groups: 1) device suitability, 2) scenario quality, 3) device convenience and 4) user interest.

Based on the quiz and satisfaction evaluation results from 29 students, we conducted the t-test to find the significance of the satisfaction difference between the BIM-based model and the PIECE 3D model. SPSS 12.0 K was used to analyze the data.

Since the sample size is small (N=29), the normality of data need to be examined before proceeding to the t-test. As the results of the quizzes do not follow a normal distribution, because they are scored either right or wrong, we decided to evaluate them separately. Figure 7 represents the results of the quiz. While BIM-based excelled in questions about terminology slightly, for processes, PIECE 3D outperformed considerably.



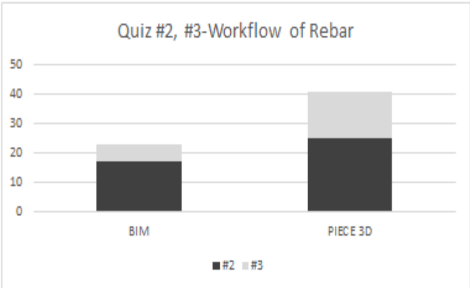


Figure 7. Result of quiz (Total: 29)

Once the students finished the quiz, they were asked to fill out the survey questionnaire to measure PIECE 3D satisfaction. Results are presented in Figure 8 and criteria are explained in Table 1.

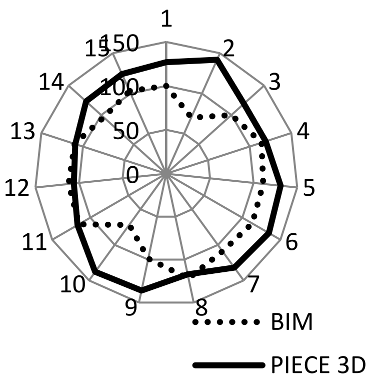


Figure 8. Results of satisfaction survey

Table 1. Criteria of satisfaction survey

Criteria (1: Strongly disagree, 5: Strongly agree)
1) Easy to access
2) Easy to carry
3) Adequate during the lecture
4) Complements traditional materials (e.g. textbook)
5) Successfully achieves objective
6) Increases understanding in 3D
7) Logical contents included
8) Detailed contents included
9) Easy to learn the terms
10) Easy to learn the processes
11) Adequate device speed
12) Easy to use
13) Convenient to use
14) Immersive
15) Interesting

Before conducting paired t-test, normality test of difference between paired data was carried out. As criteria 3, 12, 13, 14 have p-value higher than 0.05, it can be said that they follow normal distributions. Thus, a paired t-test can be conducted. For the other criteria that had p-value lower than 0.05, a Wilcoxon test was conducted.

Though there are differences in amount, for all eight pairs, PIECE 3D scored higher when it came to comparing means. Considering p-value, the author concluded that criteria 14 had significant differences between BIM and PIECE 3D. In other words, when it comes immersiveness, PIECE 3D surpassed the previous tabletop based BIM model. We also executed Wilcoxon test for the rest of the criteria.

The results reveal that for criteria 1, 2, 5, 6, 7, 9, 10 and 15 the alternatives are statistically different, and PIECE 3D outperforms the existing BIM model. Not only was PIECE 3D portable, but as it conveyed the educational objectives successfully in 3D, it was effective for students to understand the materials especially the terms and processes of rebar. It also triggered the interest of students.

5 Conclusion

This study proposed an effective education system using BIM and VR technologies. From needs analysis to model validation, four steps were taken to build ‘Portable Interactive Education for Construction Engineering (PIECE 3D).’ First, we discovered the needs from industry to find which topic would be preferred to be taught in 3D. Then, we set up a standard or a common process for the topic we want to develop. Next, we developed smartphone-based content. Finally, we compared PIECE 3D with an existing BIM-based tabletop model in two perspectives: hardware and software.

From the quiz results and satisfaction survey, it became evident that PIECE 3D outperforms the tabletop model overall. PIECE 3D not only successfully helped deliver course objectives, but it facilitated understanding in 3D. Reviewing processes from ‘Level 0’ to ‘Level 2’ enabled students to learn the terms and processes of rebar work easily.

The case study of rebar work is only a part of the whole of construction works. For the future studies, more models can be developed from earthwork to demolition. Also, this model could be extended to different types of construction such as infrastructure or plants. Although we had some technical limitations due to the small screen and touchscreen system because of our smartphone-based platform, it was intuitive and immersive.

Lastly, we would like to emphasize the importance of current education systems. The suggested framework should not replace the current systems but complement them, so that students can interact better and effectively learn in class.

Acknowledgement

We would like to record our appreciation to Jujin Kim, for developing the application, Myungdo Lee for providing BIM data and Jihong Koo for guiding us to learn the terms and processes of the rebar work. Special thanks to Professor Hunhee Cho and Kyung-In Kang for supervising Master’s thesis.

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Evaluating artificial intelligence tools for automated practice conformance checking

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Abstract –

Checking conformance of construction management practices to practice specifications is typically performed manually by experts in the Engineering and Construction (E&C) sector. Though conformance checking is known to increase performance of a project, this process takes considerable time as several professionals have to go through thousands of pages of documents, complex workflows, and personal interviews. This paper aims to evaluate AI tools including Text mining, process mining, and image data mining for their utility in assisting conformance checking in construction management. Automated conformance checking may not only reduce manual and repetitive work by experts but also reduce human errors. Examples are demonstrated for initial validation.

Keywords –

Conformance; Artificial Intelligence; Software Evaluation

1 Introduction

The Engineering and Construction (E&C) sector is slower to adopt new technologies than other industry sectors. Its conservative approach to new technology is partly due to its large scale which leads to greater risk and its complexity that involves many stakeholders. However, considering that a 1% rise in productivity could save $100B a year worldwide [1], the industry should move forward to exploit new technologies. Especially in the construction management field, the use of the state-of-the-art technology is promising.

Good construction management balances professional judgment with conformance to references such as best practices, policies, standards, and procedures. 'Conformance,' 'conformity,' and 'compliance' are used as synonyms. There has been intense debate on use of the words. ISO 9000:2000 suggested to use 'conformity' and drop both 'conformance' and 'compliance' for quality management system. The word 'conformance' seemed to have lost its status. However, according to ISO 9001:2015, 'conformance' is redefined as choosing to do something in a recognized way and 'compliance' is doing what one is told to do. Both words still exist and are widely used throughout the literature. While ISO still prefers to use the term 'conformity,' the term 'conformance' was selected for two reasons. First, 'conformance checking' is a term that already exists and is commonly used in the process mining field. This could maintain consistency and avoid confusion. 'Conformance' rather than 'compliance' was adopted because of the intention to define something less strict than abiding by the law or meeting regulations. Compliance fits better with laws or regulations, whereas conformance better suits with pursuing best practices, policies, standards and procedures.

'Checking,' 'measuring' and 'evaluating' imply different meanings, although commonality exists. Checking usually implies yes or no, true or false, or pass or fail. Measuring implies numeric results, and requires metrics, observations, and formulas to derive the values. Evaluating implies not only quantitative but qualitative assessments. This paper introduces tools that can 'check' conformance, and 'evaluate' commercial software. Thus, the objective of this paper is to evaluate how artificial intelligence (AI) technologies can be adopted to aid automated conformance checking in construction management.

In order to check conformance, relevant AI technologies were evaluated. AI is a generalized term for computers replicating human intelligence in learning, decision-making, vision, speech, etc. Text mining, process mining, and image data mining tools that have artificial intelligence background were investigated in this paper.

2 Literature Review

The concept of artificial intelligence (AI) existed since the 1950s, but the modern definition was built from research done in the 1970s. AI can be defined as a system that rationally thinks and acts like humans [2].

AI has been divided into parts, as the technology is still limited to integrate all capabilities in a single entity.

In E&C sector, AI has been constantly used to solve problems in structural engineering [3], transportation [4, 5, 6], and geotechnical engineering [7]. A conceptual model such as Industry Foundation Processes (IFP) for conformance checking has been developed [8] as well as Genetic Algorithms [9]. Though some researchers insist that much of them are often theoretical and are difficult to apply in the real world [10], the recent explosion of commercial applications of AI challenges that assessment.

For project management in E&C sector, AI was used to solve problems such as site-layout modeling [11] and generating construction project plans [12]. Levitt et al. [12] suggested that AI technology can provide ways to generate and update plans in actual project progress from stored knowledge. Tommelein et al. [11] enabled computers to mimic designer's layout and add flexibility and functionality to existing model.

Conformance checking and measurement has been investigated since early 1990s. Rajamani, and Rehof [13] developed a mathematical model for contract conformance. Abdul-Rahman [14] derived costs from non-conformance and suggested a quality cost matrix for construction projects. Yurchyshyna et al. [15] proposed an expressive model and a knowledge-based system for checking a construction project against technical norms by matching the project with the norms. Lipman et al. [16] reviewed and assessed conformance testing methods for product data models used in the construction industry. Nawari [17] optimized and simplified automated code and standard conformance checking by leveraging building information modeling. Zhang and El-Gohary [18] suggested Semantic Natural Language Processing (NLP) based information extraction for automated regulatory compliance checking.

3 Methodology

To measure conformance, four components were identified and they are illustrated in Figure 1. This paper covers documents and workflows components. However, people and actions are also included in these two components as people build and implement these components. For each component, what to check and how to check the conformance are also listed in Figure 1.

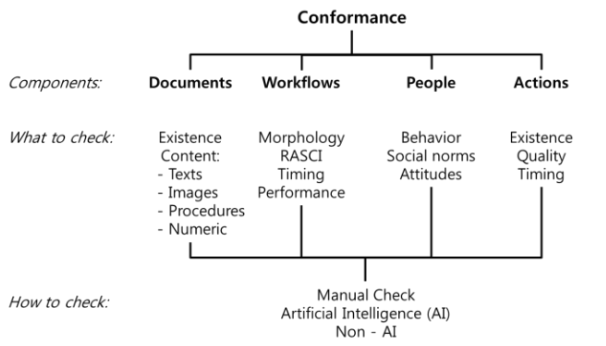

Figure 1. Conformance components

Despite the history of artificial intelligence (AI), application challenges remain in the E&C sector. The difficulty of identifying the appropriate tool to suit a new situation; the need for large amounts of input data for tools to be usable; the opaqueness of most tools; and the difficulty of realistically interpreting the solutions to highly tailored problems are some of the reasons behind [10]. On the other hand, this paper focuses on how to apply AI to improve conformance problems.

Throughout this paper, technologies that could be applied to check conformance are introduced and evaluated. Data mining is the computing process of extracting patterns in large data sets. Its goal is to transform the extracted information into an understandable structure for further use. Data mining is divided into three categories in this paper: text mining, process mining, and image data mining, and some AI tools are introduced (Figure 2).

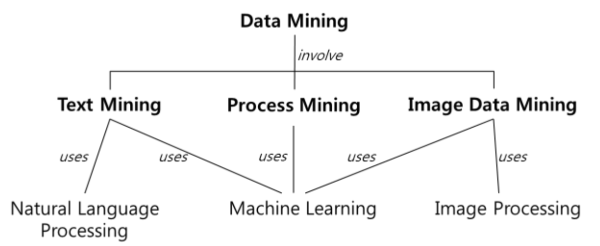

Figure 2. Tools for conformance checking

Text mining is the process of deriving high-quality information from text. Natural Language Processing (NLP) and machine learning algorithms can be used for text mining. NLP is an ability of computer software to understand human language such as speech and text. NLP is widely used to analyze large pools of legislation or documents. NLP can summarize blocks of text by extracting the central ideas and ignoring irrelevant information, automatically generate keyword tags and identify the sentiment of a text and reduce words to their roots using stemmer & lemmatization. Plagiarism detection tools, wordcloud generator tools and resume screening tools utilize NLP technology in this paper.

Process mining is also part of data mining that requires specific data such as an event log (i.e. case ID's, activities, timestamps, etc.), and machine learning algorithms. With event logs, practical workflows can be derived (process discovery), and conformance to the driven workflow can be checked (conformance checking).

Image data mining is a technology that aims at finding useful information and knowledge from large scale image data. It enables computers to gain high understanding from digital images or videos. This technology is intended to convert an image into digital form to extract information.

Machine learning is the computer ability to learn without being explicitly programmed. Machine learning enables construction of algorithms that can learn from data and make predictions or decisions. Machine learning is used for all categories in data mining.

4 Case Studies

To facilitate understanding, some commercially available software for Natural Language Processing (NLP), process mining, and image processing are introduced. Explanation of the purpose of these software, and ways to adopt them from management perspective are presented.

4.1 Natural Language Processing (NLP)

Among all the Artificial Intelligence (AI) technologies, NLP plays a critical role, as documents are mostly in the form of text. NLP can be used for preprocessing such as detecting copy and paste with plagiarism detection tools, analyzing frequency of words with wordcloud generator tools, and matching selected keywords with resume screening tools.

4.1.1 Plagiarism Detection Tools

There are two types of plagiarism detection tools: one that searches from the web or a relevant database (e.g. journal papers (iThenticate), class homework (Turnitin)) to match the result, and the other that finds similarity between two documents. To find potentially useful software tools, assessment of 15 commercial software were investigated. Texts excerpted from Construction Owners Association of Alberta (COAA)'s best practices and distortions of them, accuracy of software performance was tested (Table 1).

Table 1. Example used for plagiarism detection tools

Text A (Original Text from an institution): "It is recognized that the use of illicit drugs and the inappropriate use of alcohol and prescription and non-prescription drugs can have serious adverse effects on a person's health, safety and job performance. A solid industry-wide model, including both a policy and guidelines, will help to enhance the level of health and safety at the workplace."
Text B (Distorted text version from Text A): "The use of illegal drugs and the unsuitable use of alcohol and prescription and non-prescription drugs can have severe hostile effects on a person's well-being, safety and job performance. A solid model, including both rules and guidelines, will help to improve the level of health and safety at the workplace."

Among the 15 software tools, eight different ones were evaluated, as they were either free or offered free trials. Among them, five offered plagiarism detectors browsing the web or databases, two offered text comparison, and one offered both.

The best plagiarism detector was PlagScan. It found the original source from the web computing 98.8% as plagiarized. Even when the distorted version of the excerpt was entered, it was still able to identify the original version computing 71.8% as plagiarized. According to PlagScan, the plagiarism percentage should be less than 5%. SmallSEOTools also found the exact source of the original text estimating 100% as plagiarized; however, estimated 0% as plagiarized for the distorted version and could not the find original source. Duplichecker, QueText and Plagium were not able to identify the right source; thus, estimated 0% as plagiarized.

Next, comparison between *Text A* and *Text B* was drawn. Copyscape was the best software in terms of comparing two texts resulting 75%, 83% matching. The reason for two values is because the total numbers of words in *Text A* and *Text B* are different. Table 2 provides the results. However, Copyscape is limited to word matching. It does not understand semantics within the context. Plagium estimated 40.8% as plagiarized. Interesting part of Plagium is that it provided sentence plagiarism as well as paragraph and page plagiarism. Copyleaks estimated 16% as plagiarized only considering continuous words that are identical.

Table 2. Results for word matching (Source: Copyscape)

59 words, 75% matched	**Matching word count**	**53 words, 83% matched**
It is recognized that		
The use of	3 words	The use of
Illicit		Illegal
Drugs and the	3 words	Drugs and the
Inappropriate		unsuitable
Use of alcohol and prescription and non-prescription drugs can have	11 words	Use of alcohol and prescription and non-prescription drugs can have
Serious adverse		Severe hostile
Effects on a person	4 words	Effects on a person
Health,		Well-being
Safety and job performance. A solid	6 words	Safety and job performance. A solid
Industry-wide		
Model, including both	3 words	Model, including both
A policy		Rules
And guidelines, will help to	5 words	And guidelines, will help to
Enhance		Improve
The level of health and safety at the workplace	9 words	The level of health and safety at the workplace

Plagiarism detection tools can check conformance in construction management. Not only the original sources of documents can be found but copy and paste phrases may be detected. If two documents' matching level is higher than a threshold that has been set, conformance is no longer valid. Software that compare two sets of texts may be applied as well using same words or same sentence structures detecting techniques. By setting a threshold, conformance can be checked.

4.1.2 Wordcloud Generator

Wordcloud generator can count words included in a document. It can automatically remove stopwords. Stopwords are the words that do not have important meanings such as articles and prepositions. Frequency of words can be automatically detected and more frequently to less frequently used words can be recognized. However, this software cannot recognize synonyms nor read sentences by context. For example, 'environment' and 'environmental' are considered as two different words, and 'construction' that has two different meanings are counted as one word.

This software can be adopted to identify keywords. High frequency of words does not necessarily mean that those words are more important than others. However, it is useful to track all words at once after processing such as removing the stopwords. Once keywords or key phrases are identified, the existence of them can be an indicator among others to check the conformance. Figure 4 and Figure 5 are result screenshots for examples from Construction Extension to the PMBOK Guide section 3.1.11 Project Health, Safety, Security, and Environmental Management (HSSE) (Table 3).

Table 3. Example used for wordcloud generator

Text C: "Site security and controlled access are discussed for construction job sites. Employee health and wellness are introduced for construction personnel as these directly affect construction project risk and safety. Trends include virtual technology and environmental certifications. While HSSE is applicable to all industries, the unique hazards in construction projects intensify the need for additional measures. The Planning Process Group includes a proactive view of health, safety, and environmental policy compliance. In addition to employee health and site security, a comprehensive health, safety, and environmental management plan is developed to address specialized stakeholders, reporting requirements, documentation and record storage requirements, training, and additional government requirements."

For this paper, "wordclouds.com" was used.

Figure 4. Screenshot of wordcloud generator results (Wordcould.com)

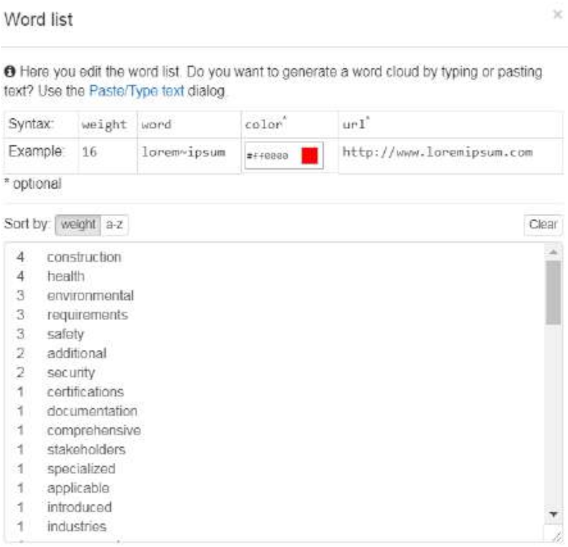

Figure 5. Wordlist from high frequency to low frequency (Wordcould.com)

4.1.3 Resume Screening Tools

Human Resources (HR) departments receive dozens of resumes a day. In order to reduce repetitive work, they use automated screening tools to match keywords they are looking for with candidates' resumes.

'Ideal.com' offers an artificial intelligence (AI) based recruiting system. Ideal's software can match keywords and can filter unqualified candidates. Powered by machine learning, next generation candidate screening software uses feedback from previous decisions. By using automated resume screening, HR can avoid skipping candidates who are competent. Candidates are screened and shortlisted instantly, so that HR knows whom to contact first.

By applying resume screening tools, comparing practice specifications with construction execution plans is feasible. If construction execution plans does not includes practice specifications, conformance cannot be achieved. With machine learning algorithms, conformance can be checked and data could be accumulated for the future usage.

4.2 Process Mining Tools

Process mining tools are for reconstructing workflows and representing them in formal process notation or iconography. They also can detect vulnerabilities automatically, analyze processing times, and detect bottlenecks. There are commercial process mining tools available such as Celonis, Disco, EDS, Fujitsu, Icaro, LANA, Minit, mylnvenio, Perceptive, and ProM. Once the process or workflow is discovered based on streamlined event logs, unrefined original event logs can be replayed or overlapped over the refined workflow, and conformance can be checked and deviations can be identified. By simply using filters, 'Disco' has allowed users to create process models. Pseudo case for Change Management was designed as illustrated in Figure 6. Case IDs, activities, and timestamps were entered and result is shown in Figure 7.

	Case Id	Activity	Timestamp
1	A-001	Initiated	2017/05/17 00:00:00
2	A-001	Modified	2017/05/30 00:00:00
3	A-001	Reviewed	2017/06/04 00:00:00
4	A-001	Approved	2017/06/11 00:00:00
5	A-002	Initiated	2017/06/20 00:00:00
6	A-002	Modified	2017/06/21 00:00:00
7	A-003	Initiated	2017/06/21 00:00:00
8	A-002	Reviewed	2017/06/22 00:00:00
9	A-002	Approved	2017/06/27 00:00:00
10	A-003	Reviewed	2017/06/30 00:00:00
11	A-004	Initiated	2017/07/01 00:00:00
12	A-005	Initiated	2017/07/01 00:00:00
13	A-005	Modified	2017/07/03 00:00:00
14	A-005	Approved	2017/07/05 00:00:00
15	A-006	Initiated	2017/07/05 00:00:00
16	A-004	Modified	2017/07/09 00:00:00
17	A-006	Rejected	2017/07/10 00:00:00
18	A-003	Approved	2017/07/26 00:00:00
19	A-004	Rejected	2017/08/03 00:00:00

Figure 6. Eventlog input (Disco)

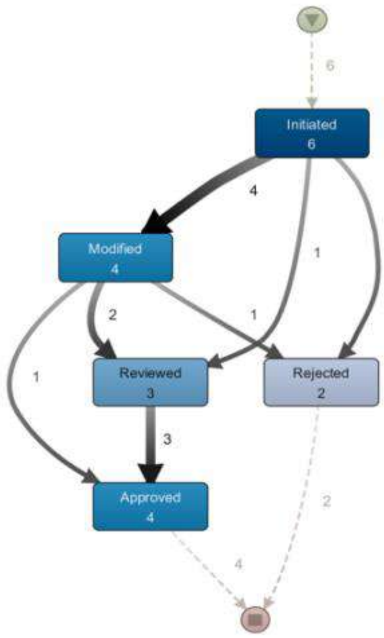

Figure 7. Result screenshot of process discovery (Disco)

LANAlab provides another software for process mining. It provides an academic version for free. LANA can discover a process model as well as develop a reference model. Figure 8 is the result screenshot of process discovery. For the input data, the same data that were used for Disco were entered (Figure 6).

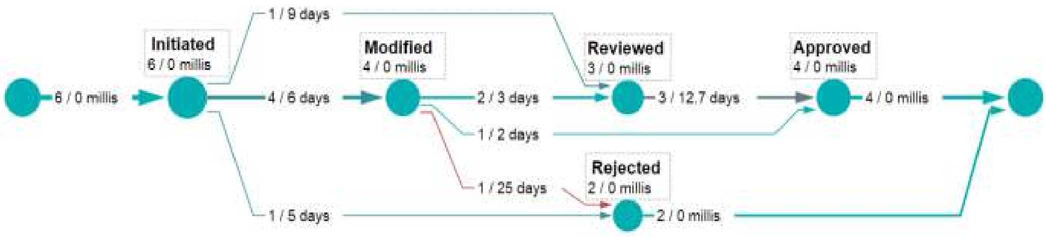

Figure 8. Process Discovery (LANA)

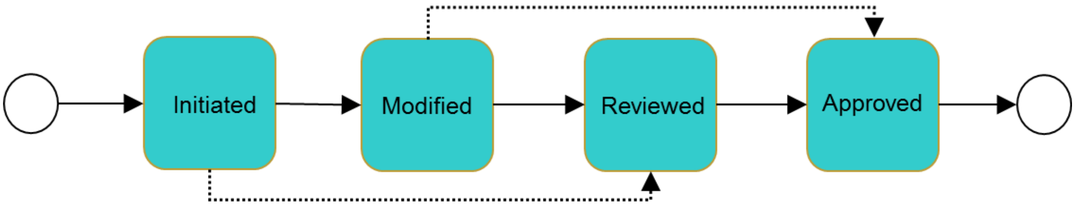

Figure 9. Reference Model in the Form of BPMN (LANA)

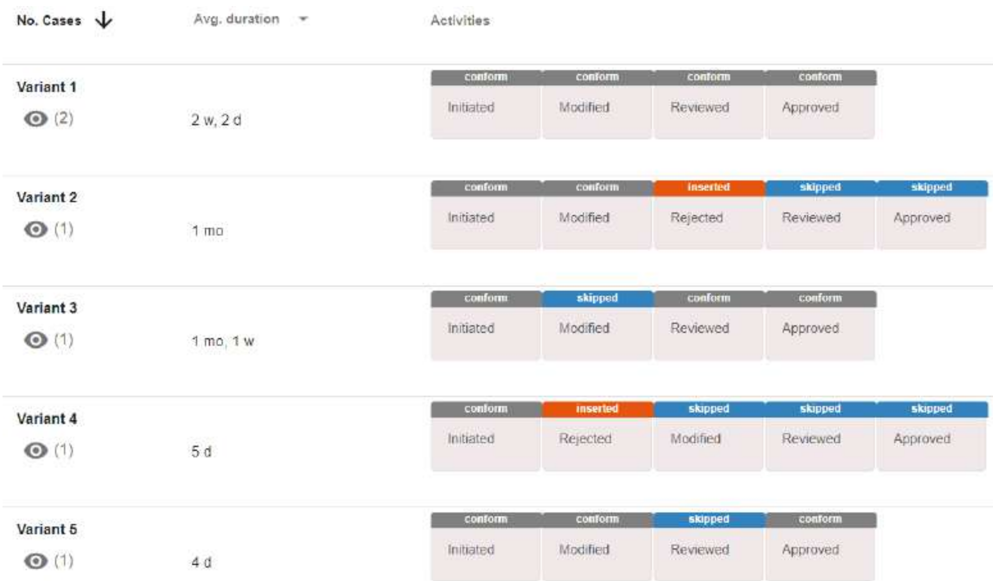

Figure 10. Variants Detected (LANA)

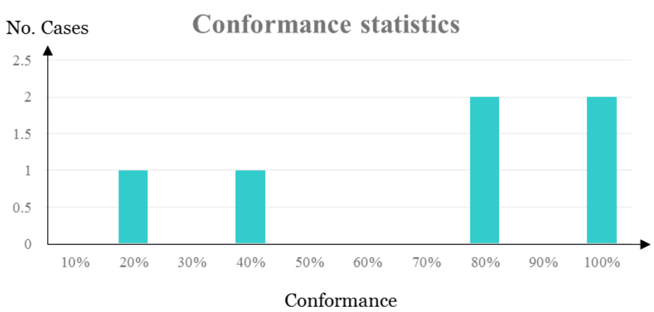

Figure 11. Conformance Statistics

The numbers in Figure 8 represent the number of cases and the average duration it takes. The reason why values are not assigned for activities is because only one representative timestamp has been entered for simplicity, and not start and finish. LANA is more advanced than Disco in terms of providing information. LANA also allows to develop reference model with process model. With the process model discovered from Figure 8, reference model was developed (Figure 9). Once the reference model was developed, variants were identified, and automated conformance checking became possible (Figure 10 and Figure 11). There are five different cases including one which is equivalent to the reference model. Conformance statistics computed how much each case conforms to the reference model. The x-axis of Figure 12 refers to conformance and the y-axis refers to number of cases.

Automated conformance checking tools from LANA can be useful for finding deviations from planned workflow. Planned workflow can be a reference model. Actual activities can be recorded in the form of event logs. These two can be automatically compared and checked.

4.3 Image Processing Tools

When communicating and implementing a good practice, images and/or photos may be included to facilitate understanding. With image processing tools, similarities or differences between two similar images or photos can be detected.

In this section, image search and image matching tools are introduced. Image search tools can browse the web to identify the original source of the image. Image matching can take place against a reference image. When it comes to conformance checking, image search tools can detect whether the query image is novel or not. Image matching tools can only be used conceptually yet because computers cannot understand the images to verify whether the images implies the same concept or not. Currently, only physical similarities or differences such as colors and shapes are detected. However, the importance is in the meaning and representation of images.

4.3.1 Image Search Tools

Image search tools are typically used for media intelligence, brand and/or copyright protection, and social media monitoring by browsing the web. It is composed of two key steps: indexation and retrieval.

The first step is to create a descriptor of the image content which can be referred as indexation. 'LTU Engine' suggests a visual signature for each image and describes its visual content with features such as color, shape, and texture. These descriptors are also called image DNAs. These image DNAs are then stored in a database. Retrieval is a special comparison technology by which an image signature can be compared at high speed with other image signatures from a database or the web for up to millions of images.

4.3.2 Image Matching Tools

LTU Engines' image matching tools use distinct pixel features to analyze visual content and identify matching images between a query image and references. Its image matching algorithm includes an optional matching zone parameter. The matching zone highlights where a query image matched with references. The matching zone details can be represented visually, as coordinates and as a percentage. The matching zone can be used to explain where and why two images matched.

4.4 Machine Learning

Machine learning can be adopted to all three types of AI software by receiving feedback from users or by learning autonomously, and learn to make better decisions. By retrieving results after checking the conformance, the computer can learn where conformance is maintained and where not. This information can be used for future conformance checking. Machine learning is often understood as data mining from a statistical point of view. It is partly because statistical cases have been solved more effectively with practical machine learning research.

5 Discussion and Conclusion

In this paper, artificial intelligence (AI) tools that can automate conformance checking have been evaluated. Although they cannot be the complete solution, there is potential for AI technology to be used as a basic toolset for aspect of conformance checking. By assisting construction management, this will not only save time and reduce human errors but also provide different perspectives and ways of checking the conformance. For future studies, more software, test cases, and data will be investigated as well as evaluated. Conformance will be measured and evaluated beyond just checking. Similarity of practice definition is necessary but not sufficient to ensure conformance. Implementation is most critical.
Plagiarism algorithms can be used in various ways. However, they are challenged to identify lexical changes, structural changes and multi-sources. Wordcloud generator should apply more of features related to semantics. There are Process Mining software tools commercially available. However, as

most of them are not open source, only two software were tested. Acquiring proper event logs was also difficult. Image processing technology still has performance gaps to be used in conformance checking. Computers should be able to understand the images so that it can categorize them.

Acknowledgements

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Crack Detection in Masonry Structures using Convolutional Neural Networks and Support Vector Machines

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Abstract –

Masonry structures in historical sites are deteriorating due to ageing and man-made activities. Regular inspection and maintenance work is required to ensure the structural integrity of historic structures. The inspection work is typically carried out by visual inspection, which is costly and laborious, and yields to subjective results. In this study, an automatic image-based crack detection system for masonry structures is proposed to aid the inspection procedure. Previous crack detection systems generally involve the extraction of hand crafted features, which are classified by classification algorithms. Such approach relies heavily on feature vectors and may fail as some hidden features may not be extracted. In this study, we propose a crack detection system which combines deep Convolutional Neural Networks (CNN) and Support Vector Machines (SVM). CNN is used in extracting features from RGB images and SVM is used as an alternative classifier to a softmax layer to enhance the classification ability. A dataset containing images of cracks from masonry structures was created using a digital camera and an unmanned aerial vehicle from historical sites. The images were used for training and validating the proposed system. It is shown that the combined CNN and SVM model performs better than the model using CNN alone with the detection accuracy of approximately 86% in the validation images. It is also shown that the system can be used to detect cracks automatically for the images of masonry structures, which is useful for inspection of heritage structures.

Keywords –

Convolutional Neural Network; Support Vector Machine; Masonry structures; Crack detection, Computer vision

1 Introduction

Maintenance and condition assessment of historic structures are vital for Thailand as they are the country's cultural heritage. Cracks are considered to be the primary concern for the durability and safety of masonry structures. Therefore, crack detection is very important for the maintenance of structures and must be detected at the earliest stage to avoid unwanted situations, such as damage to buildings, or the collapse of structure due to severe cracks.

Visual inspection is a common procedure that is used in the examination and assessment of the current state of historical buildings. However, this procedure is laborious and time-consuming as it requires the experience and specialised knowledge of inspectors to assess structural conditions based on the visual appearance of structures. Furthermore, the procedure cannot be conducted frequently due to high labor cost and prone to human-error, and often the sites cannot be easily inspected due to inaccessibility. Figure 1 shows an example picture of a temple in Ayutthaya province in Thailand, where the top of the stupa is extremely high and is not accessible for human inspection. Figure 2 shows a picture of the Chapel viaduct, which is a masonry structure, and cracks and other damages in the structures need to be detected and monitored. In this paper, we propose an image-based crack detection system to inspect these masonry structures. Figure 3 shows example images of cracks that are found from various locations around the temple and the viaduct.

Cracks in images can be detected by either using techniques related to handcrafted feature extraction or by using automatic feature learning, i.e. a deep learning, which is a technique proposed in this paper. Crack detection systems based on handcrafted feature extraction techniques generally consist of two main steps. The first step is to extract relevant features, such as edges [1], features based on a percolation model [3-4] and multi-features [6] from input images. Then, in the second step, classifiers such as Support Vector Machines (SVM) [5] and Neural Networks [8] are trained to determine if extracted features are crack or non-crack. Since cracks can have various types and forms, this makes the features extraction task difficult. Therefore, deep learning algorithms are better in learning features automatically from raw images and complex high-level features can be built from low level features [12]. Deep learning has been applied in many problem as it proves to be a better technique in the classification task [10].

In this paper, we propose an image-based crack detection algorithm, using convolutional neural network (CNN) as a feature extractor and SVM as a classifier. The image data has been collected using an Unmanned Aerial Vehicle (UAV) and a handheld DSLR camera from heritage masonry structures in Thailand and from a masonry bridge in United Kingdom as shown in Figure 1 and 2. The rest of the paper is organized as follows, Section 2 presents related works about automatic crack detection. Section 3 and 4 describe the methodology of the proposed system and experiments. Discussion and conclusion are drawn in Section 5 and 6.

Figure 1: A masory structure from Ayutthaya, Thailand, which is inaccesible for manual inspection. Hence, images are acquired using a drone.

Figure 2: The Chapel viaduct, Essex, United Kingdom, a masonry structure many visible damages.

Figure 3 :Sample images of cracks in masonry structures

2 Related Works

Many automatic crack detection systems are based on extracting handcrafted features. Abdel-Qader et. al. [1] applied four different edge detection techniques, i.e. Fast Haar Transform (FHT), Fast Fourier Transform, Sobel and Canny detectors for concrete bridges. The FHT was the best one among other detectors in the study. The limitation of edge detection algorithms is generally due to noise. Liu et. al. [9] applied image intensity features and Support Vector Machine (SVM) for tunnel crack detection. This method is prone to error due to noise.

Prasanna et. al. [7] proposed a crack detection system based on histograms for a bridge deck. Principle

Component Analysis (PCA) techniques are used for automatic inspection for concrete bridge decks in [2]. Yamaguchi et. al. [3-4] applied a percolation model for crack detection in concrete surfaces. Fujita et. al. [12] proposed a concrete crack detection system for noisy data using different filters for preprocessing to remove noise, followed by probabilistic relaxation and adaptive thresholding for the detection of cracks. Similarly, Prasanna et. al. [6] used STRUM (Spatially Tuned Robust Multi-feature) classifier for automatic crack detection on concrete bridges. In Prasanna's work, the proposed system applied intensity-based and gradient-based features with the combinations of scale-space features as the crack features, which were then classified. They demonstrated that the efficiency of the STRUM classifier was better than other image-based approach for crack detection.

For different types of cracks and images containing noise, the techniques based on handcrafted features fail to perform. Hence, automatic feature extraction based on learning techniques such as deep learning can perform well when compared to the techniques based on handcrafted features. Zhang et. al. [11] applied deep convolutional neural network for road crack detection from images collected using a low cost smart phone. Cha et. al. [13] used deep convolutional neural network (DCNN) for automatic concrete crack detection and presented 98% accuracy. Ellenberg et. al. [14] discussed several algorithms, including percolation approach, fractal method and tensor voting for crack detection. The paper also conducted a study on masonry crack detection although the paper did not provide details on their results.

3 Methodology

The outline of the proposed system is shown in Figure 4. The proposed system consists of three modules. Firstly, images are acquired using a UAV and a DSLR camera, Then, images are classified by a crack detection system based on CNN as a feature extractor and SVM as a classifier. The results from the crack detection module can then be used to localize cracks in the final module. Each module in the proposed system is explained below.

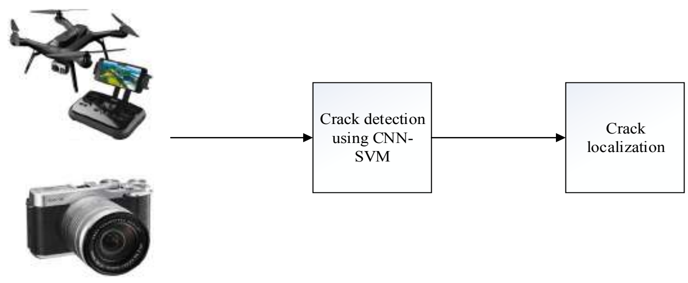

Figure 4: The outliine of the proposed methodology

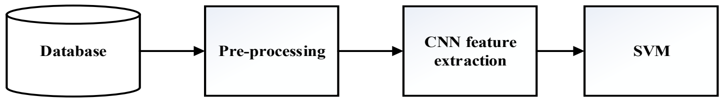

Figure 5: The outline of the proposed crack detection system.

3.1 Image acquisition

In recent years, UAVs have been utilized in surveying as an alternative to conventional surveying methods since they are faster, simpler and cheaper. UAVs can also be utilized to collect images for inspection as shown in this paper. We collected images from a stupa from Wat Chai Watthanaram, which is located in Ayutthaya in Thailand. The images were collected using a DJI Phantom 4 drone. The drone was programmed to fly around the stupa to collect images at two different heights. At the ground level, a DSLR camera were used to collect images of the stupa near the ground. Sample images taken from the drone are shown in Figure 6. As shown in this figure, the top of the stupa cannot be easily reach by human inspectors, and utilizing the drone to collect images around this area clearly provides great benefits for data collection.

In addition, with the collaboration from the Cambridge University team, more sample of masonry structures were also collected from the Chapel viaduct. This is a railway viaduct that crosses the River Colne in the Colne Valley in Essex, UK. The images were collected using a Sony DSLR camera from various locations around the viaduct. The sample images are shown in Figure 7.

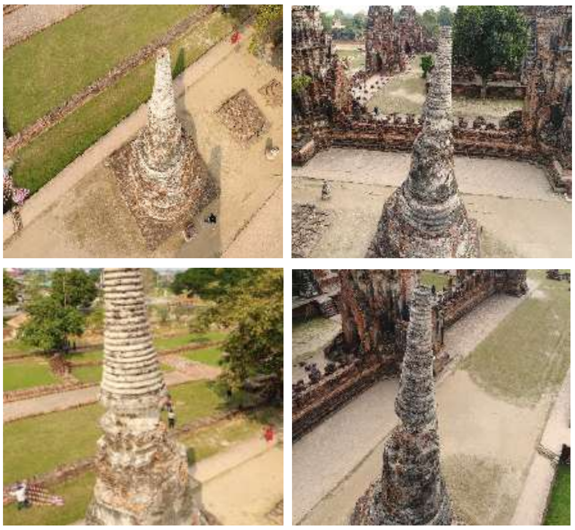

Figure 6: Sample images acquired using a UAV

Figure 7 :Samples images of the Chapel viaduct

The images collected using the drone were converted into patches of size 96x96 using a Matlab algorithm for training and classifying by CNN. Only patches belonging to masonry areas were selected and used for training, the patches containing surrounding objects (e.g. trees) were ignored. The total number of image patches used in this work were 6002, which were manually separated into cracks and non-cracks images. Out of all patches, 3162 patches were used for training and validation, and the remaining 2840 patches were used for testing the proposed system. The crack and non-crack patches were manually labelled as either 0 or 1. The example of crack and non-crack patches are shown in Figure 8 and 9.

Figure 8: An example of crack patches

Figure 9: An example of non-crack patches

3.2 Crack Detection

In the proposed crack detection system, we applied Convolutional Neural Network (CNN) as it has ability in solving many real-world problems efficiently. The architecture of CNN used in this paper is shown in Figure 10.

The multilevel deep feature extractor and a classifier are the two main tools of the CNN architecture. The role of multilevel deep feature extractor is to retrieve discriminant features from image pixel intensity values presented in the RGB colour channels and SVM is used as a classifier for the purpose of classification. In our proposed CNN architecture, Keras sequential model was used, which was composed of convolutional, activation and max pooling layers. The first convolutional layers consist of 32 filters of size 3x3 pixels as shown in Figure 10. After filtering, the max pooling operation was activated with a ratio of 2.

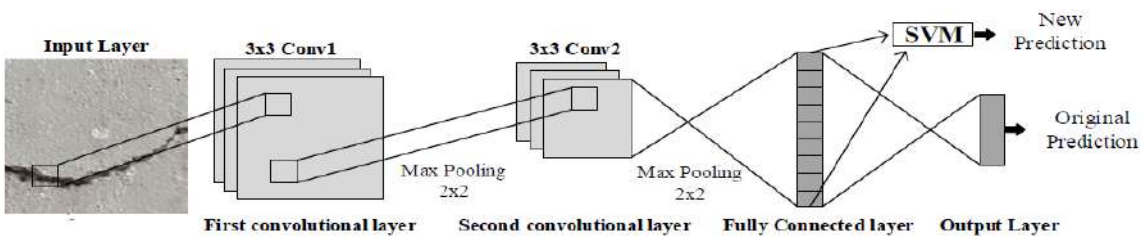

Figure 10: The architecture of CNN used in the proposed system

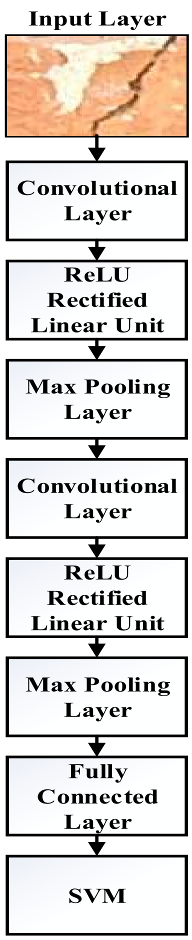

Figure 11: The architecture of CNN-SVM technique.

Figure 11 shows a more detail architecture of CNN used in this study. As shown in the figure, the key role of the convolutional layers is to detect the local connections of features from the previous layer. The output result of the feature maps is then passed to the activation layer ReLU. The max-pooling operation was used in the vision systems for two reasons, (1) to eliminate non-maximal values, which helps to reduce computation time for layers, and (2) to down-sample operations for 2x2 sub-regions to reduce the dimension of intermediate feature vectors .The filters are stacked together and fully connected layers can then be used in computing the class scores. In the proposed system, the output from the fully connected layer become the input feature vectors of size 2352 for the SVM classifier as depicted in Figure 10 and 11.

An SVM classifier was applied in the final stage of the proposed crack detection system. The SVM classifier was used to replace the softmax layer in CNN. The main objective in SVM is to find a hyperplane that separates the largest fraction of a labelled dataset for binary classification. The training data is a set of training samples pairs $\{(x_1, y_1), \ldots, (x_i, y_i)\}$, where x_i is the observation or input feature for the i^{th} sample and $y_i \in \{1, 0\}$ is the associated class label .The SVM classifier is the discriminant function that maps an input feature space x_i into a class label y_i. An interested reader is referred to read [16] for the detail of Support Vector Machines.

4 Experiments and Results

The evaluation of the proposed crack detection system was conducted on validation and testing datasets. The system was evaluated against our own ground truth data, which was manually labelled, to estimate inaccuracy that can occur from the proposed system. As mentioned in Section 3.1, a total of 6002 image patches were labelled either crack or non-crack patches in our experiment, 3162 patches were used in training and validation. The 2840 patches were used for testing. The Receiver Operating Characteristic curve (ROC) analysis, confusion matrix and classification report were used to evaluate the performance of the proposed system.

For SVM, the Radial Basis Function (RBF) was used as a kernel, hence a cross-validation technique was employed to obtained the optimal values for the kernel. Table 1 shows a parametric study for SVM, where a different combination of C and gamma values were tried in the validation dataset to obtain the maximum accuracy. As shown in the table, the best accuracy occurred when C = 4 and gamma = 1.

Table 1: Parametric study for SVM

C	gamma	Accuracy
1	0.5	0.770
1	1	0.72
2	1	0.72
3	1	0.73
4	1	0.73
5	1	0.71

The classification report and ROC curves were obtained based on the confusion matrix, which can be explained as shown in Table 2.

Table 2: Confusion matrix for class classification

Ground Truth Label	Predicted Label	
	Positive (Crack)	Negative (Non-crack)
Positive (Crack)	True Positive (TP)	False Negative (FN)
Negative (Non-crack)	False Positive (FP)	True Negative (TN)

The following equations are used for the classification analysis in the classification report.

$$Accuracy = \frac{TP + TN}{TP + TN + FP + FN} \quad (1)$$

$$Precision = \frac{TP}{TP + FP} \quad (2)$$

$$Recall = \frac{TP}{TP + FN} \quad (3)$$

$$F1score = \frac{2xPrecxRecall}{Prec + Recall} \quad (4)$$

We conducted experiment by comparing the results between the method with the CNN alone and the proposed system, where we combined CNN and SVM. Table 3 shows the results of the proposed crack detection system on the validation dataset. It can be seen that the combined method CNN-SVM offers the better accuracy of 85.94 than the CNN method with the accuracy of 82.94. Other metrics, including Precision, Recall and F1Score are also better for the CNN-SVM method.

Table 2 shows results on the testing dataset. From Table 2, it can be seen that, again, the CNN-SVM method is more accurate than the CNN method. The combined method improved the accuracy by 7.4%.

Table 3: Results of the proposed system on validation dataset

Method	Validation Accuracy	Precision	Recall	F1 score
CNN	82.94	0.83	0.71	0.74
CNN-SVM	85.94	0.84	0.79	0.79

Table 4 :Results of the proposed system on testing dataset

Method	Accuracy	Precision	Recall	F1 score
CNN	67.5	0.80	0.68	0.73
CNN-SVM	74.9	0.82	0.78	0.78

The ROC curve is shown in Figure 12. The ROC is a plot between True Positive Rate (TPR) and False Positive Rate (FPR) for the probabilities values of the output as computed by comparing predicted labels to ground truth values. TPR and FPR are calculated by the following equations,

$$TPR = \frac{TP}{TP + FN} \quad (5)$$

$$FPR = \frac{FP}{FP + TN} \quad (6)$$

It can be seen that, from Figure 12, the CNN-SVM method is better than the CNN method as the ROC curve of the CNN-SVM method appears to approach more towards the top left corner of the graph.

To localize cracks, some sample images were used to show the result. We divided an image into grid and each grid was classified by the proposed crack detection system. If the grid is classified as crack, we highlight the grid as red. Figure 13 shows an example of crack localization. It can be seen that, on the top pair of images, most crack regions are correctly identified, although some misclassification can still be observed. However, the bottom pair of images contains many false negative areas, which may be due to the proposed system was confused with the grout lines as cracks. The bottom pair of images also has many false negative, especially around the grout lines. This suggests that the inaccuracy of the system may be due to these regions as the appearance of the grout lines is similar to cracks. Nevertheless, with more training dataset, the result should improve.

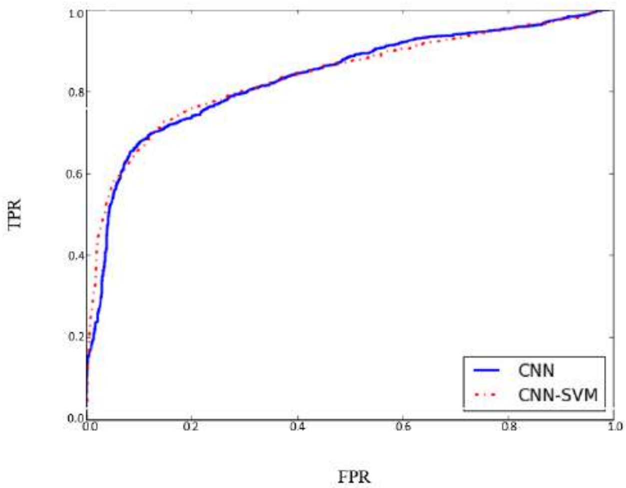

Figure 12: The ROC curves between the CNN technique, and the combined CNN-SVM model

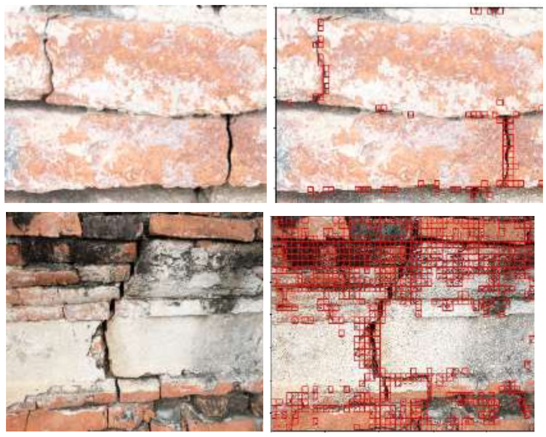

Figure 13: Crack localization of selected sample images

5 Discussion

The combined model, i.e. CNN-SVM, shows an increase in accuracy as shown in Table 3 and 4. It can be seen from the results that CNN-SVM is extremely good at extracting features and classification, although it relies heavily on good datasets. Good dataset can be difficult to create as they rely on human as a gold standard and the database may need to be verified by multiple sources. In our database, we have many non-crack patches but fewer crack patches. To overcome the problem with a small dataset, transfer learning and data augmentation may be applied.

Crack detection on masonry structures are difficult as cracks cannot be easily identified in images. Cracks in masonry structures have similar appearance to grout lines, which can be mistaken as cracks, unlike the problems of crack detection on simple concrete surface shown in previous studies. Therefore, it can be difficult to create good datasets since this type of scene, i.e. the masonry surface, is complex and confusing, even for human inspectors themselves. Nevertheless, good datasets are still required for any CNN systems.

6 Conclusion

From the experiments, we can conclude that the emerging class of technologies known as deep CNN offers the possibility of automatic crack detection for masonry structures. The combined techniques known as CNN-SVM has been implemented in this work to automatically classify image patches and to localize crack regions on masonry images for inspection. The proposed method is successfully applied to classify image in our validation and testing datasets, although with better and larger datasets, our system performance can be improved further.

We also concluded that the efficiency of the model can be further improved by fine tuning the CNN architecture and its parameters, such as adding more layers to CNN. From the results shown in this work, it can be concluded that the combined model, namely CNN and SVM performs better than the method using CNN alone. As shown in this work, CNN is best to be used as a feature extractor, and these features can be classified by any classifiers. In the future work, different classifiers can be explored to see if the accuracy of the system can be improved.

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Application of Machine Learning Technology for Construction Site

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Abstract –

Although several research studies on the application of machine learning to the construction field are actively underway, no study has yet been done on the areas where the application is primarily needed. Using the importance–performance analysis method, this paper identified the top five areas of construction sites where machine learning technology needs to be applied. Furthermore, it suggests application plans developed by using the Delphi method. The identified top five areas were unmanned tower crane, inspection of joint connections, prediction of construction safety accidents, operation of construction lift, layout of tower crane. This study is expected to facilitate the effective application of machine learning technology at construction sites in the future. Ultimately, the purpose of this study is to reduce waste of labor and the safety risks at construction sites through machine learning technologies.

Keywords –

Machine Learning; IPA method; Delphi method; Construction site

1 Introduction

In response to the reduced supply of functional labor, the increased demand for reduced construction times, and an increase in safety-related construction accidents, construction automation technologies are actively being developed. Artificial intelligence technology is a representative technology that can be used to realize construction automation. It was confirmed that the number of papers related to artificial intelligence in the field of construction in major journals increased from nine in 2000 to 50 in 2016 [1]. In particular, machine learning among artificial intelligence technologies is an effective way to respond to this trend. Much research related to machine learning is actively being carried out, such as construction accident prediction [2], analysis of construction equipment operation [3], and assumptions about the compressive strength of concrete [4]. However, it has not yet been properly identified which one of the various machine learning technologies is primarily needed to be applied for construction sites. Therefore, the purpose of this paper is to identify which elemental technologies are required on the construction site and to find those that need to be applied and developed first. Furthermore, the paper suggests approximate plans for the application of machine learning at construction sites. To achieve objective validity, experts in machine learning technology were consulted and a survey amongst field staff was conducted. First, a questionnaire was used to identify the areas of interest at construction sites that require urgent improvement. Alternative ways to improve those areas of interest using the proper machine learning technologies were suggested. The questionnaire surveyed the importance and satisfaction levels of specific elements of machine learning technologies that are considered to be applicable. In analyzing the results, the importance–performance analysis method (IPA) was used to identify the most urgent problems at construction sites.

To solve those problems, the particular problems that require improvement are presented with the appropriate machine learning skills using the Delphi method. Machine learning technologies such as artificial neural networks, support vector machines (SVMs), random forest, and genetic algorithms were selected as applicable methods to solve these problems.

The scope of the research included construction sites in and outside Korea, and includes the elements of construction work, such as construction safety, foundation work, and finishing work.

2 Literature review

2.1 Current study for application of machine learning in construction

As used in applications such as self-driving cars, drones and robots, artificial intelligence technology is an essential technology by which intelligent systems can overcome the performance limitations of traditional computing systems [5]. In particular, machine learning, one of the artificial intelligence technologies, enables the machine to directly evaluate a certain situation and take appropriate actions by collecting big data and learning from it on its own.

The application of machine learning technology in the construction field is already actively underway. As a result of analyzing articles published in major journals up to 2016, it has been established that the machine learning technologies used mostly in the construction field include artificial neural networks (50.8%), genetic algorithms (21.8%), composite models (16.3%), fuzzy theory (8.2%), and support vector machines (SVMs) (2.9%) [1].

Lee J et al. [6] suggested using machine learning technology in the analysis of reinforcement-bar images. In their study, a program for the analysis of reinforcement-bar images was separately realized using OTSU binarization through random forest and superpixel clustering. Park U et al. [7] constructed a selection model of retaining wall methods using a support vector machine, one of the machine learning technologies. As a result of its application in a real case, and with an accuracy rate of 93%, it has been proven that this particular machine learning technology can be used effectively in the construction field. Tixier AJ-P et al. [2] and Kim Y et al. [8] used machine learning technology not only to improve construction methods, but also to predict safety-related construction accidents. Kang I et al. [1] recently identified trends in the study of machine learning in the construction field by year, by category, by topic, and by technology. However, they failed to identify how certain elemental technologies were applied and the practical use of them.

Likewise, machine learning technologies are actively being studied in various areas of the construction field, but those technologies that are primarily needed have not yet been scientifically prioritized. In this paper, the elemental machine learning technologies primarily required in the construction field are identified and application plans are proposed.

2.2 Artificial neural network

An artificial neural network is a structure that has been modeled to imitate interactions among the components of the brain of a living creature. The biological brain consists of neurons that are connected to each other through synapses, and it solves problems by changing the degree of connections. Similarly, an artificial neural network also learns about solutions for certain problems by adjusting the weight between artificial neurons. Thus, it is easy to solve complex problems, since solutions can be learned not only from linear functions but also from nonlinear functions based on input variables [9].

2.3 Support vector machine

The support vector machine (SVM) is considered as one of the most robust and accurate methods among data mining algorithms [10]. Based on structural risk minimization, SVM creates a separating hyperplane that can divide multiple data types into two classes. SVM is originally an algorithm for the classification of binary data. Therefore, to distinguish between multiple data types in more than two classes, either the one-against-all (OAA) or pairwise method must be used. Because of the advantages of the SVM algorithm in solving nonlinear problems, it can be used at a construction site that has many variables.

2.4 Random forest

Random forest is an ensemble technique that overcame the shortcomings of decision trees by using bagging and random space methods. Decision trees vary greatly depending on the learning data and therefore it is difficult to use them in generalization [11]. However, random forest generates and learns multiple decision trees from the data. This characteristic allows users to avoid overfitting in the classification and enables more proper generalization than decision trees.

2.5 Clustering

Clustering is a one of the unsupervised learning methods that classifies data by creating criteria and sorting data itself by classifying data without any base information. Clustering is usually used for processing image data and can be more useful when used with deep-learning technology than when used independently. The most famous and simplest example of clustering is K-means clustering. The technology is widely used in various fields, including classification of movies or TV scenes, and clustering related to users of social networking services [12].

2.6 Genetic algorithm

Genetic algorithm is one of the techniques for stochastic search or learning and optimization. The algorithm is based on Charles Darwin's theory of survival of the fittest and Mendel's laws of genetics. The former is the theory that creatures that are well-adapted to nature survive but those that are not are eliminated. The latter is the law that the genetic characteristics of offspring are inherited from their parents [13]. Based on these characteristics, the genetic algorithm can be especially useful for optimization of various fields.

3 Method

3.1 Questionnaire development

Prior to conducting the questionnaire survey, six major journals of construction were used to define relevant categories for the questionnaire. The validity of each category was verified by two experts from the construction field. In this questionnaire survey, each category addresses a part of the construction field where it is considered necessary that machine learning technology must be applied. The number of categories for the questionnaire determined through this process was set at 12. The detailed contents of the categories are listed below in Table 1.

Table 1. Detailed categories of questionnaire survey

Categories	Division
Operation of construction lift	A
Layout of tower crane in high-rise building construction	B
Assumption about compressive strength of concrete	C
Counting the numbers of reinforcemet bar	D
Inspection of joint connections	E
Unmanned tower crane	F
Determination the lifting order between the tower cranes	G
Selection of retaining wall methods	H
Prediction of safety-related construction accidents	I
Forecast of deep excavation wall movement	J
Inspection for correct installation of the forms	K
Determination the time of procurement	L

In this study, the survey was conducted to establish the level of importance and performance of each category on a five-point scale. The number of participants in the survey was 30. Most of the participants were working for construction companies then and had experience in working at construction sites. Their average experience at construction sites was 12 years. The positions of the participants were broadly from employees to managers. The experience at construction sites and their assigned roles in their companies of the participants are presented in Table 2.

Table 2. Information about the questionnaire survey participants

Experience in construction site		Main tasks in companies	
Years	Number of participants	Tasks	Number of participants
~1	1	Construction	17
1~5	6	Office work	4
5~10	7	Quality control	4
10~20	11	Design	3
20~	5	Others	2

3.2 IPA method for prioritizing elements that need improvement

The IPA method is an easily-applied technique to measure the importance and performance for users of each surveyed category. Before using the IPA method, a survey is usually conducted that can check the importance and performance on a five-point or a seven-point scale. The survey results are then analyzed with an appropriate method and displayed on a four-quadrant grid. On the four-quadrant grid, the vertical axis indicates importance, and the horizontal axis indicates performance [14]. Note that the second quadrant includes the categories with high importance and low performance, which indicates where the primary improvements need to be made. The IPA method is highly applicable not only to marketing and the business field, but also to machinery, education, and even the construction field.

In this paper, each category of the IPA method consisted of an area that needs improvement through the introduction of machine learning technology. These categories were selected through consultation with experts from the construction field and experts in the field of artificial intelligence technology. The reason for using the IPA method was that it was impossible to deal with everything that needed improvement and the categories had to be prioritized by using an appropriate method.

4 Results and Discussion

4.1 Analysis of IPA results

The results of the questionnaire survey of each category are outlined in Table 3. To easily identify the priority of categories that need improvement, the contents of Table 3 are displayed on the four-quadrant grid as shown in Figure 1.

Table 3. Average value of importance-performance by category

Category	Importance	Performance	Category	Importance	Performance
A	3.800	2.400	G	3.833	2.567
B	4.267	2.767	H	4.200	2.900
C	4.033	2.733	I	4.167	2.600
D	3.767	2.533	J	4.067	2.900
E	4.167	2.600	K	4.033	2.667
F	3.800	2.000	L	3.700	2.400

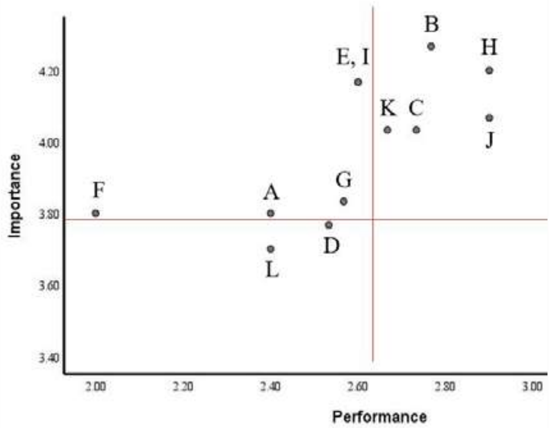

Fig 1. The values of importance-performance displayed on the four-quadrant grid

As shown in Figure 1, categories A, E, F, G, and I are located on the second quadrant. It means that these are the primary categories that need to be improved. However, the importance/performance values of the categories do not correspond exactly to Figure 1. To identify the top five categories easily, their importance/performance values were displayed as shown in Table 4. This study suggests application plans of machine learning technologies for construction sites only for these top five categories.

Table 4. Top five of categories that have the highest importance/performance values

Categories	Importance/performance value
Unmanned tower crane	1.9000
Inspection of joint connections	1.6026
Prediction of construction safety accidents	1.6026
Operation of construction lift	1.5833
Layout of tower crane in high-rise building construction	1.5422

4.2 Application plans using the Delphi method

To develop application plans for machine learning technology for the top five categories, two consultations with a group of four experts in machine learning technology were conducted. The following are proposed application plans using the Delphi method.

4.2.1 Unmanned tower crane

The tower crane is a very important piece of lifting equipment that can make or break construction work, especially in high-rise building construction [15]. It means expenses and the duration of the construction work can vary depending on the ability of the tower crane operator. Moreover, operating the tower crane is very dangerous work for the tower crane operator. Therefore, the commercialization of unmanned cranes is essential for construction sites. There are several elemental technologies for the development of unmanned cranes.

First, voice recognition technology is needed. When a person gives orders through a radio, the unmanned crane should recognize the orders and act on them. To recognize voice, the sound waves should be learned. Because of the difference in the waveforms of sounds among people for any one command, several similar waveforms should be learned as shown in Figure 2.

The waveforms are saved as coordinates. Later, when a person gives an order through the radio, the unmanned crane can find similar coordinates and act on the order by itself. In this procedure, classification technology such as clustering can be applied. This technology can increase the accuracy of voice recognition on noisy construction sites.

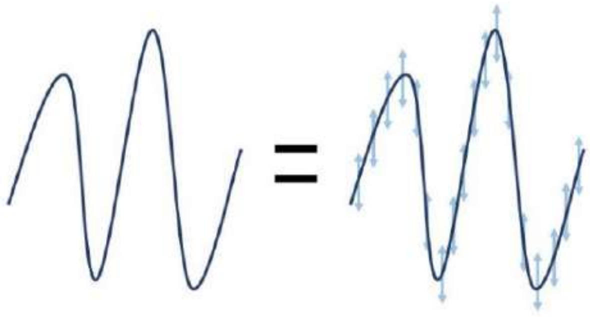

Fig 2. Original waveform and similar waveforms of voice

Second, location recognition technology is needed. When there are several cranes, the movements and distances between the cranes should be perceived by each unmanned tower crane, as the tower cranes may collide with each other while moving. This problem can be solved using global positioning system technology.

Third, material identification technology is needed to enable the tower crane to stop exactly where hoisting of the material is needed. In this case, using sensors to identify material is a more appropriate method to use than machine learning.

Proper combination of these three technologies could facilitate the development of the unmanned crane.

4.2.2 Inspection of joint connections

Construction work on joint connections requires special care and inspections on these areas are not easy. In particular, if a building consists of reinforced concrete, it is also necessary to ensure that the steel is distributed properly, as intended. Since the inspections are carried out by inspectors, there is a risk of incorrect inspections and a waste of labor. Therefore, if a technology can be developed to take a photograph of the joint connections and automatically compare it to a drawing, these problems can be solved.

For such comparisons, image classification technology is needed. Among the machine learning technologies, random forests and superpixel clustering are appropriate methods for image classification. Before image classification can be done, a technology to capture internal images of reinforced concrete, such as x-ray or MRI, is needed. Then, many images of reinforced concrete need to be learned to determine which pixel corresponds to which area. These data values make up many decision trees of the random forest. Superpixel clustering is used for separating pixels in different areas. Combined with the random forest, it can be used to correct a pixel that is incorrectly classified. The overall procedure of image classification is shown in Figure 3.

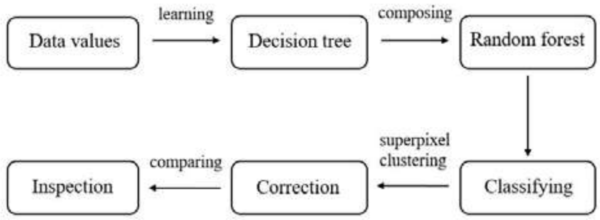

Fig 3. Overall procedure of image classification for inspection

Through this application plan, autonomous inspection of the joint connections can be done. This application plan was based on the work of Lee J et al [6].

4.2.3 Prediction of safety-related construction accidents

Safety-related construction accidents should be prevented by taking into consideration the varying and dynamic natures of construction sites [8]. Therefore, notifying workers in a timely manner of potential accidents that are most likely to happen would be very helpful to prevent such safety-related construction accidents. There are many variables at construction sites, such as types of work in progress, weather, and location. Proper prediction of safety-related construction accidents can be achieved by compiling several variables.

To predict safety-related construction accidents, the artificial neural network is useful, as is shown in Figure 4.

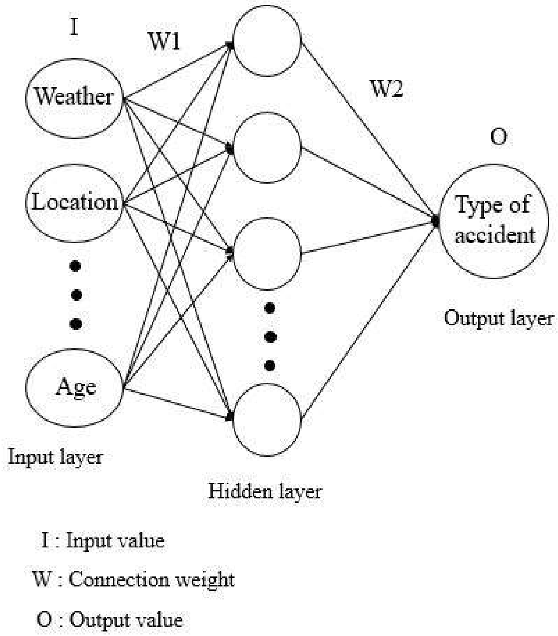

Fig 4. A structure of the artificial neural network

The variables that can affect construction safety are input values. Output values are the types of accidents, such as falling, crashing, and being hit by machines or objects. First of all, to build a model of an artificial neural network, large volumes of data from real cases of safety-related construction accidents should be learned. Then, using proper learning methods, such as error back-propagation, the connection weight for each node is determined. If input values are entered later, the connection weights are multiplied to determine the appropriate output value that is the most probable safety-related construction accident. In this way, the workers can be notified daily of the most probable safety-related construction accidents to happen. Detailed work on this topic was done by Kim Y et al [8].

4.2.4 Operation of construction lift

As more high-rise buildings are being built, the types and volume of materials that need to be lifted are increasing. Thus, the lifting plan of construction lifts is becoming increasingly important to increase efficiency of the construction work [16]. However, the decision-maker for the lifting plans faces an uncertain situation that can result in inaccurate prediction and definition of the various variables in dynamic construction sites [17]. Therefore, development of smart construction lifts that can operate themselves efficiently by referring to a schedule of construction and current situation, is needed.

The smart construction lift needs a combination of several functions. When calling the lift from a specific floor, the current loaded weight and the weight to be loaded should be considered. If the weight to be loaded will result in the total loaded weight exceeding the capacity of the lift, the lift should not answer the call. Furthermore, the lift should recognize the construction schedule by itself. If a task on a critical path is scheduled, the lift must always be waiting to execute the task. These functions of the construction lift can be realized using logical algorithms.

In addition, the ability of the lift to self-zone in context by itself is needed. The construction lift is similar to an elevator, but the number of floors it runs varies as the construction work progresses. To realize the function of self-zoning, it is more efficient to reflect on the latest data than on data of the remote past. Therefore, a recurrent neural network (RNN) that can handle time series data, is useful. RNN can further reflect the latest situation, by placing a higher connection weight on the latest time series data and forgetting the data of the remote past. In this case, the input values are information about the operation of the lift such as the number, time of driving, starting floor, and arrival floor. By learning large volumes of data about this information, the construction lifts can decide about running zones by themselves. The result of zoning the construction lift is shown as the output value. A combination of this machine learning technology and logical algorithms can realize the development of the smart construction lift.

4.2.5 Layout of tower crane in high-rise building construction

The importance of the tower crane was mentioned in Section 4.2.1. Not only the ability of the tower crane operator, but also the model, location, and number of tower cranes can have a significant influence on construction expenses and time. In particular, for high-rise building construction, the layout of tower cranes should be done by systematic calculation, not by human intuition.

In this category, the genetic algorithm is the proper method for optimization. To use the genetic algorithm, the function and the output variable of it must be determined. Using an advanced type of tower crane and a large number of tower cranes can shorten construction duration, but it can increase the daily rental fee of the tower cranes. Based on this principle, the output variable of the function was set to the total rental fee. It can be calculated from multiplying the daily rental fee and the rental duration for each tower crane. The input variables are the number, location, and model of the tower crane. A diagram of the optimization is shown in Figure 5. Next, the construction site should be displayed on a three-dimensional coordinate system. Each part of the tower crane should be displayed as well, as shown in Figure 6.

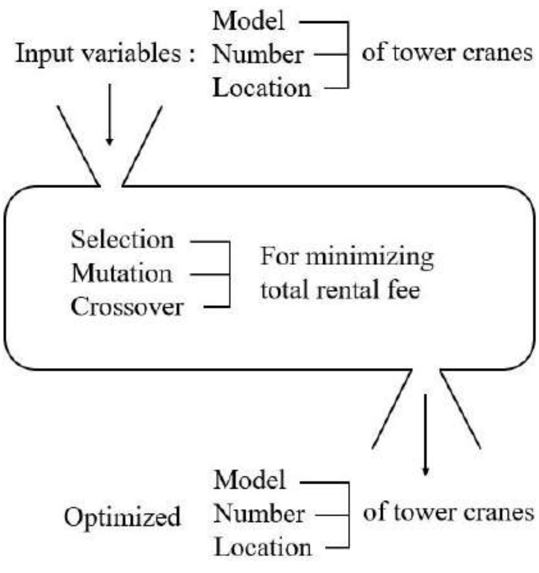

Fig 5. A diagram of the optimization

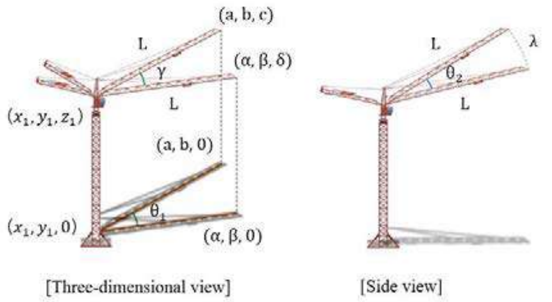

Fig 6. Images of tower crane displayed on three-dimensional coordinate systems

In Figure 6, $(\alpha, \beta, 0)$ is the location of the stock yard, (a, b, 0) is the location of the place where the material must be put down, and L is the length of a jib boom that varies depending on the model of the tower crane. Using appropriate functions, the distance that the tower crane should move can be calculated. Then, dividing the total distance by the operating speed of the tower crane, the rental duration can be calculated. The daily rental fee of a tower crane depends on the model of the tower crane.

The genetic algorithm automatically calculates the minimized total rental cost by changing the number, location, and model of the tower crane. In this way, the number, locations, and models of the tower cranes that will minimize the total cost can be obtained.

5 Conclusion

In this paper, the parts of the construction field that primarily need improvement were identified from the results of a questionnaire survey and the IPA method. Furthermore, using the Delphi method, improvement plans with machine learning technologies were suggested.

The results of the IPA method showed that the areas in the construction field that need urgent improvement are varied, and include unmanned tower cranes, inspection of construction, safety-related construction accidents, operation of construction lifts, and layout of tower cranes. It means that even though various research studies are actively underway to address problems in the construction field, many areas still exist that need further improvement.

This study will be used for the effective application of machine learning at construction sites by prioritization categories. Ultimately, it is expected to contribute to the construction field by facilitating more economical and safer construction sites through minimizing unnecessary waste of labor at construction sites. However, there are still additional areas to be examined in future studies. Above all, the proposed application plans of machine learning technologies for construction sites in this paper were too sketchy. Detailed plans for application and materialization of models for each category have not yet been proposed. Therefore, in a future study, the specific model for each of the top five categories that need urgent improvements should be developed using machine learning technologies. Furthermore, the effectiveness of the specific models should be properly verified.

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An accident notification system in concrete pouring using sound analysis

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Abstract –

In this study, a sound analysis-based detection and reporting system for accidents that occur during concrete pouring is proposed. First, the process of the existing monitoring system was examined and problems were noted, and studies and technical approaches to sound analysis were analyzed. Pouring sound samples were then collected from construction sites, the frequencies and patterns were identified, and accident sound patterns were created by superimposing leakage and other noise onto pouring sound samples. Finally, logic and an algorithm to identify accidents were proposed based on the results of patterns retrieved from the above datasets. In the future, it is expected that accident notification systems using the sound analysis proposed in this study will be useful not only for the prevention of accidents but also for safety management throughout construction sites in general.

Keywords –

Sound analysis; Accident notification; Concrete pouring

1 Introduction

1.1 Background and purpose

Accidents due to the collapse of forms and struts occur frequently while concrete is being poured. It is necessary to monitor the status of both the inside and outside of the concrete and formwork during pouring because concrete leaks due to formwork collapse pose a great threat to the quality of a structure as well as human and material loss during the project.

Direct, manual inspection by a project manager is the best case scenario, but condition management of formwork is typically performed using surveillance cameras and measuring sensors due to the unpredictable nature of pouring sites and safety issues. However, surveillance cameras cover a limited range of vision and require numerous installations in order to monitor the project area. Moreover, the measuring sensors require attachment at each formwork and are not economical. For that reason, constructing a monitoring system that covers a wide construction area economically is necessary.

1.2 Method of research

In this study, sound analysis-based detection and a reporting system for accidents during concrete pouring are proposed. First, the process of the existing monitoring system was examined and problems were noted, and studies and technical approaches to sound analysis-based monitoring systems in the construction industry were analyzed. Pouring sound samples were then collected from construction sites, the frequencies and patterns were identified, and accident sound patterns were created by superimposing leakage and formwork rupturing sound patterns onto pouring sound samples. Finally, logic and an algorithm to identify accidents were proposed based on the analyzed sound patterns retrieved from the above datasets.

2 Literature review

Sound is a wave transmitted by the vibration of an object, and an accident may be detected using the sound pattern of a unique frequency. Women scream at a frequency of 1,000–2,000 Hz, while men scream at a frequency of 500–1,500 Hz. Studies using the frequency and pattern differences of sound have been performed in many different areas.

Existing studies using speech analysis are mainly conducted in humanities by analyzing the characteristics of rhyme change, intonation, and the rate of accentuation. The biomedical field aims to develop a medical system for laryngeal cancer detection and voice therapy. In the field of information and communication, techniques for matching the facial expression and voice of a character in an animated game are being developed. This is also seen in artificial intelligences such as Siri in the form of speech recognition. It may be used to detect a situation around a car, identify diseases and anomalies through the cries of livestock, and determine whether a person is the guilty party during the investigation of a crime. Speech analysis technology has also been applied to disaster response by judging human emotions or reactions.

Figure 1. Sound analysis of vehicle road[10]

Figure 1 shows an analysis of sound in an intersection. Though it is typically in the frequency range of 30–40 dB and 5,000 Hz or less, the sound of a skid occurs in the range of 1 kHz–3 kHz[10]. An accident notification system for tunnels is being developed using the frequency differences taken from the road, as above. An automatic accident detection system in the transportation sector installs CCTV in the designated area and analyzes the data in real time to automatically detect an accident in the tunnel while also providing information for the prevention of secondary accidents [3][4]. However, since this study is applied to a tunnel, which is a linear space, its application to a construction site in a three-dimensional space is limited.

Studies for detecting accidents have been steadily carried out in the field of construction. In recent years, many studies have monitored risk situations in real time using miniaturized equipment. In an existing study on accident monitoring using advanced equipment, real-time monitoring based on USN was performed with various measurement sensors (ultrasonic, load, slope) in formwork construction [6][9]. However, there are limitations with installing measurement sensors at a construction site, and there are economic problems regarding their application to a large-scale construction site.

A landslide monitoring system in the civil engineering field detects the change in water temperature with a temperature meter and analyzes the sound when the ground is pushed out to predict risk in advance. However, since it is necessary to perforate the ground and detect the accident sound in a state where external noise is blocked after perforation, it is difficult to apply due to the characteristics of the construction site since such a wide variety of sounds are generated. Studies monitoring the work status and productivity of heavy equipment through sound analysis seem to have improved the problems of monitoring through the attachment of existing sensors [1][2]. However, since heavy equipment monitoring only analyzes single machine activity at a distance from external noise, sound analysis is not performed for the construction site.

An accident detection system that analyzes the frequency and pattern of the sound can detect a wide range if it is installed at a single point rather than attached to individual members. Therefore, it can be combined with noise management in the construction site in an economical and efficient fashion.

3 An accident notification system

3.1 The process of accident notification based on sound analysis

It was found that most of the causes of collapse occurred while concrete was being poured. Therefore, it is necessary to understand the accidents that may occur during concrete pouring and to propose a process to detect and respond to these accidents.

While concrete is being poured, the form or the shore may break down due to the side pressure of the concrete, resulting in loss of life or material damage. Even if there is no collapse at the construction site, if a gap is created due to the weight, a concrete leakage accident will affect the structural quality of the building.

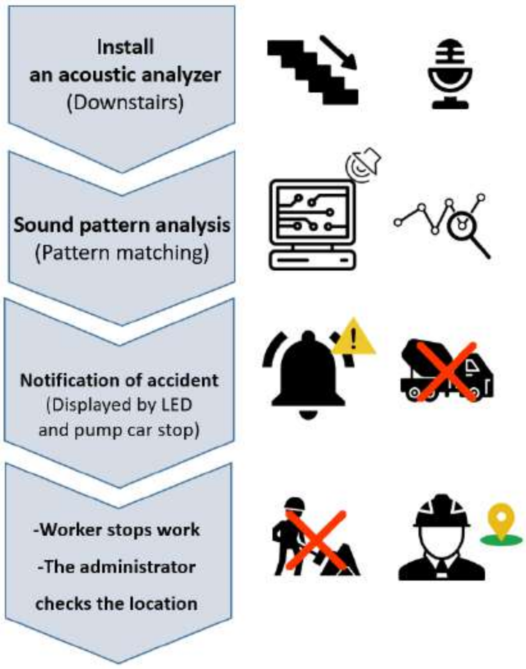

Figure 2. Accident notification process

Accidents that occur while concrete is being poured require quick action, but this is generally not possible. The problem with accidents is that when concrete is being poured, an accident in the lower layer goes completely unnoticed by those pouring concrete in the upper layer. In order to solve these problems, we propose a process to detect an unexpected situation while monitoring the downstairs situation through sound analysis during concrete pouring

First, a portable sound analyzer is installed under the concrete pouring layer. In the next step, the sound collected by the sound analyzer is sent to the server in real time. When a pattern that is similar to previously collected accident sounds is detected by the server, the installer's LED indicator warns of danger. When this sign is displayed, the pump car automatically stops and the worker is forced to stop as well. The administrator knows that the sound is coming from the server, finds the exact location, and takes action.

3.2 Sound analysis in concrete pouring

A A basic experiment was conducted to propose an accident detection process using sound analysis. Before the prototype of the portable sound analyzer was developed, a basic experiment was conducted to determine if it would be possible to distinguish between noise and accident sounds at a construction site.

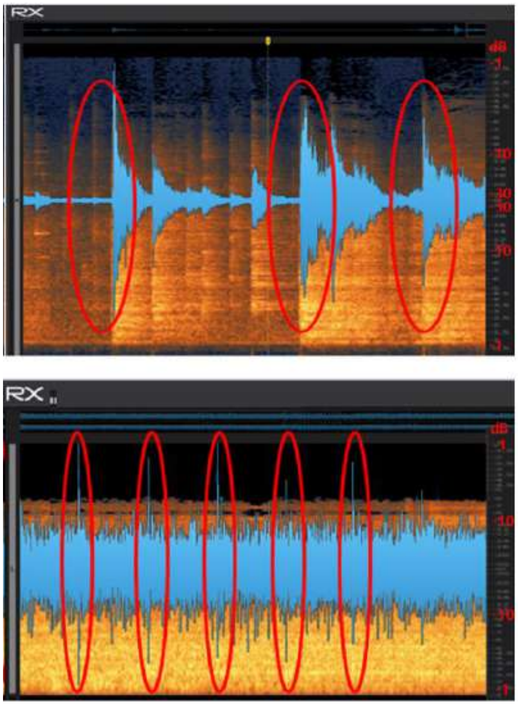

Figure 3. Sound analysis of concrete pouring

The upper picture in Figure 3 shows the analysis of the pattern created by generating impact noise among the noise of a general construction site. In the lower part of Figure 3, the pattern of the impact and plosive sounds during concrete pouring were analyzed. It can be seen that the upper picture clearly distinguishes the impact sound. High impact sounds and plosives are clearly visible in decibels because of the low ambient noise.

In the lower picture, a very loud noise was generated during concrete pouring. At the time of direct recording, the putting noise was too large to check other sounds with the ear. However, frequency analysis showed that the impact sound and the plosive sound were distinguishable by their unique pattern and size even in a loud noise situation. It was confirmed that the impact noise and the plosive sound have different threshold values from general noise, as found in previous studies that classify work noise at the construction site. It was judged to be possible to use sound analysis monitoring in the concrete pouring section.

3.3 An algorithm to determine an accident

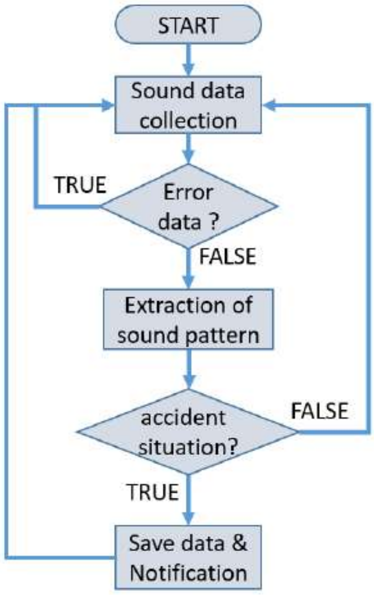

Figure 4. An accident detection process

An accident detection process based on data analysis using an sound collector was designed. Analog signals of accidental sounds and various noises in the field were digitized and converted into data. The more data is collected by applying the Big Data Analysis Theory, the higher the accuracy of the judgment algorithm. The algorithm works by probing and filtering the data collected, generating an accident sound data pattern interval, and examining the similarity between the real time sound data and the accident sound pattern. Data collection and filtering implement logic to filter error data because there is the possibility of collecting noise and error data. The similarity between the generated accident section pattern information and the currently collected sound pattern is examined, and when the value of the currently collected sound deviates from the threshold value, it is judged to be an out-of-sight condition.

4 Conclusion and Future research

This study investigates the current status of sound analysis research through literature review, and a process for an accident notification system based on sound analysis was proposed. Through a basic experiment in which the system was applied, the noise pattern was analyzed at a concrete pouring site and the validity of the system's application was confirmed.

A sound analysis-based accident detection system is a field of interest and research in transportation. So far, accident detection has been dependent on CCTV, but the present limitations of image reading have been reached. However, it is possible to identify and prevent many accidents using the immediate and wide range advantages of sound.

The following is the future directions for this study's sound analysis. First, a significant amount of sound data is required to apply an accident notification system using sound analysis in the field. There is also a need for data not only regarding the mechanical sounds and noise of a construction site but also of actual accident sounds. To design a program using a Neural Network or Deep Learning, accuracy is improved when many data points are collected. Collecting ample noise and accident sound data through case studies at various sites will contribute to the detection rate of the system in the future.

In addition, it is necessary to know the positioning of the sound's source. According to the patent registered by Samsung Electronics, each of the input sound source signals inputted through two or more microphones are combined to generate output signals, and the generated microphone output signals are calculated. The distance to the sound source may then be calculated using the distance between the calculation result and the frequency of the input sound source signal. Using this technique, the system can create a map of the source and determine the direction and distance of the source. When applied to accident monitoring, an accurate location for accident sound in the field can be obtained.

An accident notification system based on sound analysis will increase the accident detection rate by fusing various sensors, deep-running technology, and wireless network technology. In addition, accurate positioning and the immediate response of the system will contribute greatly to the field of safety management.

Acknowledgement

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BIM- and Mobile-Based System for Supporting Facility Maintenance Management

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Abstract –

Facility maintenance tasks require extensive historical data and information to be stored, retrieved and managed. Although several mobile-based devices have been proposed to access the maintenance information from three-dimension (3D) building information model (BIM) environment, these devices are deficient in simultaneously updating the maintenance information both in the field and the BIM. This study proposes a BIM- and mobile-based system that integrates BIM model, MySQL database, Microsoft Access database, and Android App modules for supporting facility maintenance management. The Android App module consists of the functions of 3D visualization, information inquiry, and view/edit maintenance work orders. While MySQL stores all the BIM information and work order databases, the manager can then update the BIM model. Allowing to update maintenance information in the BIM model in a cloud environment improved the existing relevant systems. Thus, by updating all the information in a cloud environment, it can then update the maintenance information simultaneously both in the field and the BIM with simple mobile-based devices.

In this study, it applied BIM-and Mobile-Based System for Supporting Facility Maintenance Management on a case project. In this project, it demonstrated how this system worked in a project. The results of the case project show that the maintainers in the project can immediately update the latest information and so reduce not only the time that takes but also the potential mistakes that may happen. To sum up, the efficiency of Maintenance Management boosted significantly.

Keywords –

Building information modeling; Facility maintenance management; Mobile devise; Android App.

1 Introduction

Considering the importance of building maintenance and a rise in BIM technology all over the world, many are paying more attention towards the study of maintenance management systems. A NIST study suggested that by improving interoperability and efficiency during facility operation and maintenance, a total of $15.8 billion annual cost could be significantly reduced [1]. In order to have a successful facility management (FM), managing information about facilities will be a major contribute [2].

Recently, building information model (BIM) have been a trending topic regarding the implementation and potential applications of BIM into the whole building lifecycle [3]. More importantly, BIM is increasingly considered as an Information Technology (IT)-enabled approach that allows design integrity, virtual prototyping, simulations, distributed access, retrieval and maintenance of the building data [4]. With the vast amount of information in BIM model, intra-disciplinary collaboration and multi-disciplinary collaborations will be needed to be able to efficiently utilize these information [5].

Currently, to develop a BIM-based maintenance management system, several mechanisms must be present. Frist, a BIM-based 3D model is developed using commercial BIM software (such as Bentley MicroStation or Autodesk Revit). Second, information in the BIM model will need to be exported and stored externally, since information could not be retrieved straight from the BIM model file format. Third, a maintenance management system developed on a selected platform (such as website based, API based, or mobile based) for users to retrieve information.

However, the current maintenance management systems are limited in that they do not fully integrate BIM into the maintenance management system. That is, other systems utilize the information exported from BIM model as if it is an independent entity from the BIM model. Though this allows a much better flexibility with the usage of information, such as 3 inserting or deleting information, but it doesn't fully tackle the problem of information exchange in BIM, since it lacks the information exchange from the maintenance management back to the BIM model.

To improve the BIM's integration with maintenance management systems, this work develops a maintenance management system that enables information to be synchronized from the management system and BIM model. The proposed system processes the information in different way. By separating the model and information to two, the proposed system can then apply on mobile computing, and for the information, it will be processed and stored in the cloud database. Applying mobile computing and cloud database technology into the system allows instant information sharing and retrieving.

2 Review of Current Studies

This section reviews current studies of maintenance management systems that address issues regarding building maintenance management. Previous researches have tried several ways of integrating BIM with maintenance management systems and had come up with some very interesting results. Unfortunately, information exchange between software still remains a crucial issue when it comes to BIM based maintenance management systems. Many provided methods to link information, once it had been exported out, but rarely talked about how to import information back into BIM model. It should be noted that this research believes BIM model collects and holds vital information throughout the building lifecycle, and that it should continue to do so when used in operation and maintenance phase.

2.1 Building Maintenance Management

To define the term building maintenance, according to Seeley (1976) [6] building maintenance is work undertaken in order to keep, restore or improve every part of a building, its services and surrounds, to a currently accepted standard, and to sustain the utility and value of the building.

While others proposed a list of objectives to define building maintenance, as listed below [7].

- To ensure that the buildings and their associated services are in a safe condition;
- To ensure that the buildings are fit for use;
- To ensure that the condition of the building meets all statutory requirements;
- To carry out the maintenance work necessary to maintain the value of the physical assets of the building stock
- To carry out the work necessary to maintain the quality of the building.

In maintaining a building, there are usually several strategic options available to management, and many alternative decisions to be considered. There is, for example, the possibility of reducing the demand for maintenance by addressing the actual cause of failure and identifying its consequences. Therefore, we could also define building maintenance by dividing it into three strategies [8]: Reactive/Corrective Maintenance.

Corrective maintenance is the simplest type of maintenance, where a component of a building is used until it breaks down, meaning that the component no longer performs its required function. When this happens we perform corrective maintenance to repair or replace this broken component to restore the component to its original functioning state. This type of strategy is also referred to as reactive maintenance because it happens when a component had already broken down, in which the maintenance crew then reacts to this failure in building component. Even though corrective maintenance can be expensive, it is still an important management strategy because it is how we collect vital predictive information. Corrective maintenance can be extremely expensive because of two reasons:

1. The failure of the component can cause large amount of consequential damage to other components in the building.
2. The failure of a component is unpredictable and may occur at a time when it's inconvenient to both the user and the maintaining authority.

2.2 BIM-based Maintenance Management System

Recently all over the world, scholars are starting to pay more attention towards the study of BIM-based management systems. Scholars are researching on how to integrate the cloud into BIM-based management systems, so in this section we would be reviewing what other scholars have achieved throughout the years First we'll review the study regarding using BIM to construct a building facility management system [9]. Second, Chuang (2011) [10] constructed a webpage providing 3D visualization while also showing construction progress. Third, Lin and Su (2013) [2] developed a maintenance management system through Navisworks API. Jian (2011) [9] constructed a BIM-based management system on a webpage, providing users the ability to search, insert, delete, and edit component information exported from Autodesk Revit. This system also utilizes the Autodesk browser plugin to provide users with 3D visualization of the BIM model through the constructed webpage. His research used ODBC export function to export information into Microsoft

SQL database, then by using ASP.NET to create webpages.

Lin and Su (2013) [2] believes that the performance of facility maintenance management can be enhanced by using web technology for information sharing and communication. They proposed quite an innovative system regarding BIM-based facility maintenance management. Unlike what other scholars had proposed, this research constructed a facility maintenance management system through Autodesk Navisworks API which enables the user to operate the 3D BIM model in Autodesk Navisworks while integrating cloud computing to retrieve maintenance related information

The main reason that the system they proposed is unique is because it stores all the information in an independent database, instead of storing the information in BIM model. In the management layer, the maintaining authority edits the BIM model and then export it into NWD file for Navisworks to read and open. When the user opens this read-only BIM model (NWD file), the system will start data mapping all the components in BIM model to all available information in FMM database. This means that all the crucial information regarding maintenance will be stored in the FMM database instead of the BIM model. The reason behind this setup is because the author believed that the amount of maintenance information stored will increase over time if all FMM pieces of information are recorded in the BIM model. Since BIM models cover a wealth of building information, central BIM models storage space should be reserved for crucial information, such as spatial information, facility ID and name of facility, facility location, and other critical information. In order to keep the system performance at an acceptable level, the information derived by other applications should be stored in an external location [2].

Though this is the most thorough system compared to others, the fact that it was constructed on Navisworks API still causes problems. This means that the user will need to use a tablet or light weighted notebook in order to actually use this system because it needs to be able to operate Autodesk Navisworks. In order to truly enhance and promote the benefits of cloud computing, a system that works on something more convenient, something that everyone would carry wherever they go need to be constructed.

2.3 Interoperability of BIM and Maintenance Management Systems

The main exchange format for BIM files is Industry Foundation Classes (IFCs). However, the initial problem with IFCs is that they are not intended to store and carry all relevant data for all multi-featured construction processes. Furthermore, not all relevant data can be structured in a single super schema [11]. Many BIM software provides IFC conversion when exporting files, but there are still some issues when implementing IFC which was stated in Redmond's research. For example, IFC information models use schemas represented in EXPRESS (data modelling language).

3 Proposed System

The key to developing the proposed system is to store and provide information indirectly from BIM model to the maintenance management system.

In this system, it consists of four parts: BIM model, MySQL database, Microsoft Access database, and Android App. The following sections provide detailed explanations of each part.

Figure 1 presents the framework of the proposed system; it shows the main relationship between four parts of the system and how the system cooperates with each other.

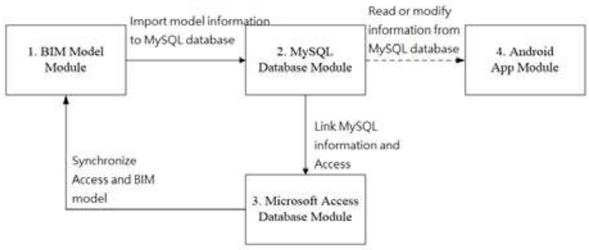

Figure 1. Framework of the System

As shown in figure 1, the proposed system divides the model and information into two, and links to two different parts, Microsoft Access Database (see section 3.3) and Android App (see section 3.4). Compare with other system, usually the information and model are unseparated, the proposed system can both read and modify the information on Android App devices.

3.1 BIM Model

Autodesk Revit is used to develop the BIM model owing to its popularity in Taiwan, and in case to implement the proposed system, a BIM model with level of detail (LOD) 300 is required.

A LOD 300 BIM model contains different objects such as columns, beams, walls, slabs, windows, and doors, along with these objects' information like sizes, shape, locations, orientation and geometric data (such as length, area, and volume). Also, non-geometric information/data (including the maintenance related data) are included in the 3D BIM objects.

To ensure this system work properly, some required fields in Autodesk Revit needs to be set up. The most crucial part of constructing a workable BIM model is to make sure the information required in the maintenance system exist in Revit as component's custom parameters, and that it is exactly identical as to the name we presented, since the android application will be retrieving information from that specific column. These parameters created in the BIM model are determined by interviews conducted with the maintenance unit and through the system proposed by Wang et al. (2013) [12].

These maintenances related shared parameters were created manually in Autodesk Revit 2014 and can be separated into four main information categories: maintenance company information, inspection information, component's property information, and historical maintenance information. These four categories consist of all the information that will be retrieving through our android application all of them would be crucial regarding the backend usage for queries in MySQL database, below are the detailed explanations of what information are included in each category.

3.2 MySQL Database

In the system, MySQL database management system is used to store all of our information that will be used by the simple mobile devises application. There are several advantages for using MySQL database, for it is supported by different computer operating systems and it is also very user-friendly. But the main reason is due to MySQL is an open source system, in which it is convenient in searching for other users' shared experience and any other related information that helps with solving problems. In this section it will highlight on the setup of MySQL database management system for model data to be exported to and stored in. It includes two procedures; First procedure includes a total of five steps for installing WAMP and configuring the system settings. Second procedure includes Creating and editing MySQL databases.

3.3 Microsoft Access Database

The proposed system used Microsoft Access to enable synchronization of model data in MySQL back to BIM model in Revit, in order to tackle the problem regarding the inability of interoperability between MySQL and Revit BIM Model, see figure 2.

As shown in figure 2, the information between BIM model and Access Database is a double-side path. Compare with traditional application of BIM, since traditional works as a one-way path, the proposed system can both read and rewrite the BIM information, which makes it possible for operators read and modify the information by their simple mobile devices immediately. Eventually, reduce the work time for transferring the information, and the potential mistakes that may happen.

Figure 2. Information flow from Access

3.4 Android App

In order to create a convenient yet user-friendly platform for interacting with the data stored in MySQL database, android operating system is applied to build an android application. Two reasons explain why android system is applied. First, android is the most common operating system nowadays. Second, it is easy to obtain for most of the people.

By developing an android application, the proposal aims to provide users with a more user-friendly platform in accessing data through the cloud. Any person with an android operating system mobile device would be able to open up this application and view or update the BIM information in MySQL database.

The main profit that Android app offer is convenience, and since AR (Augmented Reality) tech is imported in this app, users can view the model through AR by the markers. Compare with traditional 2 dimensional blueprint, viewing the model in AR makes it more intuitive for the users. About AR function, it will be fully introducing in section 4.1.

4 Application Selections of Android App

In the application, it consists of three different modules. First, 3D Model Visualization Module, providing users with the function to view the desired 3D model. Second, Information Inquiry Module, providing users with function to search for component information in four different ways while also providing instant updating capabilities regarding the information acquired. Last, Maintenance Work Orders Module, providing users with the function to generate maintenance work orders upon the selected components and to review previous generated maintenance work orders. Figure 3 shows the framework of application functions, and the following sections will introduce the three modules step by step in detail.

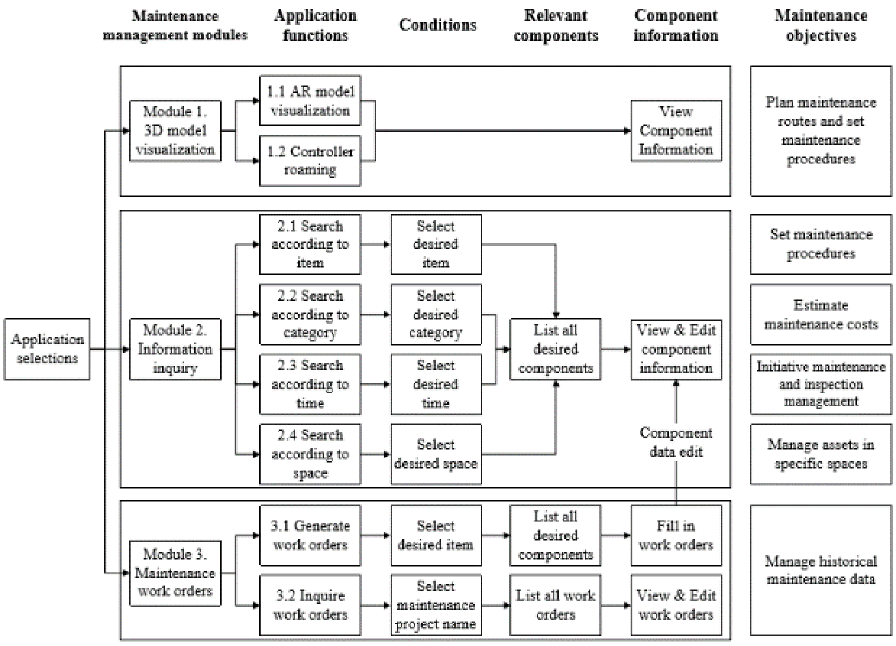

Figure 3. Framework of application function

4.1 3D Model Visualization Module

In 3D model visualization module, it can divide into three parts; 3D model, mobile screen, and QR code markers. 3D model's information is stored in MySQL database, and will be presented on mobile screen by scanning the QR code markers.

In this module it provides two types of unique functions; AR model visualization and controller roaming. Users are allowed to view 3D models created by Revit and stored in MySQL database through this module with AR technology or with controller roaming function. Both functions will be able to acquire information from MySQL database by pressing the component on the mobile screen, which is accomplished by querying the information through component element ID generated by Revit.

In the proposed system, both functions put emphasis on offering users a much more convenient operating environment. As figure 4 shown, users can view the information and model by scanning the AR markers. And for figure 5, it shows that the users can also use controller roaming function to travel around in the model by SMD. Before the proposed system, users had to carry lots of devices or papers for operation, however, the proposed system overcomes these inconveniences.

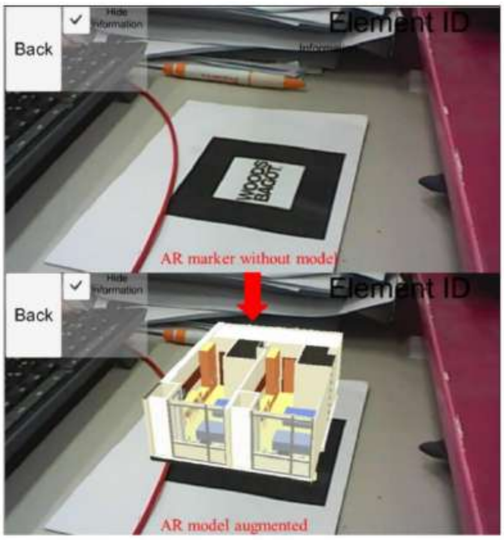

Figure 4. Markers and AR model augmented

Figure 5. Controller roaming function

4.2 Information Inquiry Module

There are two types of information that would be displayed in application. The first type of information is the basic information. It includes type name, component dimensions (width x height), serial number, location (space number), level, construction cost (direct cost), net width and height, room area, and material names.

This type of information is linked with the model directly, so the users are unable to modify the information by app (mobile devices), but are able to view the information.

The second type of information is the maintenance information in which the data are changeable by users. Including maintenance company name, person in charge, installation date, previous and next inspection date, previous maintenance cost, condition, general and detail category, all the information can be change on the app which the users are using.

Since the proposed system consists of two databases, it guarantees that the information changed from app can imported back to BIM model, compare with other systems, the BIM model and database are setted up together, people can only view the information yet are not able to modify it. For the second type of the information, which just mentioned, can then be able to change on the app in the proposed system.

To search for the desired component and its information, the information inquiry module provides two types of inquiry functions, namely, search according to item and category. Shown in Figure 6 and described as follows

Figure 6. Information Inquiry

- Search according to item: This function lists the six types of components in the spinner for users to choose. For example, if a user knows which door to search for, then the user would only need to choose the component type to be "door" and then search through all the doors to acquire information regarding the desired door, see Figure 7.
- Search according to category: This function provides two spinners for users to choose the general and detail category of maintenance work. General category is the architectural construction, and detail category includes maintenance work for masonry finishes, paint finishes, water leakage, doors and windows, room partitioning, metal materials, plumbing fixtures, and ceilings. These detail category describes several maintenance projects that components would undergo.

Figure 7. Demo of search according to item

4.3 Maintenance Work Orders Module

In Maintenance work orders module, it consists of two parts. The first part is Generate work orders. By selecting desired item, it will then list all the desired components which the users can fill in the work orders. After filling the work orders, the users can both View & Edit component information. The second part is Inquire work orders. By selecting maintenance project name, users are able to view and edit the work orders.

The main purpose of this module is to allow the users generate and search for work orders at any time and any place. The other purpose of this module is to help users manage historical maintenance work orders, with all the maintenance work orders stored in MySQL, maintenance work orders database, the users will be able to effortlessly manage this historical data. Additionally, each maintenance work order was created based on a component, meaning that this one to one relationship between work order and a component will decrease any uncertainties when users are reviewing work orders.

Since all the work orders are stored in MySQL database, the information of the work orders will also be able to store back in the model.

- Generate Maintenance Work Orders: Generate maintenance work orders based on a selected component.
- Inquire Maintenance Work Orders: Inquire maintenance work orders based on the selected maintenance project name

5 Case Study

The proposed system is applied to a building project of a national research center located in northern Taiwan. This building built with reinforced concrete (RC), including four upper-structure floors and two underground-structure floors, which is a multi-purpose building that provides guests with accommodations, parking spaces, several event venues or spaces to host conferences and meetings, and a dining hall.

All of the 75 housing rooms in this building include various types of furniture components, which can be further divided into several categories including, beds, closets, cabinets, electronic devices (TV and refrigerators), tables, and chairs. These added up to more than a hundred of components to be managed.

5.1 Maintenance Practice of Case Project

The case study of this research focus on a new-built academic center (four upper-structure floors with RC), during construction stage, BIM model is built. The manager of the building is a team of construction from the owner. Usually the team focus on 3 different works. First, planning and constructing for the new building. Second, maintaining and repairing the existing build and facilities. Last, Space setting and numbering for the building. After starting the operation management stage, the owner proposes an operation management system in order for the convenience of the building in the future. This research helps the manager establish the operation management system.

5.2 Applications

Based on the information exported from the BIM model to the MySQL database, one can start using the application (maintenance management system) by first logging into the system by entering the correct email and password. The system will then go to the module selection page of the system.

Next, users can choose to visualize 3D models through AR or controller roaming functions. For example, a maintenance staff could be able to visualize the whole floor and identify each component located and seen on that model. This helps maintenance personnel with planning maintenance route, since they will be able to easily observe the whole layout of the floor in 3D. The users could also be able to have a better idea of where the component is located at and the difficulty of maintenance. Figure 8 shows a user using a mobile device to visualize the AR model of a room from the case study.

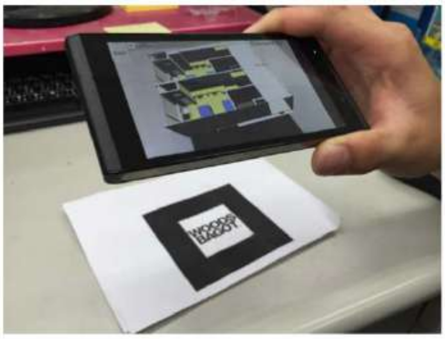

Figure 8. AR model application

Users can also quickly acquire information through Information Inquiry Module by using condition-based functions to find the component and view its information, as shown in figure 9 as an example. Users first select the conditions then choose the desired component from a list in order to view and modify information.

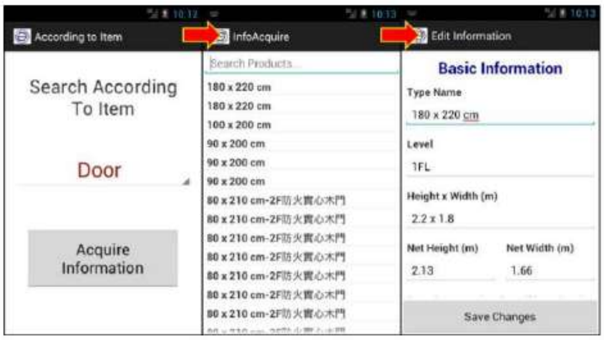

Figure 9. Steps for information inquiry

Lastly, the users will be able to generate and view maintenance work orders. The first function, generate maintenance work orders, let users create maintenance work orders targeted to one component, meaning each maintenance work order corresponds to a single component. The second function, inquire maintenance work orders, let users search for all the maintenance work orders by their maintenance project, which would list out all the components that belongs to a maintenance project.

6 Conclusions

This work demonstrated that integrating BIM based maintenance management system and mobile computing is feasible via the development of a mobile application. The integration provided by this system is significant in three aspects. First, BIM can support information exchange through the internet by providing BIM model information to MySQL database. Second, the 3D model visualization module allows BIM model to be viewed through mobile devices with augmented reality technology. Third, a truly complete integration between BIM and maintenance management system in enabling data exchange from maintenance management system back to BIM model. Overall, the proposed system demonstrated its effectiveness in enhancing the current BIM-based maintenance management system applications.

Future research in this area may also include the following directions in expanding the proposed system. First, while the current system considers 6 popular component types, other types of components, such as MEP system components can be included. Second, implementation of this system towards various BIM software could be tested. Third, evaluation of maintenance companies or other analytical functions can be included into the application, to focus on how information can be used to help make better decisions. Last, the AR tech in this project imported markers, however, it is possible to make it mark-less, which enable that in future, operators no need to carry papers or find the markers that is hided in the structures.

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Do Handstorm Principles Support Creative BIM Collaboration?

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Abstract –

Building Information Modelling (BIM) and Internet-based tools are communication aids. During the product and process design phase partners must coordinate, cooperate and collaborate with stakeholders. Creative and collaborative work is necessary in order to create value for the end consumer and society and to develop smart buildings. For this type of work design managers must have collective skills, expertise, understanding and knowledge. Furthermore, there must be an atmosphere of openness, honesty, trust and mutual respect. Merely using the current BIM tools may not be enough for future creative and collaborative work.

To enhance creative and collaborative work, the Handstorm principles have been developed based on a literature review and empirical research on collaborative design. The Handstorm principles are interventions that encourage professionals to be creative, to work collaboratively, and to support each other during design meetings. To help professionals learn and practice these skills, a *creativity facilitation* course has been developed, tested and validated.

The research question in this paper has been formulated as follows: *Do the Handstorm principles support creative BIM collaboration?* During the first phases of BIM, the collaboration can be effectively realized by using models and internet-based tools. However, subsequent phases must involve more of the knowledge and experiences of the stakeholders. To encourage this involvement, design managers must have specific skills to plan, organize and lead creative processes. These skills can be learned in a creativity facilitation course based on the Handstorm principles.

Keywords –

Social BIM, collaboration, creative thinking, design meetings, design principles

1 Introduction

In this paper the results of the PhD study *Handstorm Principles for Creative and Collaborative Working* [1] have been used to determine whether these principles support creative BIM collaboration. In this paragraph we will first discuss the field problem of the PhD study and the solution approach. Subsequently, the limitations of BIM and the research question will be addressed and then the structure of the paper will be described.

1.1 Field problem and solution approach

A field problem is a problem that occurs frequently in practice and for which there is still insufficient generic knowledge to solve it [2]. At the moment, professionals, stakeholders, clients and users in the Architectural Engineering Construction (AEC) sector make too little use of each other's knowledge, skills and experience during design meetings. This poor collaboration is evident in the way in which building joints are sometimes engineered in practice. It is important for designers to ask questions that can help determine whether the following issues have been sufficiently addressed: preventing thermal bridging, labour-friendly delivery, positioning and fixing of building components on the building site, and environmentally friendly ways of dismantling building components [3]. The conclusion reached during a seminar that was organized by the Universitair Centrum voor Bouwproductie (UCB) was that intensive collaboration between various professionals is needed when designing joints in a changeable and sustainable building [4]. In his PhD research, Olie [5] characterized this problem of collaboratively designing building joints as follows: "Good joints in buildings depend on good connections between parties."

For the PhD study, the field problem has been described as follows: *Creative and collaborative working during face-to-face design meetings in the AEC sector is not planned, organized or conducted with adequate knowledge and skills.* The word "meetings" in this problem description can be defined as a "process undertaken by two or more interested individuals, sharing their collective skills, expertise, understanding and knowledge (information) in an atmosphere of openness, honesty, trust, and mutual respect, to jointly deliver the best solution that meets their common goal" [6]. The aim of a design meeting can be any of the following: (i) assessing the situation, (ii) exploring the vision, (iii) formulating the challenge, (iv) exploring ideas, (v) formulating solutions, (vi) exploring acceptance and (vii) formulating a plan [7]. Meetings in the AEC sector are primarily conducted in a face-to-face setting. Rhoades and O'Connor stated that "in face-to-face groups the affect, or emotion, experienced by group members has an impact on the group's cohesiveness" [8]; this factor has implications for group performance, which is not the case with computer-mediated groups.

One approach to solving the field problem is to augment the knowledge and skills of the professionals by having them take part in a creativity facilitation course. The main aim of the creativity facilitation course is *to teach professionals to better plan, organize, and conduct face-to-face design meetings in the AEC sector*. The following aspects of successful creativity facilitation are listed below.

(i) Oriented to the AEC sector

The participants of (design) meetings in the AEC sector generally originate from very diverse professional groups. These professionals often have their own language, tools, codes, unwritten rules, and scientific paradigms. Facilitating a creative meeting that effectively makes use of this diversity requires a specific approach to make the participants responsible for the wishes of the client, and to help them let go of their personal solutions. By definition, participants of a meeting do not form a team; if a participant is unable to attend, he/she may send a replacement without announcing this in advance.

(ii) Involved facilitation

In most meetings, the project leader guides the meetings by focusing on his/her own issues, and insufficiently considers the contributions of the participants. In order to avoid this lack of participation, a leader should have an enterprising spirit and a proactive attitude which can contribute to an atmosphere of involved facilitation.

(iii) Stimulating cooperative learning

The professionals participating in design meetings are very experienced in their own disciplines. Collaborative working means that aspects of each discipline contribute to a final concept or idea. To realize this synergy, the facilitator must stimulate the participants' empathy and eagerness to learn

(iv) Using varied skills and intelligences

Professionals come from diverse disciplines, and have their own specific skills and intelligences. To help them work together, the facilitator should make use of all of their skills and intelligences by incorporating effective working methods that can be characterized by the values of playfulness, imagination and inventiveness.

(v) Creating an open culture

Participants of a meeting often have their own agenda to optimize their interests. There is a lack of transparency regarding these agendas, minimal respect for other participants' professionalism, and poor exchange of knowledge and experiences.

(vi) Consulting a set of design principles

Planning, organizing and conducting design meetings is not part of the (design) process manager's or project manager's daily work. He/she is engaged in construction engineering and management processes and not in running group creativity processes. Therefore, these managers must learn how to use scientific prescriptive statements, which in this study is a set of design principles. A safe environment, such as a course can be very helpful in this regard.

The knowledge and skills required to plan, organize, and conduct face-to-face design meetings can be taught with a course that has been developed using a suitable set of prescriptive statements or design principles.

1.2 Limitations of BIM

Building Information Modelling (BIM) and Internet-based tools are aids for automated workflows. These 'hardware' aids have an impact on the interactions during product and production design of building objects. Some impacts have been described in the literature and are identified hereunder.

In the study *BIM-based collaboration design and socio-technical analyses of green building*, El-Diraby, Krijnen and Papagelis [9] "noticed a few limitations/opportunities in the way current BIM tools address the needs for integrated design, collaboration and analysis", namely communication and interactions did not use BIM tools and end users were not engaged.

The bibliometric-qualitative literature review *Collaboration in BIM-based construction networks* (BbCNs) [10] aims to analyse the scholarship on collaboration on BbCNs. Two factors that need to be investigated are team members' knowledge, skills and abilities and the match between different members in BbCNs.

By developing and prototype validating a dedicated collaboration platform for Integrated Project Delivery (IPD) [11] to improve efficiency and reduce waste AEC projects, the researchers came to the conclusion that "offline meetings are still needed when complex and important problems are discussed".

1.3 Research question

Design managers need specific knowledge and skills to enhance creative BIM collaboration. These skills can be learned by following a course on planning, organizing, and conducting face-to-face design meetings. Therefore, the research question in this paper is formulated as follows: *Do the Handstorm principles support creative BIM collaboration?*

In the following paragraph a summary will be given of the PhD study *Handstorm principles for creative collaborative working* [1] and in paragraph three the developments of BIM collaboration will be explored. Paragraph four will provide an answer to the research question.

2 Handstorm principles

In this paragraph the above-mentioned PhD study will be described, focussing on the following aspects: (i) research design, (ii) the necessary conditions for successful automated collaboration in construction, (iii) developing a design principles-based creativity facilitation course, (iv) validating the set of design principles, and (v) conclusions, reflection and discussion.

2.1 Research design

The research set-up is design based and scientific. Research activities were formulated using the *research-design-development cycle*, which is a framework that describes knowledge flows and experience flows between praxis and science [12].

The central research topic, *developing a creativity facilitation course based on validated design principles,* has been broken down into three main research topics:

- Finding parameters to describe collaborative working in design meetings
- Developing the creativity facilitation course based on design principles
- Validating the set of design principles

When carrying out the research on these topics, the following research strategies were used: desk research, case study, experiment, and survey research.

This *design scientific research* aimed to achieve maximum practical relevance and maximum methodological thoroughness. The latter was achieved by developing the design principles on the basis of existing scientific knowledge and by validating them through practical implementation and evaluation. The requirement of maximum methodological thoroughness was also met by assessing the validity of the evaluation and qualification results by applying the rival explanations method. The requirement of practical relevance was met by implementing the course, which is based on a set of design principles, in practice. A beta test was carried out by publishing some of the design principles and evaluation questions at an early stage and inviting fellow academics to experiment with and report on them. The methodological thoroughness requirement was also met by the triangulation of this data – the use of different samples, spaces and persons.

2.2 The conditions for collaboration

For the first main research topic, *finding parameters to describe collaborative working in design meetings,* desk research and a case study were carried out. The desk research yielded a research perspective from which to consider collaborative working. The case study consisted of the analysis of 37 meetings held during the design and production phases of a prototype for an industrial, flexible and demountable construction system. The parameters found – ‘aim of meeting’, ‘control of meeting’, ‘participants’, ‘tools’ and ‘outcomes’ – were linked to the basic elements of the Structured Analysis and Design Technique (SADT). This resulted in a system model that can be used to describe and design meetings. An article on the implementation of this main research topic was published by Van Gassel, et al. [13].

2.3 Developing creativity facilitation course

The second main research topic, developing the creativity facilitation course based on design principles, has been broken down into four sub-topics:

1. Finding mechanisms that enhance collaborative working in a literature review of PhD studies.
2. Finding successful interventions based on the practical experience of the researcher.
3. Developing the design principles by synthesizing the mechanisms and the successful interventions.
4. Developing the creativity facilitation course based on design principles.

The research consisted of desk research and experiments. Sub-topics 1, 2 and 3 yielded 15 design principles; the syntax for each was classified on the basis of Context Intervention Mechanism Output (CIMO) logic. These design principles are described briefly below.

The set consists of 15 design principles, which can be summarized as follows: (i) plan a detailed meeting scenario, (ii) invite a variety of participants, (iii) explain work methods simply, (iv) have participants listen to each other, (v) put reluctant participants to work, (vi) create rhythm in the group’s activities, (vii) reformulate the definition of the problem, (viii) don’t be afraid to deviate from the meeting plan, (ix) continually change the circumstances, (x) take participants out of their comfort zones, (xi) let the participants do the work, (xii) let the hands do the thinking, (xiii) alternate between strict and lenient, (xiv) close the meeting with perspective, and (xv) choose the work method most appropriate for the meeting. To plan and conduct these meetings, design managers need knowledge of creative and collaborative work and creative (leadership) behaviour.

The final sub-topic yielded a course program and an enrolment leaflet. This leaflet sums up the aims of the course: oriented to the AEC sector, about involved facilitation, about stimulating cooperative learning, about using varied skills and intelligences, about creating an open culture, and about consulting a set of design principles.

The design principles and development process have been reflected upon. The design principles cover the meeting parameters ‘control of meeting’, ‘participants’ and ‘tools’ equally for each design principle. Background information was provided for each design principle and it was demonstrated that design principles strengthen the sub-aims of the course. The development process has yielded a method that synthesizes scientific knowledge and practical results into new design principles.

2.4 Validating the set of design principles

The third main research topic, validating the set of design principles, was broken down into three sub-topics:

- Evaluating the creativity facilitation course in practice;
- Qualifying the implementation of the set of design principles;
- Assessing the validity of the evaluation and qualification results.

The course was evaluated after it had been delivered six times. A questionnaire was used to measure learning results and participant satisfaction. This measurement showed that the course scored well regarding ‘knowledge of joint creative thinking’ and it was scored very highly regarding ‘improvement of creative behaviour’ and ‘improvement of creative leadership behaviour’. Course participants were very satisfied and after the course exercised the skills they had learned in practice.

The qualifying of the implementation of the set of design principles involves considering the measurement results of the learning outcomes and demonstrating the coherence between the three learning outcomes ‘knowledge of creative and collaborative thinking’, ‘creative behaviour’ and ‘creative leadership behaviour’, and the set of design principles. The coherence between the descriptions of the learning outcomes and survey questions can be qualified as fair based on the 5-point Likert scale (i.e. poor, fair, average, good and excellent).

The beta test was carried out at the Federal University of Juiz de Fora in Brazil, as part of a bachelor course based on the use of design principles. The answers given to the evaluation questions show that students were satisfied with the course (on a scale of one to five with a mean score of 3.75 (standard deviation 1.28 and $N = 8$)). Although there was initially some resistance among the students, it disappeared during the test. The coaches found that the results obtained when applying the design principles were better in comparison with situations in which the design principles were not used. It would seem reasonable to conclude that the use of the design principles is useful. The beta test was described by Pinheiro and Queiroz [14].

2.5 Conclusions, reflection and discussion

The central research topic, *developing a creativity facilitation course based on validated design principles,* results in an attractive and broadly applicable solution to the mentioned field problem, and fulfils some needs of ‘structuring face-to-face meetings’ and ‘guidelines for trained facilitators to enhance group creativity’ from the academic domains of *building design management* and *small group creativity*.

The creativity facilitation course is *applicable* for the professionals working for companies that are involved in performance-oriented tenders in the AEC sector and the course now forms part of the education program at the BAM Business School. The research has also yielded a set of Context Intervention Mechanism Output (CIMO) structured design principles that can be used as a guide when planning, organizing and conducting all kinds of design meetings. The principles can also be used to develop creativity techniques, such as two simulation games (‘Partner selection’ and ‘Creative supply and demand’) and two creativity techniques (‘Constructing a platform’ and ‘Constructing metaphoric objects’). The practical use of the design principles is publicized under the brand name Handstorm® on the www.handstorm.nl website.

The research further yields the following tools and findings for the domain of *design science research*: (i) a system model that can be used to devise and describe meetings, (ii) a procedure that has been devised to develop design principles by synthesizing successful interventions and mechanisms, (iii) a questionnaire in which participants evaluate the course, (iv) the *research-design-development cycle* has proven to be very suitable for designing the research, and (v) a procedure for the assessment of the validity of the evaluation results attained on the basis of the plausible rival explanations method.

To enhance the *reliability* of the results, the researcher has implemented the course six times in practice, used existing knowledge, initiated a beta test, and evaluated the course on the ‘indicative’ level.

The *validity* of the set of design principles has been assessed by qualifying the evaluation results and the results of the beta test. To estimate the validity of the set of design principles, the plausible rival explanations method has been used. The beta test that was carried out at a university in Brazil shows that design principles are useful when devising, organizing and planning education-related meetings.

Regarding the *generalizability* of the design principles, these principles are described as a robust basis for attractive and broad applications for creative and collaborative working.

The research has a number of *limitations* and thus suggestions are proposed for *future research*. Only the *indicative* evaluation level was chosen for the course because the course had been implemented only once in practice. In future research the higher evaluation level *causal* should be chosen, as now more are data available regarding the impact of the interventions on the outcomes.

The experiences of course participants were measured with a survey. The learning outcomes were only measured at the end of the six courses. In this study, the participants were asked to rate how much they had learned during the course. This form of self-assessment is less objective than taking measurements before and after training. In future research, it might be better to measure the knowledge and behaviour of participants at the beginning and at the end of each course.

The usefulness of the set of design principles was determined by measuring the coherence between the text of the questionnaire and the keywords of the 15 design principles. This coherence can be considered *fair* but there are clearly differences between the learning outcomes ‘creative behaviour’ and ‘creative leadership’ in relation to the design principles. Further research can more explicitly test the course participants’ knowledge about the set of design principles as a part of the evaluation and can thereby enhance the coherence.

The Structured Analysis Design Technique (SADT) system model for meetings is based on just one case study, but it has on numerous occasions been used to analyse and describe various construction processes during the Master’s degree program in Construction Management and Engineering at the Eindhoven University of Technology. It is recommended that further research be carried out on the validity of the SADT system model for meetings (e.g., in the form of additional case studies).

Other worthwhile research would involve testing the effectiveness of the Handstorm principles during every phase of creative and interdisciplinary collaboration processes, for example in the ICT, government and health care sectors. In addition, it would be advisable to establish whether the principles are applicable outside a Dutch or Brazilian context.

3 Developments BIM collaboration

Answering the research question in this paper, *Do the Handstorm principles – as learned in a creativity facilitation course – support creative BIM collaboration?* requires insight into the developments in BIM collaboration and the competences desired by design managers to enhance this collaboration. The findings of several authors regarding theses aspects are summarized hereunder

Grilo and Jardim-Goncalves [15] distinguish five interaction types along the x-axis: communication, coordination, cooperation, collaboration and channel. Each type of interaction has three value levels along the y-axis: efficiency, differentiation, and value innovation. Collaboration is related to value innovation and described as 3D BIM & Collaborative working environment. During the design of the product and production processes for the built environment, partners must coordinate, cooperate and collaborate. Creative and collaborative work is necessary in order to create value for the end consumer and society and to develop smart buildings.

Uhm, Lee and Jeon [16] have analysed BIM jobs and their required competences. The BIM jobs were classified into eight BIM job types: BIM project manager, director, BIM manager, BIM coordinator, BIM designer, senior architect, BIM mechanical, electrical and plumbing coordinator, and BIM technician. According to their study, the BIM project manager did not require a number of *common* competences in relation to creative collaboration. Some relevant competences include the following: “work styles of cooperation”, “design knowledge”, “work activity of thinking creatively”, “work activity of commutating with supervisors and peers”, and “work activity of providing consultation and advice”. This study may contribute as a guide to developing a training program for BIM design managers.

In the study *Enhancing collaboration in BIM-based Construction Networks (BbCNs)*, the authors Mignone, Hosseini, Chileshe and Arashpour found four main approaches for enhancing BIM collaboration in the literature. The second approach “suggested the incorporation of the principles of effective team working in tertiary education programmes” and the third “contended that members of BbCNs should be regarded as constant learners to foster collaboration” [17].

Future generations of BIM systems need real-time co-creation capabilities during the development phase. It is the people who collaborate and not the systems. Therefore, the future systems, which are known as Social BIM, focus “on the *procedural aspects of BIM* by encapsulating the metacognitive, behavioural, interpersonal and confidence skills that shape effectiveness of collaboration”. This statement comes from the study *Social BIM: Co-creation with shared situational awareness* [18].

Based on the findings of these authors, it is clear that enhancing creative BIM collaboration requires collective skills, expertise, understanding and knowledge by design managers in an atmosphere of openness, honesty, trust and mutual respect.

4 Do the Handstorm principles support creative BIM collaboration?

The research question in this paper has been formulated as follows: *Do the Handstorm principles support creative BIM collaboration?* During the first phases of BIM, the collaboration can be effectively realized by using models and Internet-based tools. However, subsequent phases must involve more of the knowledge and experiences of the stakeholders. To encourage this involvement, design managers must have specific skills to plan, organize and lead creative processes. These skills can be learned in a creativity facilitation course based on the Handstorm principles.

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The automation of the process of updating the curing time activity in 4D schedule

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Abstract –

In todays practice, we encounter different approaches to solving the problem of planning a curing time for wet processes. The article focuses on concrete processes where the length of the curing time needed for formwork removal is dependent on numerous factors. By using sensors that monitor the internal temperature in the concrete, we can determine the time of stripping of the formwork more precisely. The aim of this article is to describe the process of possible automation of the update in the duration of the technological break (curing time) and the integration of this data into the BIM model. The proposed process will be used to solve the active link to the update of the formwork removal activity in 4D simulation of the construction.

Keywords –

BIM, 4D simulation, Formwork removal

1 Introduction

The effectiveness of cooperation between construction participants can be clearly increased by sharing information from the BIM model. However, it is essential to ensure the sharing of digital files, not only between design applications but across all stages of the building's life cycle. In the past, it was almost impossible to open and edit files in a different environment than where they were created. Such an approach has limited cooperation and also freedom in choosing software. Today the situation is different.

Updating the 4D models, if done manually, is time-consuming and labour intensive, which discourages their use among industry practitioners (Lopez et al. 2015). There is a need for solutions that automatically incorporate the detected progress data into 4D BIMs and update the schedule and tasks associated with 3D model objects (Chen et al. 2015; Kim et al. 2010).

According to our study, there is potential in optimization of the process of updating the construction schedule with partial automation. Such an example is formwork removal activity that could be updated without the need of manual input. This can lead to savings related to cost and time and providing direct source of information in order to make a right decision.

2 Building Information Modelling

2.1 Process

The goal of BIM is not to create a model itself, but to gain complete, reliable, accessible and easily exchangeable information to anyone who might need it throughout the whole life cycle of the building.

The data rich information model, today interpreted as BIM model basically consists of three parts. We can characterize it as a combination of graphic and non-graphic data and any documents related to a construction project according the definition of English standard PAS1192-2. In some definitions, metadata is included as part of the information model except for the three above mentioned components. For BIM to be complete, we need all this information for each element, object, product, material or system that is included in the project. The detail of this information can be referred to as the Level of Definition, which includes the level of detail and level of information, and therefore describes the specification of the information model on a graphical and non-graphic base.

Graphic information can be 2D or 3D and are expressed in shape and layout in space. This information is basically a 3D model, its graphic, a geometric representation (in native or exchange format) that provides visual orientation, location and context, defines relationships between rooms, spaces, and other elements in the model. Although it is estimated that the graphical representation, respectively. A 3D model that contains geometry only represents only 5% of the project information, this part of the model is necessary for computer coordination (for example, for collision detection) and serves to link and determine relationships with the systems. Simplified, the 3D object serves as a container for some non-graphical information or parameter information and potentially provides a link to other information in other formats and placements.

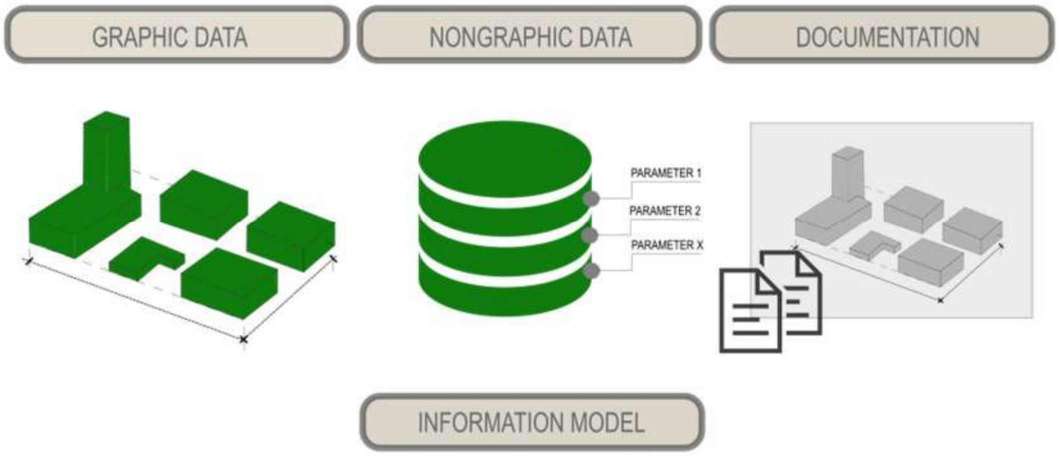

Figure 1 Building Information Model

The Level of Detail (LOD), i.e. the detail of its geometric representation, can define the relevant standard or is defined in the BIM (BIM Execution Plan) and expresses the required detail in each phase of the project.

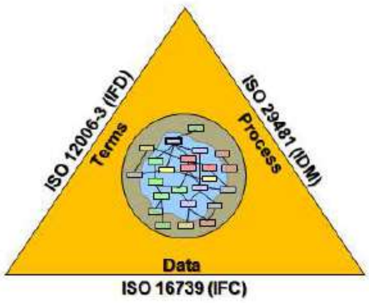

Figure 2 Basic schema of standards

2.2 Interoperability

Another fundamental prerequisite of BIM process is interoperability. Individual software applications store information primarily in their native formats, which is a major challenge in the digital world of the construction industry. In order to make information available to all participants throughout the life cycle, software applications must enable and secure reliable data exchange.

Interoperability refers to the property of a product or system communicating and working with other products or systems without any limitations. It could also be said that interoperability is the ability of a system or product to work with other systems or products without the need for particular effort on the part of the user. It is true that interoperable systems are capable of communicating and exchanging information to avoid uncontrollable modification and loss.

IFC (Industry Foundation Classes) file type – a neutral data format used to describe, exchange and share information between stakeholders and various software.

There are various methods, software systems and information, respectively. communication technologies that deal with effective data exchange between software applications. Basically, it can be plug-ins and programs, individual file-sharing formats created by software vendors, DXF (Data eXchange Format), or standards and open data models such as XML (Extensible Markup Language) and IFC (Industry Foundation Classes - a standardized and fully documented file format created and defined by buildingSMART).

The BIM itself is based on open cooperation and also through the IFC ensures the exchange of information from the data model between the different professions within the life cycle, thus also between different program environments. In this area, it is good to rely on the available ISO 16739 standards, which define the data themselves - IFC, ISO 29481 which defines the Information Delivery Manual (IDM) and ISO 12006-3, which define the framework for object-oriented information.

The development of IFCs is constantly advancing, and standards are tailored to the needs of the industry. In fact, the IFC1.0, IFC1.5, IFC1.5.1 and IFC2.0 have been on the market before 2000, are no longer used today. In October 2000, a stable IFC2x platform was launched, a year later updated with IFC2x-Add1. In 2003, the IFC2x2 platform was also released, which was also updated by IFC2x2-Add1. Currently, IFC2x3-TC1 - "IFC2x Edition 3 Technical Corrigendum 1" is the most used platform - it supplements version IFC2x3 from July 2007.

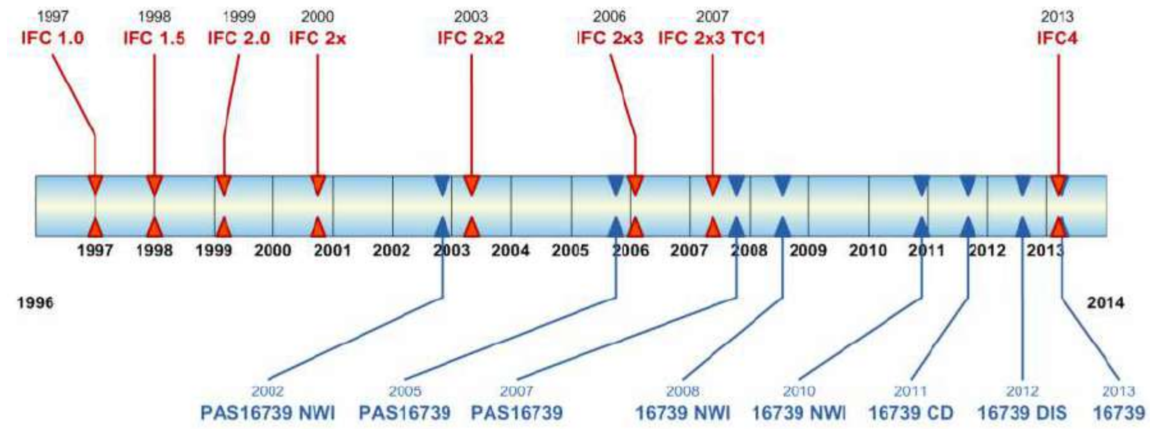

Figure 3 IFC schema, BuildingSmart

The new version, released in 2013, is the IFC4 platform (formerly IFC 2x4). IFC4 includes additional extensions related to the building, component, geometry improvements, resources, significant quality enhancement, and fully integrated ifcXML. In July 2015, IFC4 - Add 1 (Addendum 1) was released, incorporating the necessary improvements that were discovered during pilot implementations and development activities for MVD (model view definition). The next version of IFC5 is currently under preparation. The date of its issue has not yet been confirmed.

The basic schema of the most frequently used version of IFC2x3-TC1 is shown in Fig. 1. The IFC schema consists of a set of defined ways to divide information into individual classes along with the information structure that defines the objects. This structure formally specifies the attributes within the classes and defines the form in which the data will be exchanged within ISO 10303, Industrial Data Systems and Integration (Part 21, 22). The diagram is divided into three basic layers respectively. level, namely Core, Interoperability, and Domain. Platform components are shown in green.

Although definitions and structures are comprehensive, many types of information that individual users want to replace are not directly part of the IFC Model. However, it is possible to define them within the IfcPropertyResource scheme.

3 Formwork removal

Concrete is a composite material composed of fine and coarse aggregate bonded together with a fluid cement that hardens over time. Many types of concrete are available, distinguished by the proportions of the main ingredients. The rate of hardening of concrete or the concrete strength depends on several aspects.

The curing period may depend on the properties required of the concrete, the purpose for which it is to be used, and the ambient conditions, i.e. the temperature and relative humidity of the surrounding atmosphere. These aspects affect the formwork removal time. The process of removal of formwork in the process of casting concrete is also known as striking time. Once the concrete has achieved the initial recommended strength, to support the self-weight and any imposed loads, the shuttering is removed for further curing.

Curing is the process of controlling the rate and extent of moisture loss from concrete during cement hydration. (Curing of Concrete, 2006).

Leaving formwork in place is often an efficient and cost-effective method of curing concrete, particularly during its early stages.

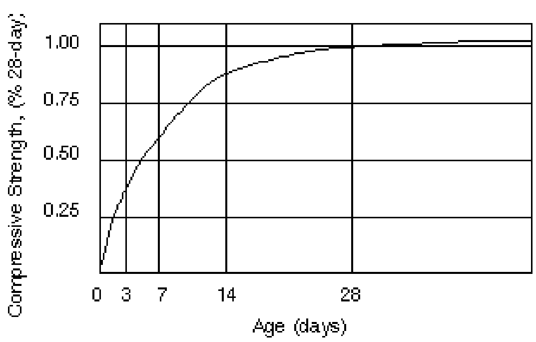

Figure 4 Typical strength-gain curve, University of Memphis

3.1 Actual approach

Stripping should be carried out only after the time when concrete has gained sufficient strength. This time represents the time lag between concrete casting and formwork removal activity.

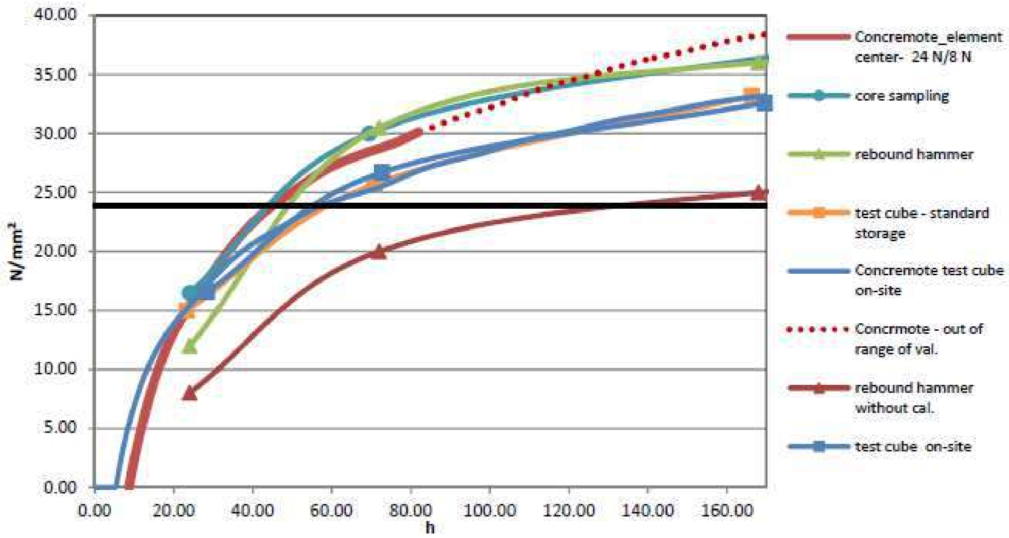

Figure 5 Compressive-strength-developments derived from different methods

"The delay after the first activity completes and before the second activity starts (wait period), is called lag and this delay is known as the Lag Time." (Project Management, book)

Throughout local construction industry, the most common understanding of the process of hardening is that it takes 28 days to cure and reach 100% of proposed strength. This is strongly connected to lag time and according to our research, this affect their estimate of duration of this task. In some cases, constructors estimate for necessary time lag until striking is possible is 28 days (form and complete set of support removal). Of course, the decision to specify date of formwork removal activity need to be confirmed via various methods.

Nowadays, companies tend to estimate striking time unsystematically, mostly relying on their previous experience or company´s internal standard. They use non-destructive tests (mostly Schmidt hammers) or obtain this information from reference samples or query the information from structural engineer.

The most common approach is using rebound-hammer to confirm the date of formwork removal. However, construction companies frequently use uncalibrated rebound-hammer and it is proven that uncalibrated rebound-hammer deliver the most inaccurate results.

In many cases, the removal of formwork process could have occurred sooner, which has a major impact on the construction process and the optimization of concrete workforce.

3.2 Sensor-based strength measurement

Non-destructive methods based on maturity calculations can be applied. There are several commercial systems on the market (Concremote, Con-Cure NEX, SmartConcrete, ...) providing non-destructive measurement of fresh concrete strength based on real-time hydration heat.

„*Most of the destructive test methods have the disadvantage of the late availability of the data. The evidence for strength is usually too late in time to make decisions regarding the building process (e.g. striking times). For optimising construction processes the real-time concrete strength methods on the basis of the calculations by de Vree are generally a promising technology.* " (Reinisch et al, 2015)

Using such a system for sensor-based strength measurement have advantages in various cases e.g.:

- decision on striking time of wall and ceiling formwork,
- information about load capacity for special type formwork for vertical concrete structures e.g. climbing formwork,
- temperature monitoring and recording due to prevent possible cracking,
- casting concrete roads to estimate cutting times for concrete joints,
- estimate aesthetic concrete maturity in order to achieve the same shade

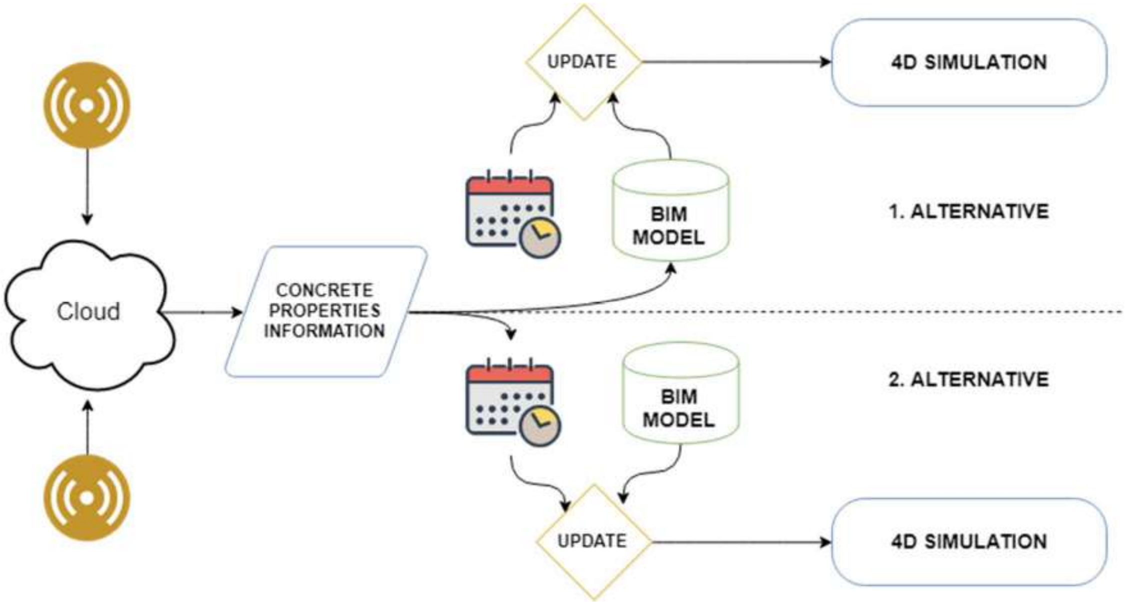

Figure 6 Flowchart diagram of proposed methodology

Primary benefit of this approach is that the measured data are collected, stored and reachable from cloud-based service. Some systems store (backup) data through local storage device e.g. SD card. Prior to use, all sensors must be calibrated to provide reliable information.

Sensors can be wired or communicate remotely and most of the built-in sensors available on the market can be used multiple times. After activation, sensor record measured temperature on predefined time span (for example each 5, 10, 30 min). Individual values are incorporated into diagram representing strength of concrete. Once the strength predefined by the customer is reached, the system automatically notifies the person responsible for the construction management via SMS or e-mail. This capability of the system to communicate autonomously in a predefined form is a base for further development of the platform for the automation of the process of updating the curing time activity in the schedule as activities related to striking task management which are its successors could be linked dynamically.

4 Proposed methodology

For the purpose of the possible automation of the process of updating the curing time activity in 4D schedule we will consider two approaches.

One approach is based on enriching 3D BIM model either by modifying IFC file or model in native format and the second is based on modifying time schedule.

4.1 Modification of 3D parametric model

Approach based on modifying BIM model either by through IFC file or native format is the platform where time information about the exact date of striking is delivered directly into model as a parameter using excel predefined template custom macro or Dynamo script. Further update of schedule by modification of the input value of model objects with assigned tasks is done in 4D scheduling software.

4.1.1 IFC based modification

Modifying IFC file allows the wider spectrum of utilized software. There are several software allowing you to edit IFC data without having access to the original model. Various authors already worked with the topic of IFC-based automation of schedule progress updating (Hamledari, et. al, 2017)

It is known that the IFC 2x3 schema specification provides a reasonable basis for the use case of model-based scheduling. The benefits of model-based scheduling are widely recognized (Porkka, Kähkönen 2007).

The aim of the rule-based linking approach is to reduce the effort for the overall set-up process by using semi-automated linking mechanisms and improve the management of data dependencies to react more efficiently on design changes. (Weise et. al, 2016)

Each IfcTask is distinguished from others by its GUID. The schedule control information, on the other hand, is modeled through subtypes of IfcControl, such as IfcScheduleTimeControl, which holds all the necessary attributes for scheduling a task such as early and late start and finish dates, duration, and float information.

For each task, the ScheduleDuration and ScheduleFinish attributes of the IfcScheduleTimeControl are updated (Hamledari et.al. 2017).

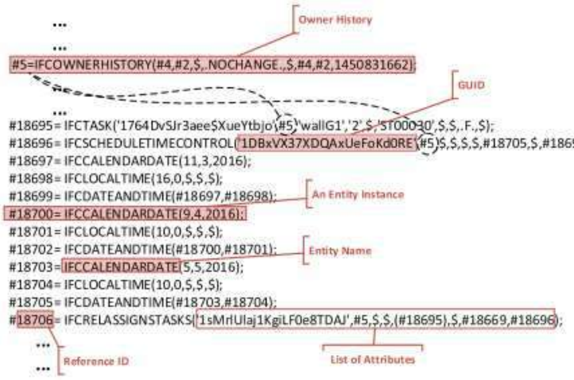

Figure 7 Parts of an IFC data model, Hamledari et.al.

Using special software, you can edit properties of IFC model. In general, you can modify property values, combine and split values and move values from one property to another. It is also possible to Enrich the model by adding new data to IFC models from external data sources (import and export of IFC2x3 and IFC4 models using the .ifc and .ifczip file formats) allowing to export the property data of BIM model into Excel.

4.1.2 Modification of model in native format

Option that we are considering is also modification of time information directly in the native format. This allows the user to work in an environment they already know and without investment into additional software. For this purpose, we are using the Navisworks to simulate construction processes. We can either manually enter information about project tasks or import schedules from many project planning software applications (MS Project, Primavera,..) and to follow with linking the elements in the model with tasks in the schedule. The procedure in Navisworks would be to link Revit model and the project plan document; followed by mapping Revit Elements to corresponding construction activities. After this Navisworks can simulate the virtual construction on Revit model using the dates provided in project plan.

In order to tag the Revit Elements with four construction dates (Planned Start Date, Planned End Date, Actual Start Date and Actual End Date).

For achieving this you can create mentioned dates as a Project Parameters (Text Type & Instance). Further you can select the individual elements as required and update fields.

4.2 Modification of time schedule

Approach based on modification of the time schedule apply when time information about the exact date of striking is delivered directly into schedule using excel predefined template and custom macro. Further update of schedule by modification of the input value of the formwork removal task is done in master scheduling software (either directly in 4D environment or in MS Project).

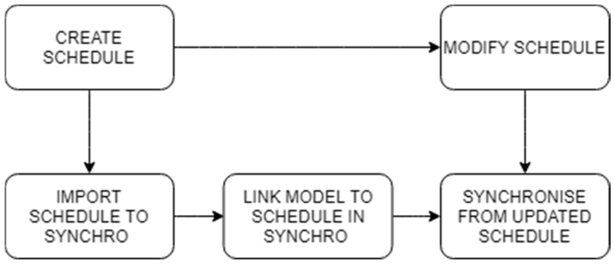

Figure 8 Synchro update process

Synchro PRO, that could be used as a tool uses XML format to Synchronise when working with MS Project. In a process of updating the schedule in 4D environment (e.g. Synchro PRO) you should skip task synchronization when synchronizing with an IFC file that contains a 3D model only, since IFC files may contain task data too.

When using Synchro PRO, it is important to be aware of various techniques of schedule modification. You can use Skip, Synchronise, Consolidate of Integrate option. For the purpose of prolongation of shorten of the lag time for striking, Consolidate of Integrate option must be used where the new schedule will be merged with previous version of schedule and depending on selection objects that were deleted in update version will be deleted (Integrate) or not (Consolidate).

5 Conclusion

Interoperability and BIM itself provides wide options for construction optimization either for reaching higher quality or mostly by using advanced techniques for partial or full automation of some processes and therefore reducing the need of manual inputs and reducing time consuming activities.

We assume that solving even partial tasks of automation of construction schedule results in better construction management.

In the local industry, the topic of formwork removal appears to be solved unsystematically. We believe that by using sensors to accurately determine the achievement of the required strength of concrete and linking the information about actual time lag to the model, we can simplify the process of schedule update. Moreover, we can provide reliable information that the striking can be done and when it can be done to the person in charge in an efficient way.

Further research needs to be performed in order to develop exchange templates, to verify reliability of proposed method and compare versatility of suggested approaches and evaluate most effective way of data exchange.

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BIM Guidelines Review for Public Post-secondary Institutions

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Abstract

Despite its documented success, the use of Building Information Modelling (BIM) continues to raise questions related to its implementation at an institutional level. Therefore, several institutions have produced guidelines specific to BIM to communicate their expectations in regard to BIM in their projects. However, such guidelines do not exist among Canadian post-secondary or public institutions despite the wide implementation of BIM technology. To better address the requirements of BIM usage by public post-secondary institutions, a review of existing BIM guidelines is needed. The research includes three phases: (1) assessment of existing processes; (2) a comprehensive review of twelve guidelines from institutions with various backgrounds; followed by (3) recommendations for further BIM implementation. We reach the conclusion that no one institution's BIM guidelines are capable of fully accommodating the context and requirements of all Canadian public post-secondary institutions. Hence, a BIM guideline based on the key findings of the analyzed documents for each stage of the building lifecycle, as well as knowledge about current operations and local context, is recommended as future research. To achieve a comprehensive set of guidelines, the local construction industry should be consulted to account for existing BIM expertise; the guidelines should also incorporate important documents found in the guidelines of other institutions. Moreover, it is recommended that the future guidelines focus on the management of the BIM model for the operation and maintenance phase since this phase incurs the highest costs in a building's lifecycle, and is the responsibility of the owner (i.e., the institution).

Keywords –

BIM; BIM Guidelines; Post-secondary institutions; BIM Implementation;

1 Introduction

Building Information Modelling (BIM) has made a significant impact on the construction industry, affecting all areas of a facility's lifecycle. However, there is a lack of standardization with regard to the implementation of BIM across different areas, thus constituting a major barrier to the adoption of BIM with its associated benefits for the construction industry [1].

To streamline BIM requirements and expectations, organizations develop documents that regulate the technical and contractual aspects of the BIM models provided to the owner/client by the consultants and contractors. These documents, i.e., BIM Guidelines or BIM Standards, help the local design and construction market to standardize design and construction services and the use of BIM models to contribute to the maturation of the local industry [2].

A guideline consists of a "general rule, principle, or piece of advice", while a standard is a "required or agreed level of quality or attainment" [3]. According to [4] the implementation of BIM at an institutional level is highly dependent upon guidelines and standards since they provide a common orientation to the local community. However, these documents are dependent on the level of understanding, readiness, and implementation of BIM within the given jurisdiction, such that applying the guidelines or standards from one jurisdiction to another one is an ineffective practice.

Considering this, the University of Alberta—one of the leading post-secondary institutions in Canada—performed a review of existing BIM guidelines and standards in North America, since the adoption of BIM in Canada is still in its early stages and no other post-secondary or government institution in Canada has this kind of documentation in place.

1.1 Methods

The research presented in this paper consists of a review of existing guidelines with the objective of investigating procurement strategies and the potential use of BIM by the University of Alberta. Figure 1 provides an overview of the methodology employed in this research, which is performed in three phases: (1) an assessment of the existing processes within the University of Alberta to gain understanding of its existing process and expectations pertaining to the use of BIM; (2) selection and review of existing guidelines in North America relevant to the context of this research; and (3) a set of recommendations for the procurement and use of BIM models for the University of Alberta.

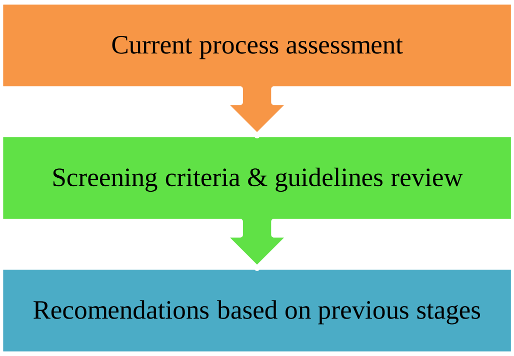

Figure.1 Overview of research methodology

This assessment endeavors to define the needs of a given organization with regard to the implementation, use, and management of BIM, and thereby tailor the development of future guidelines accordingly. Based on the requirements of an organization, a set of criteria is developed to assist in the selection of existing relevant documentation that is to form the basis of the new guidelines. Existing guidelines that satisfy the selection criteria are then reviewed to match the BIM requirements of the organization with the components of the existing BIM guidelines.

Although it is a qualitative assessment, the research presented in this paper makes use of semi-structured interviews and structured questionnaires in order to provide metrics and quantitative data to be used during the screening and review processes and direct the process toward addressing existing issues pertaining to the use of BIM at the University of Alberta. These methods are explained in detail in the following sections.

2 Current Process Assessment

The current process assessment aims to identify the existing requirements and expectations of the University of Alberta's Facilities and Operations (F&O) with regard to the use of BIM, to evaluate the existing procedures of each organizational unit, and identify possible improvements that could be realized by adopting BIM for its capital projects. Table 1 summarizes the organizational units assessed and their primary responsibilities under the F&O portfolio.

As described in Table 1, these organizational units which F&) comprises are responsible for the planning, design, construction, operation, and maintenance of all facilities at the University of Alberta, thus controlling every aspect of the performance of each building in the institution's portfolio throughout its lifecycle. The Office of the University Architect (OUA) carries out the planning for new facilities and retrofit of existing buildings. After the Request for Proposals (RFP) stage is complete, the Project Management Office (PMO) procures the project to a general contractor and oversees the construction until the facility is commissioned and handed over to the University; Operations & Maintenance (OM) then assumes the role of maintaining and operating the facility.

Table **Error! No text of specified style in document.**1 Units investigated and their respective roles

Unit	Main role
Office of the University Architect (OUA)	Planning of new construction or retrofit while overseeing design compliance during construction
Project Management Office (PMO)	Procurement and control of new construction or retrofit
Design and Technical Services (DTS)	Document management for operation and maintenance of existing buildings
Operations & Maintenance (OM)	Maintenance of existing buildings and management of daily operations
Energy Management & Sustainable Operations (EMSO)	Optimization of operations of existing buildings with a focus on energy management

During commissioning, Design and Technical Services (DTS) receives all drawings and documents related to the project and manages these documents throughout the facility's lifecycle, including updates and generating new documentation as necessary. Energy Management & Sustainable Operations (EMSO) assesses performance of existing buildings in order to optimize their operations and provides key information to OUA that can inform future renovations and new construction across campus. A semi-structured interview is developed to gain understanding about the requirements and expectations of each organizational unit while generating data for use in future assessments. Using the data collected during this process, a review of the guidelines is conducted for addressing the needs identified and concerns raised by the various organizational units.

Table 2 presents the results of the semi-structured interviews. It is clear that the different organizational units vary considerably in size, but all face challenges in with regard to communication, lack of resources, and tight schedules as per the first and second questions. The response to the third question indicates that each unit has their own experience with BIM in isolated cases with little to no communication between units. In fact, the use of BIM—since it is not mandated by the University—is driven by consultants and contractors that already use BIM in their own operations and is perceived by the University as an add-on rather than a fundamental component of its design, construction, and facility management operations.

Despite the fragmented use of BIM in F&O's existing operations, organizational units such as OUA, PMO, and DTS acknowledge the potential use of BIM to improve communication among units and other stakeholders (e.g., consultants, general contractors, etc.) while OM and EMSO see value in the application of BIM to improve other decision-making processes such as predictive modelling and lifecycle assessments.

Still, as can be seen in Table 2, responses to the final two questions indicate three main challenges and concerns regarding BIM implementation at an institutional level: (1) further maturation of the existing BIM implementation framework, and training both of University personnel and other stakeholders in its capital projects (e.g., consultants, trades, etc.) in order to increase the University's capacity to implement BIM in its projects and facility management; (2) the interoperability of BIM models between various platforms and other existing management systems (document and asset management); and (3) concerns about the ownership of the model.

Table 2 Results of semi-structured interview according to each unit

Question	OUA	PMO	DTS	OM	EMSO
Number of employees in each unit	6 to 10	15 to 20	13	200 + 200 from subcontractors	4
Current challenges in unit	Short deadlines	Bureaucracy and change management	Communication among various stakeholders	Communication across different stakeholders and short-term planning	Lack of trained personnel
Current use of BIM	3D imaging during conceptual phase	Mainly used to communicate consultant’s proposal	Uses parametric tools non-related to BIM for document management	None	Uses model (when available) for energy modelling
Potential use of BIM	More information during conceptual phase and design oversight	Enhance communication and constructability analysis	Enhance communication and integrate operation documents with drawings	Predictive maintenance and personnel training	Lifecycle assessment and decision making
Current challenges for BIM implantation	Personnel training	Scope required from the model and actual benefit from BIM	Interoperability between existing infrastructure and BIM systems	Personnel training, incomplete models, and clarity regarding the ownership of the model	Sharing information across different platforms
Questions about BIM and its applicability	Possible interaction between BIM and existing systems	Maturity of local community (consultants and general contractors)	None	Ownership, cost of the model, and impact on daily routine	Ability to develop custom solutions for each project

3 Screening Criteria & Guideline Review

Based on the current process assessment, this section will discuss the screening criteria used to select which documents shall be included in the analysis and the review of these documents based on the findings of the previous sections.

3.1 Screening Criteria

Based on the data gathered in the assessment of existing processes, a series of questions is developed by the research team which are then incorporated into a structured questionnaire to streamline the review process and create data that can be compared on a quantitative basis when applicable. The following is a list of statements incorporated into the structured questionnaire:

1. Information exchange through the model during its lifecycle.
2. Workflow change due to the use of BIM.
3. Which software to use (use of open or closed architecture application approach).
4. Ownership of the model.
5. Costs incurred from BIM.

The criteria used to select which documentation to review are described below:

1. Only documents from North America are considered due to the geographic location of the case institution, with the exception of standards from the United Kingdom and Singapore due to their relevant work on BIM implementation at an institutional level.
2. Guidelines from post-secondary institutions: to evaluate the requirements of other similar institutions imposed on their contractors.
3. Guidelines from public institutions to address how these institutions overcome barriers such as interoperability and how they standardize their requirements across a larger sample of contractors.
4. Standards from national standardization organizations to address general requirements from each jurisdiction of origin.

Table 3 presents the documents selected for review based on the presented criteria, listed according to the areas of interest addressed during the current process assessment stage. As per Table 4, the documents are separated into three groups: (1) third-party organizations, which regulate the use of BIM through standards and have a national range; (2) guidelines from government organizations, which regulate the use of BIM in their respective jurisdictions (e.g., state/province, city, etc.); and (3) university guidelines, which regulate the use of BIM for a given post-secondary institution.

All the documents selected encompass the use of BIM during the design stage and address the interoperability of the various systems involved, and thereby speak to the questions raised in the current process assessment of the case institution. Moreover, the government and university guidelines reviewed predominantly encompass the use of BIM during the construction stage, while relatively few cover the use of BIM for facility operation or energy modelling assessments.

It is also important to note that most of the documents reviewed specify procedures to be performed during the delivery process of BIM models and the respective legal aspects of that delivery.

3.2 Guidelines Review

This section presents a summary of all the guidelines reviewed, important findings regarding the questions raised during the current process assessment, and relevant information for each stage of the facility lifecycle. The structure of this section corresponds to the list of questions raised during the assessment of existing processes.

3.2.1 Information exchange through the model during its lifecycle

Government and university guidelines provide further clarity in addressing this question since these institutions need to inform consultants and general contractors of their requirements throughout the entire project. The guidelines identified as having the greatest potential to clarify information exchange through the BIM model are from the University of Southern California, the City of New York, and the State of Ohio, and these guidelines are thus recommended for use as a benchmark by the case institution when preparing their BIM guidelines.

3.2.2 Workflow change due to the use of BIM

After the analysis of the guidelines is complete, it is observed that the introduction of BIM is not substantially disruptive to the way projects are being developed, coordinated, built, and operated. Rather, BIM is a key to enhancing existing processes by allowing construction practitioners to process information more rapidly and make important decisions regarding project performance based on accurate information. However, the guidelines for USC, the City of New York, and Singapore recommend specific full-time positions to oversee the management of the BIM model and the process associated with it (e.g., BIM Facilitator/Engineer, BIM Trade Coordinator, etc.). Post-secondary institutions, including the University of Alberta's F&O, should acknowledge the importance of BIM-facilitating roles and consider including these roles in its projects' contracts.

Table 3 Documents reviewed within research scope

Name	Country	Release Date	Organization Type	Organization Name	Design	Construction	Operation	Energy Modeling	Procedures	Implementation	Legal	Interoperability
National BIM Standard - United StatesTM	US	July, 2015	Third party	buildingSMART alliance (bSa)	X	X	X	X		X		X
AEC (UK) BIM Technology Protocol	UK	June, 2015	Third party	AEC (UK) Intiative	X				X	X		X
AEC (CAN) BIM Technology Protocol	CA	September, 2014	Third party	CanBIM	X				X	X	X	X
Singapore BIM Guide	SG	August, 2013	Government	Singapore Government	X	X	X		X	X	X	X
New York City BIM Guidelines	US	July, 2012	Government	City of New York	X	X				X	X	X
GSFIC BIM Guide	US	March, 2013	Government	State of Georgia	X	X			X		X	X
State of Ohio BIM Protocol	US	July, 2011	Government	State of Ohio	X	X	X	X		X	X	X
Texas Facilities Commission Professional Architectural/ Engineering Guidelines	US	February, 2008	Government	State of Texas	X	X			X	X	X	X
USC BIM Guidelines	US	April, 2012	University	USC	X	X	X		X	X	X	X
Georgia Tech BIM Requirements & Guidelines	US	September, 2011	University	Georgia Tech	X	X	X	X	X	X	X	X
IU BIM Guidelines and Standards	US	July, 2015	University	IU	X	X		X	X	X	X	X
MIT CAD & BIM Guidelines	US	April, 2012	University	MIT	X	X					X	X

3.2.3 Which software to use (use of open or closed architecture application approach)

Figure 2 depicts the recommended working platforms and file-delivery format based on the reviewed guidelines. The importance of defining the working platforms and file format upon delivery arises from the need to eliminate the dependence on specific software vendors, which is substantial for the integrity of public bidding and contracting process.

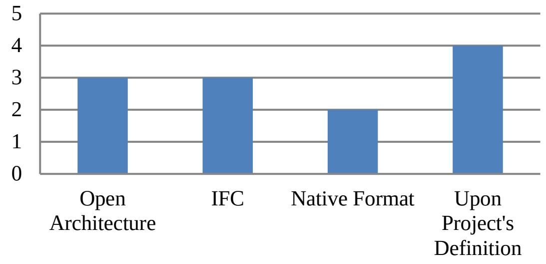

Figure.2 Summary of recommended work platforms required by guidelines

An intriguing finding from this study is that, although most guidelines encourage the use of open file formats for project coordination, several institutions require specific file formats for submittals. The authors believe this is since these institutions have obtained licenses and personnel training for specific software companies. To overcome this potential barrier, the University of Alberta's F&O can adopt a provision from the Texas Facilities Commission guideline, which states that, in the case that a consultant or contractor is using a different software than the one used by the client's F&O department, the consultant may provide the software license and necessary training as necessary for the given project. Figure 3 demonstrates the deliverable formats specified in the guidelines reviewed. It is clear that Autodesk products are preferred, along with the requirement for COBie at the Operation & Maintenance stage. This is presumably due to the predominance of these products in the North American market. In light of possible inconsistencies or problems encountered from not using a native file format, further reading in Singapore's guidelines and extra documentation is recommended since they have specific documentation for each of the notable commercial BIM authoring software suites available.

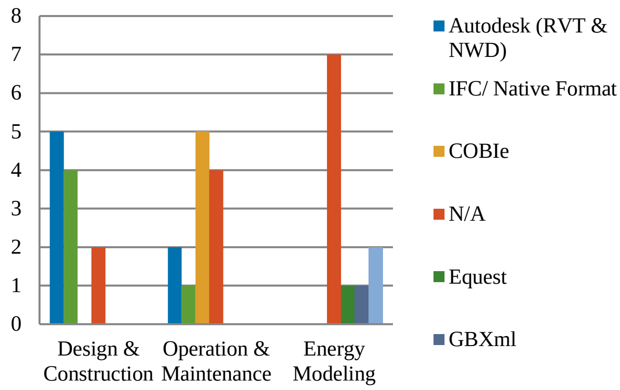

Figure.3 Deliverables format required in the guidelines reviewed

3.2.4 Ownership of the model

Clarification regarding the ownership of the model is a key component for successful implementation of BIM in any institution. Figure 4 summarizes the provisions laid out in the guidelines reviewed regarding this matter. It is noted that institutions with a broad portfolio do not have clear provisions regarding this matter (probably because of the high variability of projects within their scope). Most institutions require full ownership of the model and any related documents, establishing a precedent for the case institution to do the same. For more information about this matter, CanBIM and the State of Ohio's guidelines are recommended for further reading.

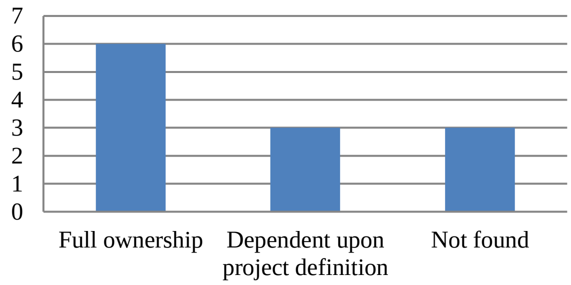

Figure.4 Stances of analyzed institutions regarding ownership of the model

3.2.5 Financial investment incurred from BIM

Manging the cost of BIM is also a cornerstone of its successful implementation. This issue is best characterized in terms of two questions: (1) from a cost perspective, when does it become feasible to implement BIM in a project as opposed to using conventional tools? and (2) how much are other institutions investing in BIM services? (The State of Ohio recommends using BIM for projects with a value of $4M or greater, while Georgia Tech and Indiana University recommend a threshold of $5M.) In order to quantify the potential savings resulting from the use of BIM, Table 5 summarizes the cost incurred from the use of BIM tools and services in consultant fees gathered from the BIM guidelines of Singapore and the State of Ohio. As shown in Table 5, these institutions do not intend to pay any premium for the use of BIM in their projects, but instead reallocate money among each project's stages to account for cost increases due to BIM implementation.

Table.4 Cost incurred from the use of BIM in total consultant fees (Adapted from Building and Construction Authority, 2013 and Ohio General Services Division, 2011)

Project Stage	% change from the use of BIM	
	Singapore	Ohio
Preliminary Design	+2.5%	0%
Schematic Design	0%	+5%
Design Development	+2.5%	+5%
Construction Documents	0%	-10%
Bid and Award	0%	0%
Construction Administration	-5%	0%
Contract Closeout	0%	0%

3.3 Define requirements of BIM guidelines for post-secondary institutions

After performing a comprehensive review of twelve guidelines from various institutions/jurisdictions, the authors conclude that there is a need for the case institution to develop their own guidelines, as no guidelines exist that fully address the expectations of the stakeholders. In this regard, three recommendations are made:

- The guidelines should span BIM uses and implementation during all project phases as per the project's lifecycle breakdown followed in the practice of the case institution.
- As per the guidelines reviewed, the case institution's guidelines should incorporate the following:
    - **BIM Execution Plan:** a document demonstrating which tools, responsible personnel, and strategies are employed by the Design Team and/or General Contractor regarding BIM tools.
    - **BIM Objective & Responsibility Matrix:** a document intended to define the level of detail of BIM objectives according to the design stage and personnel responsible for developing the model.
- The operational stage of a facility represents the largest proportion of cost in its lifecycle. Hence, the BIM guidelines should also consider the use of BIM to reduce the operational cost of the facility.
- The guidelines should clearly address the ownership of the models and other legal aspects of BIM implementation and use in the institution's regular practice.

These recommendations can be applied to public post-secondary institutions with similar responsibilities as the University of Alberta.

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Development of Web-based BIM Models Inspection and Modification Management System for Supervisions

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Abstract –

The building information modelling (BIM) approach, which is utilized to retain information in a digital format, facilitates easy information updating and transfer in the three-dimensional (3D) CAD environment. When the application of BIM models are adopted in the project, the inspection and and the inspection and modification records of BIM models are necessary to be communicated and managed effectively. However, emails, one of the most convenient ways, is selected and adapted as a communication tool among BIM manager, BIM engineers, and supervisions during the BIM models inspection and modification process. Also, it cannot record and manage the BIM models inspection and modification information and results effectively during the process. Therefore, this study develops a web-based BIM models inspection and modification management system integrated with workflow management. Concepts for supervisions to enhance BIM models inspection and modification work efficiency. The proposed system is applied to a case study of a building project in Taiwan to verify its efficacy. Finally, the study identifies the major benefits, limitation, and facing problems throughout the case study.

Keywords –

BIM; Building Information Modeling; Workflow Mangement; Web-based System

1 Introduction

Development of information communication technology(ICT) arouse the modern architecture, engineering, and construction (AEC) industry upgrading to Informatization. Researchers have been investigating the components and repercussions of building product models[1].Building Information Modeling(BIM) as a new term appeared in 2006 Autodesk new product description[2]. From conceptual to descriptive in nature, research or industry bodies as well as commercial software vendors import BIM into advanced study and practical applications. BIM is becoming mature due to developing collaboration platforms and related BIM uses. So stakeholders focus to manage BIM models information better than before.

Nowadays Cloud-based collaboration platforms have solved the interoperability of multi-disciplinary team. All of them have BIM models collaborative function corresponding to specific stakeholders. But this kind of operating mode have not been implemented in traditional inspection yet. Currently, supervision still inspects construction company BIM models in construction phase by email approach, a unilateral delivery method, which is lacking of communication with each other and leads to dispersing BIM models information. Therefore, the current traditional BIM models inspection must be improved, and also modifiable management workflow between supervision and construction company.

To address the above problems, this study expects to integrate BIM models with workflow management and web-based technology to develop an inspection and modification system of BIM models. It can improve the workflow management of inspection and modification for BIM models, and interactive coordination efficiency of supervision and construction company. Furthermore, supervision may utilize this system to control BIM models status in process. Through BIM models inspection and modification management system, supervision can proactive manage BIM models in the construction phase and confirm BIM models status in workflow. The system will also promote the consistency, correctness and completeness of BIM models information in the inspection and modification workflow.

2 Literature Review

Building information modeling (BIM) is an emerging technological and procedural shift within the Architecture, Engineering, Construction and Operations (AECO) industry[4], then BIM is not just a technological change, but also a change of process[5]. A set of interacting policies, processes and technologies are generating a “methodology to manage the essential building design and project data in digital format throughout the building's life-cycle”[3].

Establishing the goal of each phase in the building’s life cycle play an important role in BIM application. Each phase of milestones need to deliver documents, meeting records and signing contracts. Besides, milestones would separate design, construction and operation phase. The content of policy decision must be finished at this stage and the promise must be fulfilled at next stage[6]. Therefore, there is need for a framework that positions BIM as an ‘integration of product and process modelling' [7] and not just as a disparate set of technologies and processes.

Tien-Hsiang Chuang et al.(2011) indicate that BIM desktop applications can only integrate information on-site. Difficulties remain in obtaining and updating information from other sites, which restricts communication and information distribution between different sites. The study utilize the concept of software as a service (SaaS) and cloud computing in order to develop a visual system for BIM visualization and manipulation. This system cannot only visualize three-dimensional (3D) BIM models,but manipulate 3D BIM models through the web without the limitations of time or distance. Therefore, the system can facilitate communication and distribution of information between related participants in order to manage projects effectively and efficiently[8].

Rong-Chin Kuo et al.(2014) describe current BIM integrating, exchanging and managing information in BIM collaboration. Across disciplines have been major challenges in the AEC industry. This research designed and constructed a “BIM collaboration cloud platform” is based on Microsoft virtual desktop infrastructure (VDI). The platform benefits of the advantages of cloud computing which helps facilitate the integration of information across disciplines during the design and construction phase[9].

Zhiliang Ma and JiankunMa et al.(2017) indicate that existing collaboration platforms may be unable to support the collaboration among multiple participants and specialties due to this characteristic. The study formulates the application functional requirements for such a BIM-based collaboration platform by analysing case studies of integrated project delivery(IPD) projects. And then their conclusions indicated that a dedicated BIM-based collaboration platform is necessary. Formulated application functional requirements can be used in the development of such a platform or for customizing an existing commercial collaboration platform to improve the support of IPD projects[10].

3 System Development

Web-based BIM models inspection and modification management system includes three-tier framework : BIM models inspection and modification management and BIM model tracking mechanism.

3.1 System Framework

The system primarily assists BIM models inspection and modification between supervision unit and construction company. In order to dynamic communication in the workflow the study integrates BIM models inspection and modification management and three-tier framework, supplemented by permissions check. Furthermore, supervision unit may monitor the progress of BIM models inspection and modification status via configuring BIM model status as well as BIM model tracking mechanism for effective managing BIM models (see Figure 1).

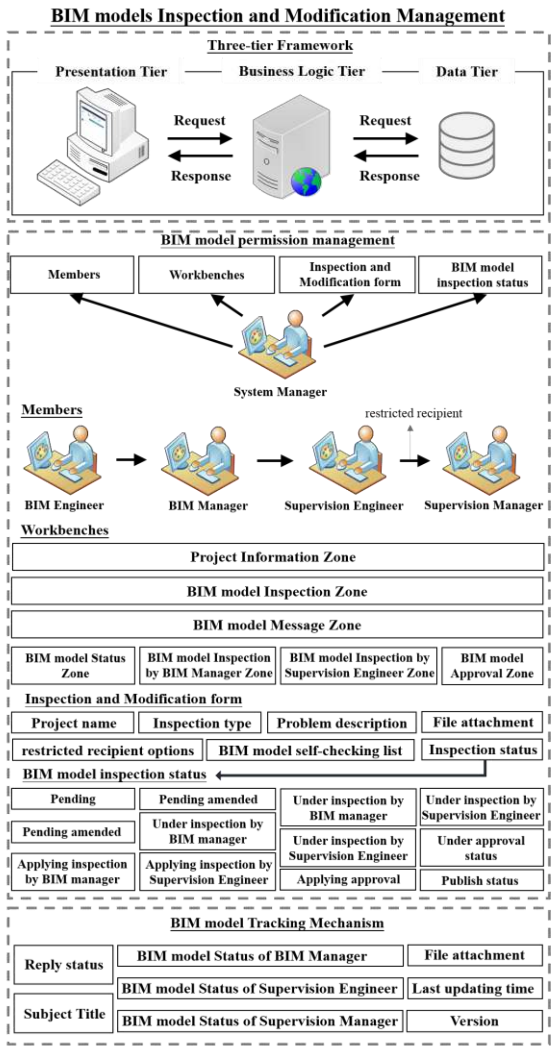

Figure 1 The Framework of BIM Models Inspection and Modification Management System

3.2 System Workflow

The main purpose of the system provides supervision unit the wok flow of BIM models inspection and modification to manage the AEC models of a construction company during the construction phase. Moreover, the system utilizes the same form throughout the work flow of the system for guaranteeing the correctness, completeness and consistency of inspective and modifying information (see Figure 2).

1. After BIM engineer has finished AEC models, logging in web-based BIM models inspection and modification management system, the BIM engineer get into BIM model inspection zone completing the inspection and modification form. In order to properly manage AEC BIM models uploading in a file attachment method, the format of BIM models allows txt, pdf, doc, jpg, png, nwc, nwd format, and then must get standardized name of the file. When BIM engineer submit the form at first time, the status of BIM model will display "pending" status.
2. If BIM manager has received the notification in BIM model inspection, the inspection of the form will start related BIM models. If BIM model inspections were passed by BIM manager, BIM models status of the form will ask for applying inspection status by supervision engineer. In case they were rejected by BIM manager, BIM models status of the form will be asked for modification of BIM engineer, pending amended status by supervision engineer.
3. When supervision engineer has received the notification of BIM model inspection then supervision engineer started to inspect the form and related BIM models. If BIM model inspections have been passed by supervision engineer, BIM models status of the form will be ask for applying approval status of supervision manager. If they were rejected by supervision engineer, BIM models status of the form will be ask for under inspection by BIM manager.
4. When Supervision manager receive the notification of BIM model approval then start to inspect the form and related BIM models. If BIM model inspections are passed by supervision manager, BIM models status of the form will become publish status update information of BIM models for owner and supervision unit. Otherwise, if they are rejected by supervision manager BIM models status of the form will proceed to under inspection by supervision engineer for reinspection.

3.3 BIM models inspection and modification management

BIM models inspection and modification management consists of three-tier framework, BIM model permissions management, and BIM model tracking mechanism, as follow:

Three-tier framework consists of Pesentation Layer, Business logic Layer, and Data Layer, as follow:

- Presentation Layer

This layer mainly transports the system members requestments to Business logic Layer and obtains Business logic Layer's output to display to related members. According to permissions of the system members to user's interface via Bootstrap for allowing supervision unit and construction company to utilize the system by computer or mobile device.

- Business logic Layer

This layer provides the web service for the BIM models inspection and modification by Drupal content management system and Apache HTTP server transporting the request of the presentation layer to data layer and extracts information from it. And transports the information of data layer to presentation layer.

- Data Layer

The system manages database and data backup via phpmyadmin. This layer stores all of the related system information.

BIM model permissions management consists mainly of members, workbenches, inspection and modification form and BIM model inspection status of BIM models inspection and modification management system. The workbench of system includes Member Management Zone, BIM model Inspection Zone, BIM model Status Zone, BIM model Inspection by BIM manager Zone, BIM model Inspection by supervision engineer Zone, BIM model Approval Zone, BIM model Message Zone, and Project Information Zone. Each workbench has specific rules to control system permissions. But all system members have access to project information zone, BIM model inspection zone and BIM model message zone.

The system has four kinds of members：BIM engineer, BIM manager, supervision engineer, and supervision manager, as follow：

1. BIM Engineer: This member mainly fills out the inspection and modification form and has BIM model status zone alone for BIM model condition in inspection and modification progress.

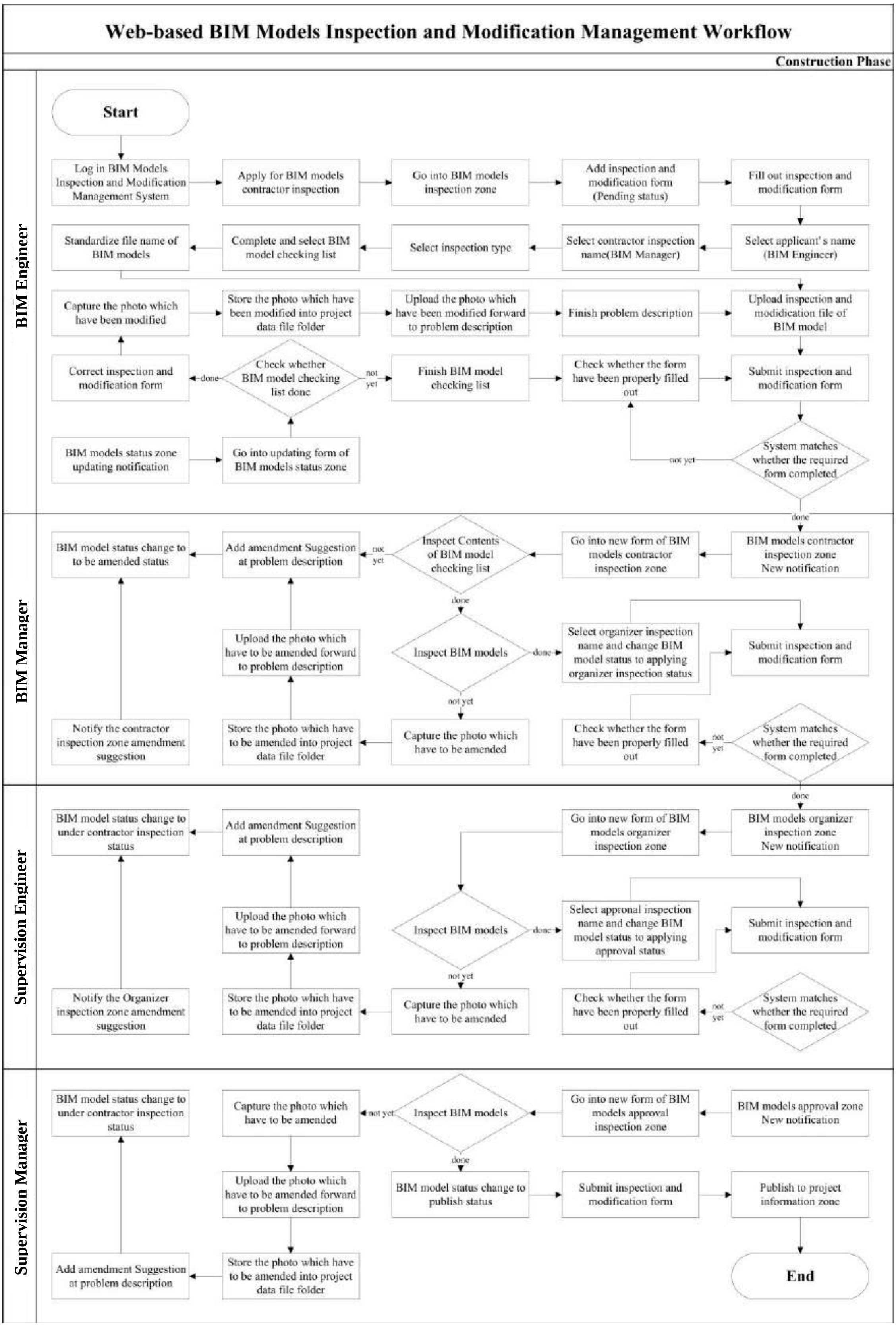

Figure 2 Web-based BIM Models Inspection and Modification Management Workflow

2. BIM Manager: This member primarily inspects BIM Engineer’s BIM model and has BIM model Inspection for implementing models or giving advice.
3. Supervision Engineer: This member inspects BIM Engineer’s BIM model being received by BIM manager and has BIM model inspection for implementing models inspection or giving advice.
4. Supervision Manager: This member primarily inspects BIM Engineer’s BIM model having received from supervision engineer and has BIM model Approval Zone for implementing models approval or giving advice.
5. System manager: This member primarily sets up the system, which masters members registeration and system permissions management before the project starts.

The content of inspection and modification form includes project name, BIM model inspection status, restricted recipient options, inspection type, BIM model self-checking list, problem description and file attachment. Especially, the name of file attachment is according to PAS1192-2:2013 published by British(as shown in Figure 3) .

Figure 3 The name of file attachment in the system

BIM model inspection status consists of pending status, pending amended status, applying inspection by BIM manager status, under inspection by BIM manager status, applying inspection by supervision engineer status, under inspection by supervision engineer status, applying approval status, under approval status and publishing status. According to permissions configuration, both system member and their workbenches have particular BIM model status before the project starts.

3.4 BIM model tracking mechanism

Permits each system member clear rights and efficient management is according by each permission of system members for clear rights and efficient management. BIM model tracking mechanism has eight kinds of functions including reply status, subject title, BIM model status of BIM Manager, BIM model status of Supervision Engineer, BIM model status of Supervision Manager, file attachment, last updating time, and version, as follow:

1. Reply status : When inspection and modification form has been changed, this column will display two kinds of symbols, one is “New”, another is “updated”. New symbol will display to each members, when they receive the form for first time, and updated symbol will show to all the system members when someone modifies or adds suggestions(as shown in Figure 5).
2. Subject Title : The content of the column shows the name of inspection and modification form via BIM engineer applying.
3. BIM Model Status of BIM Manager : The column shows the result of BIM model status which has been changed by BIM Manager. BIM Model Status of BIM Manager has four items, including pending amended status, under BIM manager status, applying inspection by supervision engineer status, and pending status.
4. BIM Model Status of Supervision Engineer : The column shows the result of BIM model status which has been changed by Supervision Engineer. BIM Model Status of Supervision Engineer has three items, including under inspection by BIM manager status, under inspection by supervision engineer status, and applying approval status. These three items represent three situations. When Supervision Engineer choose under inspection, BIM Manager must inspect again and then choose the BIM model status. When Supervision Engineer choose under inspection, it means that the form is inspected. When Supervision Engineer choose applying approval status item, Supervision Manager must inspect and then choose the BIM model status.
5. BIM Model Status of Supervision Manager : The column show the result of BIM model status which has been changed by Supervision Manager. BIM Model Status of Supervision Manager has three items including under inspection by supervision engineer status, under approval status, and publish status. These three items represent three situations. Under inspection by supervision engineer status item means that the form needs to be inspect again. Under approval status item means that the form is being inspected, and publish status item means that has been notified every system member.
6. File attachment : The file of BIM models inspection and modification management system is mainly nwc format because it commonly used to view and discuss BIM model.
7. Last Updating time : The column primarily provides the newest updating time. System members inspect and modify early to improve efficiency between members and shorten the period of inspection amd modification for proactive management.
8. Version : The column indicates that the sum of inspection and modification and allows time

control by Supervision unit and applies related knowledge management in the future.

4 Case study

4.1 Description of the case study

The present study used Autodesk Revit 2017 developing the proposed BIM model and converting rvt to nwc format. And then, the system as BIM model inspection and modification platform exists between construction company and supervisions. The case type chose construction phase of medium building engineering to test the system benefits and limitations, because of general and ordinary scale.

4.2 Implementation

The case building that is examined in the present study is construction phase of National Taipei University of Technology, Sixth Academic Building. First, BIM engineer converts the built rvt format BIM model to nwc format, and furnishes inspection and modification form then applying inspection. Second, BIM manager receives notification of BIM model inspection by BIM manager zone. When the form passes, BIM manager turns the BIM model status to apply inspection by supervision engineer status, on the contrary turn the status to pending amended status. This moment the reply status column of BIM engineer's BIM model status zone display new update message. BIM engineer utilizes this zone to modify the BIM models and gets the latest inspection status(as shown in Figure 4). Finally, by repeatedly modifing and inspecting the BIM model, passing the inspection of BIM engineer, supervision engineer and supervision manager, and then publishing the BIM model information to project information zone by supervision manager for renewing the latest information to all members in the system.

4.3 Discussion

The system solves many of practical problems, for example BIM engineer may transmit BIM models to wrong recipients, BIM manager or supervision unit's members may inspect incorrect models because lacks version control, and all members cannot understand what situation BIM models inspection are. So the system provides some solutions as follow:

- The inspection and modification form of system limits authors and recipients via fixed button items to avoid wrong submitting.
- The system utilizes BIM model tracking mechanism to monitor BIM model status and centralize BIM model information, for example versions and BIM model status of all members.
- Through web-based BIM models inspection and modification management workflow clear defines responsibilities of supervision unit and construction company for more efficient and higher quality production.

However, the system handles many of practical problems above. Some limitations and difficulties still existence as follow:

- The system only designs photos uploading and text editing for describing BIM model, it cannot operate BIM construction management software online. System members have to view, rotate, and markup models by their own BIM construction management software.
- The system status changes by permitted members presently, it is inconvenient because members must change status by themselves. In the future, the system may optimize for automation of BIM model status changes.

5 Conclusion

BIM technology has already developed the BIM modeling mode by changing design model to construction model. But Supervision unit cannot control the status of BIM model's modification and inspection during construction BIM modeling process, as well as construction company cannot timely obtain the result of BIM models approval and the suggestion of the unit concerned. In addition, supervision receives the file of BIM model by papers, emails, FTP, or cloud-based platform which are one way delivery, and the whole procedure lacks permission of management.

To improve the efficency and workflow management of BIM models inspection and modification between supervision unit and construction company. The study develops Web-based BIM models inspection and modification management system, integrating BIM models inspection and modification management and tracking mechanism with permission management and dynamic communication method.

1. For submitting BIM models inspection, Web-based BIM models inspection and modification management system proposes permissions management solution. It helps supervision unit managing BIM models information and actively controlling inspecting progress.

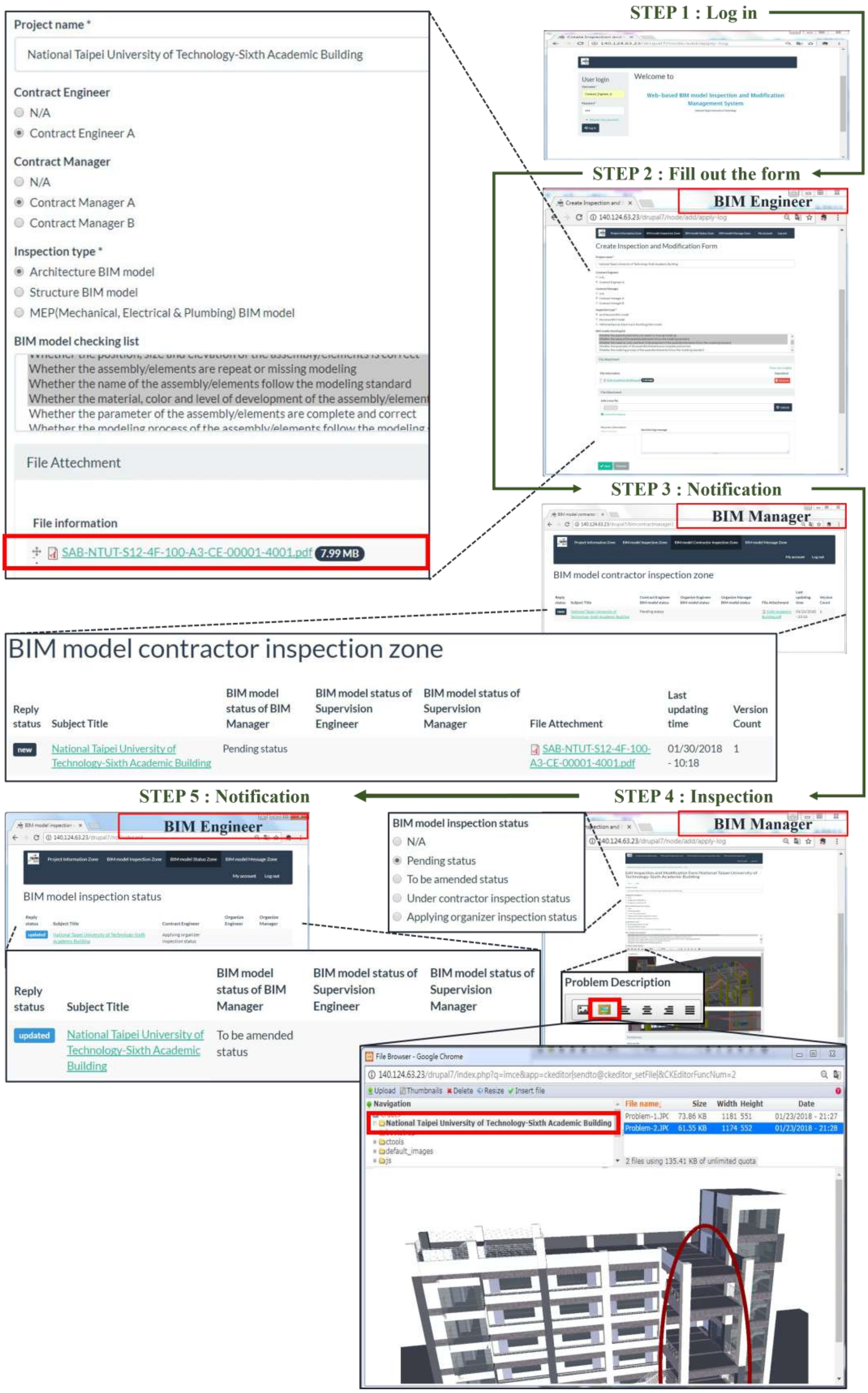

Figure 4 Operation of the BIM model inspection and modification management system

2. BIM models inspection and modification management system supplements traditional inspection workflow. BIM manager, supervision engineer and supervision manager inspect BIM models by single inspection and modification form. It helps improving the correctness, completeness and consistency of BIM models information.
3. BIM model self-checking list helps BIM engineer examining models and providing other members initial inspection. Supervision unit can obtain error-prone items in the list at the end of the project, for next related project inspecting focus.
4. BIM model message function strengthens communication and the efficiency of BIM models modification among BIM engineer and BIM manager, and then enhances BIM engineer the site experiences.
5. BIM model tracking mechanism provides active BIM models inspection and modification management in the construction phase. Let all members understand what present BIM models inspective phase is now and which version is.
6. BIM model developing process information will be stored in system’s database, analyzing the amendment suggestion and feedback to inspection and modification form to adjust the form item for assisting construction phase BIM modeling and BIM knowledge management.
7. Frequently, BIM models have variety of elements and components in the construction. The numerous number of inspection and modification forms will be submitted, so we need to visualize the inspective status for better management.

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Classification of Images from Construction Sites Using a Deep-Learning Algorithm

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Abstract –

Field engineers take and collect several pictures from construction sites every day, and these pictures serve as records of a project. However, many of these images are loaded to and remain on computers in an unorganized manner because tagging, renaming, and organizing them is a time-consuming process. This paper proposes a method for automatically classifying construction photographs by job-type using a deep-learning algorithm. The first goal of this study is to classify construction images according to 27 job-types based on OmniClass Level 2. Google Inception v3—a deep learning algorithm used in this study as an image classifier—was trained using 1,208 construction pictures labeled by job-type. To improve the performance of the classifier, the optimized number of trainings was determined by examining the changes of accuracy and cross-entropy during trainings. The first result shows the incidence of several trainings over 50,000 was not meaningful. The retrained Google Inception as a construction image classifier was validated using a total of 235 images. The validation result shows that the classifier demonstrates an accuracy of 92.6% in classifying inputs properly and an average precision of 58.2% in correct classification. This means that retrained classifier can classify approximately nine out of every ten images correctly and that the deep-learning algorithm has high potential for use in the automatic classification of images from construction sites.

Keywords –

Image classification; Deep learning; Construction site monitoring; Convolutional neural network;

1 Introduction

Pictures taken by field engineers on a construction site contain various information about the site. From a daily report of construction progress to the construction method implemented for each project, pictures have an important role in project documentation, and enormous amounts of pictures are taken to establish a visual record. However, because thousands of pictures are taken for construction projects, the pictures are usually stored in a computer in an unorganized manner after a project has been completed. To properly utilize the information available from these pictures, the pictures must first be classified before they are stored.

This paper proposes the use of a deep-learning algorithm to automatically classify pictures from construction sites according to the job-type that each picture contains using a deep-learning algorithm. After AlexNet [1] won the first prize at ILSVRC 2012 (ImageNet Large Scale Visual Recognition Challenge) using a convolutional neural network (CNN), CNN became the most popular deep-learning method in image classification. Since then, the field of image classification has been developing rapidly. Through the constant development of image classification algorithms, recent studies have reached 96% accuracy in image classification [7].

This study uses Google Inception v3—the latest CNN developed by Google [2]—as an image classifier to automatically classify construction pictures by job-type. To test the performance of the trained classifier, 1,208 pictures were used for training, and 27 images were used for validation.

This paper is divided into five sections. The second section presents a review of previous studies related to this research. The third section describes the overall design of the research and, section 4 reports the experiments and the analytical results. The final section reports the paper's conclusions.

2 Background

2.1 Image Classification on Construction

Several studies have been conducted regarding how

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to extract information from images of construction sites. A recent study related to image processing focused on object detection from pictures of a construction site. Chi and Caldas [9] suggested a way to find objects from images using an artificial neural network (ANN), and Zhu et al. [4] proposed a method of finding concrete area in a picture using parameter optimization. In addition, Wu et al. [15] used image filtering in order to find specific objects from construction images.

Currently, however, meaningful data is generated from images using the previously developed technique. Kim et al. [3] derived information regarding construction progress from construction images by combining project schedule data and filtered images. Also, Kim et al. [16] suggested a method of measuring the construction progress that uses the 4D information of a given building. More recently, adopting deep-learning, Fang et al. [10] proposed a way to detect non-hardhat users in a construction site. Like the above two studies, not only detecting object from images, but also extracting data that can be useful is the main problem of recent studies. Thus, in this study, we extract the job-type information from construction pictures and use it to classify those pictures as a standard using a deep-learning algorithm.

2.2 Deep learning

In 2012, an image classifier constructed with a deep-learning algorithm was introduced at ILSVRC 2012. The name of the algorithm was AlexNet [1], and it was composed of a CNN with eight layers. With a 16.4% error rate, it surpassed its competitors, whose error rates were over 26% on average, and won the first prize. Since then, CNN has become prominent in the field of image classification, and algorithms composed of CNNs show high accuracy nowadays [5][6][7].

The major difference between deep learning and conventional machine learning based on image processing is not only the high accuracy of image classification but also the ability to conduct feature extraction. The former requires a pre-process of image filtering or feature extraction, whereas a deep learning algorithm can conduct feature extraction automatically by using a huge amount of training data [8]. Although deep learning is being criticized for being a black box approach, its implementation process requires a clear goal first, a deep learning network design, and data collection and analysis based on the goal. Moreover, a considerable amount of programming and optimization efforts is required.

2.3 Google Inception v3

In general, when the structure of a neural network deepens and widens, the performance of the network improves. However, the likelihood that overfitting and vanishing will occur also increases. To prevent overfitting and vanishing, GoogleNet [5] is designed with multiple (22) concatenating layers. Based on its structure, GoogleNet won the first prize at ILSVRC 2014 with a 6.7% error rate. To classify images, we used Google Inception v3 [2], which is developed from GoogleNet. Compared with the previous version, Inception v3 has an improved network structure.

When supervised learning is implemented, both images and label data are needed. The label data indicates what information each image contains. Therefore, in order to use this network in our research, we must retrain the network with labelled pictures that have been prepared for retraining in advance. Using the pictures from the training dataset with label data, the classifier learns each picture and label data in a pair. For example, if an image is given to the classifier after retraining a similar picture with a "Foundation" label, it may determine that the input image is about "Foundation".

3 Research Method

Figure 1 describes the overall research flow. First, pictures from construction sites are gathered for training and validation of the image classifier: Google Inception v3. One of strengths of Google Inception v3 is that it has already pre-trained with a very large set of various types of images from ImageNet [12]. Google Inception v3, however, should be "retrained" with an additional set of images if it is used for a new purpose [13]. Thus, the second step is to retrain Google Inception v3 with construction images labeled by job type so that it can be used as an image classifier for construction pictures [13]. During the retraining process, the classifier learns which image features are associated with which job type.

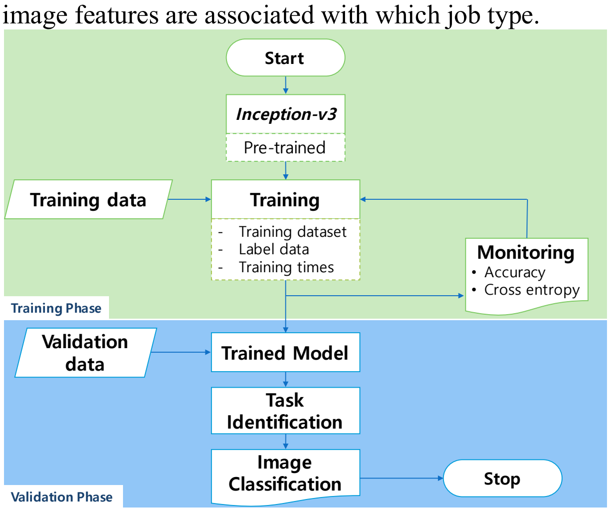

Figure 1. Overall flow of research

At first, we optimized the number of training times with the given training dataset before validating the classifier. Then, after the retraining procedure with the optimized training times was conducted, new images from the validation dataset were inputted into the classifier. Comparing the results, we checked the accuracy and precision of the classifier.

In this study, OmniClass was used as a standard for labeling pictures by job-type. OmniClass is system for classifying the type of construction industry [14]. According to OmniClass, there are 16 tables that can be used to classify the type of industry, and we chose Table 21 – Elements. Originally, there are 29 categories in that table, but we eliminated two categories because they have ambiguous definitions: Integrated Automation and Facility Remediation.

3.1 Training dataset preparation

Because the input image should be classified according to the job-type of construction, we set the 27 standards referring to OmniClass Level 2 categories. After the standard of construction elements was classified according to OmniClass, prepared pictures of the training dataset were labeled by each adequate category. A total of 1,208 pictures in 27 categories were used as construction job-types and the training dataset, and 44 pictures on average were distributed for each category.

4 Experiment & Result

To validate the module, we conducted two different experiments. First, we retrained the classifier 400,000 times with 1,208 pictures in order to find the optimized training time. It is ideal to train a very large number of pictures many times, but, in reality, it is challenging to acquire a large number of pictures and a long training time. Thus, observing the training graph, we tried to determine the optimized point of the training times using a given number of pictures. Second, after retraining the classifier again with the optimized point, we put new images that were not used for retraining into the classifier. Through the two experiments, we yielded a retrained classifier that was optimized and how well it classifies images accurately and precisely.

4.1 Optimization in training times

We used the stochastic gradient descent (SGD) algorithm for the optimization process. SGD requires training of the classifier with the same set of data multiple times to progressively fit the classifier to the training dataset. After the trained classifier is fitted well to the training dataset as the training time increases, it can classify new input data based on the optimized parameters inside the classifier [18]. Thus, training should be repeated for fitting with the same dataset. In general, the performance of a classifier improves as the training time increases. However, too much training can cause an overfitting problem, which worsens performance. Training also takes much time. To maximize the efficiency of the training process, we retrained the classifier 400,000 times and looked for the optimized point. During the retraining, the accuracy value when random data are inputted and the cross-entropy data are extracted, and they were used to assess performance.

4.1.1 Accuracy

Giving the classifier random data during the retraining process, we extracted accuracy data (Figure 2). The average accuracy refers to how well the classifier distributes the random input data into correct categories. In this process, the input data is not an image used for retraining but the randomly created image that has label information.

Figure 2. Accuracy (y-axis) changes according to the number of trainings (x-axis). Average accuracy (thick line) first rises dramatically but then hardly changes after the training time exceeds 50,000.

The accuracy value initially increased, but after about 50,000 times of training, the increasing stopped and the value started to fluctuate. With a value of 0.770, the average accuracy is the highest with a training time of 36,700. Figure 2 shows that conducting more than 50,000 trainings is not meaningful in terms of efficiency.

4.1.2 Cross-entropy

Figure 3. Cross-entropy value (y-axis) initially decreases (x-axis) but gradually increases as the training time exceeds 50,000.

In information theory, cross-entropy is an index that shows the difference between two probability distributions. It is well used for optimization problems and machine learning as a loss function. For one layer, when we suppose p_i represents the probability of the true label and q_i represents the distribution of the predicted value, we can define the cross-entropy loss $H(p,q)$ as follows [17]:

$$H(p,q) = -\sum_i p_i \log q_i$$

However, as we have N layers in the classifier algorithm, we need the averaged loss value J so that we can infer the loss of the whole layers. Then, J can be calculated as follows:

$$J = \frac{1}{N}\sum_{n=1}^{N} H(p_n, q_n)$$

In this study, p_i indicates the value distribution of the classifier in the retraining process, and q_i indicates that of the training dataset. Then, the value J represents how different the distribution of the classified output is from that of the original training dataset when random noise data are inputted during the retraining process. Therefore, the low value of cross-entropy indicates a well-trained model, and it is utilized as a loss function in the optimization problem in a direction that minimizes its value [11]. Therefore, a low cross-entropy value indicates that the training was done well.

The result graph (Figure 3) shows that the minimum cross-entropy value, 0.9561, occurs with 36,700 training times and starts to increase gradually after about 50,000 training times.

4.1.3 Determining optimized point

When it comes to accuracy results, the performance of the classifier does not change after the training times exceeds 50,000 although there is some fluctuation. However, when the result of cross-entropy is considered with accuracy together, it is recommended to select an optimized training time that is between 35,000 and 50,000. In this study, we retrained the classifier 37,000 times and conducted further research.

4.2 Validation

After retraining the classifier with optimized training times, validation of whether the retrained classifier works well. In this study, the validation process was implemented by inputting new images that were not used for training. Eight images on average for each category were prepared, so a total of 235 images were inputted to the classifier and some example images are shown in Figure 4.

The result is shown in Figure 5. Categories on the x-axis are the labels of input images, and categories on the y-axis are those for labels created automatically. The numbers in the cell indicate the averaged probabilities of the input images having the label of the y-axis when the images labelled with the categories on the x-axis are inputted. The probability numbers are used to indicate precision, and their sum on each column should ideally be 1.00. However, some of them do not reach 1.00 because probabilities below 0.05 are eliminated during the process of being averaged. The yellow cell also indicates the highest number in each column, and the classifier defines the image as the label on the y-axis of the cell at that time.

Figure 4. Example images used for validation

For example, if the input images are classified arbitrarily, the numbers of every cell should converge to 3.7%, and the output labels should be determined randomly. However, when the unlabeled images that

Resulted Categories \ Label of input images	Foundation	Subgrade enclosure	Slab on grade	Water and gas mitigation	Substructure related activity	Superstructure	Exterior vertical enclosure	Exterior horizontal enclosure	Interior construction	Interior finishes	Conveying	Plumbing	HVAC	Fire protection	Electrical	Communication	Electronic safety and security	Equipment	Furnishings	Special construction	Demolition	Site preparation	Site improvement	Liquid and gas site utilities	Electrical site improvement	Site communication	Miscellaneous site construction
Foundation	0.31		0.06		0.03						0.01													0.20			
Subgrade_enc		0.26	0.16		0.05	0.12			0.09		0.04				0.03			0.03									0.03
Slab on grade		0.07	0.11	0.02				0.03				0.03						0.02							0.06		
Water and gas mitigation		0.02	0.14	0.66	0.03																		0.02	0.02			0.15
Substructure related activity	0.05	0.15	0.03	0.02	0.55			0.05													0.01	0.03					0.03
Superstructure		0.19	0.12		0.01	0.68	0.04				0.17				0.06			0.11		0.02							
Exterior vertical enclosure	0.09	0.01			0.01		0.45	0.12	0.08	0.02	0.02	0.09	0.07														
Exterior horizontal enclosure		0.03	0.04				0.07	0.50	0.08							0.28				0.01			0.07				
Interior construction						0.01	0.09	0.02	0.48	0.12	0.04		0.04		0.06		0.06										
Interior finishes									0.02	0.73																	
Conveying	0.27	0.06						0.01	0.02		0.17				0.08					0.03							
Plumbing			0.07	0.14	0.03			0.06	0.02		0.03	0.38	0.02	0.08	0.10								0.01				
HVAC						0.09				0.02	0.09	0.03	0.56	0.09	0.21			0.02			0.01						0.05
Fire protection												0.17		0.68				0.08									
Electrical						0.01	0.13	0.14	0.01	0.02	0.10	0.07	0.07		0.25												
Communication																0.34											
Electronic safety and security												0.03					0.73	0.04							0.01		
Equipment									0.06		0.05		0.03				0.03	0.48	0.02								
Furnishings																	0.02	0.02	0.94	0.12							
Special construction							0.03				0.01	0.01	0.09							0.66							
Demolition	0.16				0.01						0.05							0.02		0.01	0.77	0.07			0.09		
Site preparation				0.04	0.14																0.07	0.81	0.01		0.01		0.07
Site improvement												0.03		0.03							0.01		0.73		0.01		0.01
Liquid and gas site utilities			0.01	0.03																			0.07	0.75			0.03
Electrical site improvement	0.08										0.03	0.02				0.35				0.03	0.04				0.67	0.09	
Site communication							0.03							0.03												0.86	
Miscellaneous site construction											0.04				0.02			0.08									0.50

Figure 5. Distribution of averaged precision (numbers) and resulted labels of job-type (y-axis) when the original label of input images (x-axis) is given. The numbers in yellow cells indicate the maximum precision of each column

should be classified under "Foundation" are inputted into the classifier, they are classified under the correct category with 31% precision. They could be classified under the "Conveying" category with 27% precision, but it is not considered because job-type inferring only follows the category with the maximum precision.

The classifier shows 92.6% accuracy, and the average precision on correct data is 58.2%. Among the 27 categories, 25 categories were classified properly and two categories were classified incorrectly. While the result of "Communication" is close to those of the adequate categories, that of "Slab on grade" has less precision than 12%. Also, the precision of some job-types is distributed to other job-types that have similar visual characteristics. This indicates the confusion that can occur due to human error can be similarly occurred by deep-learning, and it can be fixed to some degree by complementing more featured images or combining those categories.

5 Conclusion

Although there are lots of pictures taken from construction sites, not enough studies to manage them are conducted yet. We propose a method of classifying pictures taken from construction sites using deep-learning algorithm in order to automate the process.

The performance test shows that a deep-learning algorithm (Google Inception v3) can automatically classify construction pictures into OmniClass Level 2 with more than 90% of accuracy when it was trained with 1,208 images. The major contribution of this study is on suggesting a method of automation in documentation. The result shows that the classifier with deep-learning can do some of documentation task instead of human only after retrained with pictures taken in advance.

In fact, recognizing the process of optimization when a deep learning algorithm is used is difficult. However, it is only based on complex mathematical calculation, not on the black box totally [19][20]. For the appropriate result from deep learning to be obtained, the algorithm should be designed first, and a large volume of data for training should be arranged well. This study used over 1,400 images for training and validation, but more reliable results can be derived if a larger number of images were used during the training and validation. Moreover, this study shows that an automated construction-picture classification method solely based on CNN has room for improvement. This paper reports the first step toward developing a reliable classifier for construction work by using deep learning. We are developing it further to improve its reliability. We are planning to develop a new algorithm based on a semantic approach and deep learning (CNN) to improve performance in terms of precision and accuracy with the use of a larger number of construction pictures.

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Crack detection in frozen soils using infrared camera

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Abstract: Frozen soils are encountered on construction site in the polar regions or where artificial frozen ground (AFG) method is used. Thus, efficient ways to monitor the behaviour and potential failure of frozen soils are on demand. The advance in thermographic technology presented an alternative solution as the deformation occurred in frozen soil would generate inter-particle friction heat, and hence increase in temperature. In this research, uniaxial compression tests were conducted on cylindrical frozen soil specimens of three types, namely clay, sand and gravel. During the tests, the surface temperature profiles of the specimens were recorded by an infrared video camera. The thermographic videos were analysed, and the results shows that temperature increase caused by frictional heat can be observed in all three frozen soil specimens. Therefore, such temperature increase can be deemed as an indicator for the potential failure of frozen soil and such method is applicable for monitoring purpose.

Key words-
Frozen soil; Infrared camera; Crack

1 Introduction

Historically, human has been living and building structures on frozen ground in arctic area where the annually average temperature is below the freezing point of water. And artificial frozen ground (AFG) method has gained its popularity as a technique to stabilise soil during excavation recently. Due bonding effect of ice, frozen soil is more rigid and stronger than normal soil and may demonstrate mechanical behaviour similar to concrete. The crack initiation and propagation in concrete has been studied by many researchers, but few studies are focused on cracks of frozen soil.

As crack occurs, there is relative movement of soil particles around the crack, and hence frictional heat. The frictional heat may cause temperature increase, which can be observed using thermographic devices such as an infrared camera.

Researchers successfully used infrared camera to detect phenomenon with temperature changes, such as oil product spreading on water surface [1], wild fire [2], and wind flow[3].

Specifically, thermographic technique has been applied to defection in structures. Seo and Choi [4] detected crack formation in pillars using infrared camera. Though in some cases, the defection does not generate temperature change when the structure is at rest. When heated by external source, defections will show different temperature comparing to the rest of structure. Broberg [5] used infrared camera to detect defection in welds based on temperature difference between defection and its surrounding surface while the weld was heated by a flash lamp as an external IR source. Štarman and Matz [6]observed the propagation of artificially generated thermal pulse the in steel bars using infrared camera to locate the presence of cracks.

2 Thermal graphic imaging

Infrared is an electromagnetic radiation emits by all body above 0 K. The characteristic of the radiation depends on the temperature of the body so that the temperature of the body can be determined by the measured temperature. When an object is photographed using the infrared camera, the infrared radiation energy emitted by the object is received by the sensor of infrared camera and simultaneously converted to electronic signal. Then the electronic signal is processed by the controlling software to generate the thermal graphic image or, in short, thermograph.

Although to measure the absolute value of temperature with high precision using infrared camera requires robust and sophisticated calibration and strict control over atmospheric condition, the change in temperature can be detected remotely and non-intrusively on a large or small scale desired in specific scenario. Additionally, the thermograph also provide 2D geometry information which cannot be provided by other types of thermal sensors. Therefore, infrared camera is used in this research to detect crack formation in frozen soil in this research.

3 Experimental apparatus setup

In this research uniaxial compression test are conducted on frozen soil specimens while the specimens are subjected to an infrared camera. The arrangements of the experimental apparatus are shown in Figure 1.

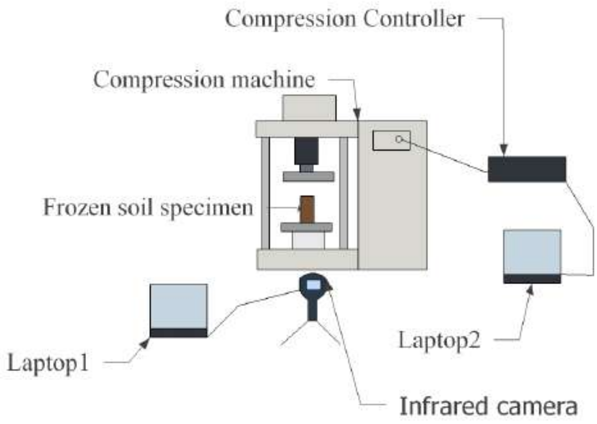


Figure 1. Experimental apparatus setup

The infrared camera is place approximately 1 m in front of the compression machine. The load is recorded at a frequency of 10 Hz. The Time-load curve is visible simultaneously on the laptop2 controlling the compression machine. The uniaxial compression test is terminated when the specimen fails or the lift of piston reached its capacity.

3.1 Specimen preparation

Three cases of soil category are considered in this study, namely clay, sand and gravel. For the clay specimen. The undisturbed clay sample extracted from 3 meters depth is cut into a cylinder of 100 mm (diameter) by 150 mm (height). And then submerged in a water tank for 24 hours to reach saturation. Afterwards it is put in the freezer for at least 24 hours. For the Sand and gravel cases, the soil particles and water are poured into moulds iteratively to make sure the specimen is fully saturated and composition relatively uniform across the height. Then they are frozen in a freezer before removed from the mould. Afterwards, the specimen are again stored in the freezer for 24 hours before test. Figure 2 shows process to make the frozen sand specimen.

Figure 2. Preparation of frozen soil specimen

Due to mechanical disturbance during the removal of the specimen, the height of sand and gravel specimen are not strictly controlled. The geometric information of specimens are shown is Table 1Figure 3 and the photos of specimens taken before the uniaxial compression tests are shown in Figure 3.

Table 1. Geometry of specimens

Material	Height (mm)	Diameter (mm)
clay	150	100
sand	171	100
gravel	179	100

(a) (b) (c)

Figure 3. Frozen clay (a) sand (b) and gravel (c) specimens before uniaxial compression tests

3.2 Infrared camera

The infrared camera used is Flir E60.When an object is photographed using the infrared camera, the infrared radiation energy emitted by the object is received by the sensor of infrared camera and simultaneously converted to electronic signal. Then the electronic signal is processed by the Flir R&D controlling software to generate the temperature profile. The exported results file consists sequence of thermographic photos taken at a frequency of 30 Hz and resolution of 320*240 pixels. Each pixel in a frame has its temperature measured. The exported thermographic files are analysed using software Flir Research IR. The thermal sensitivity is 0.05°C and accuracy is ±2°C.

4 Result and Analysis

Due to lack of pre-existing knowledge of what and how a crack would appear in thermograph of frozen soils. The thermographs were carefully examined frame by frame. The qualification of a crack can be qualitatively described as follows:

- Significant temporal temperature variation, comparing to the immediate surrounding area (baseline), occurs at certain spots of relatively small area.

- The temperature variation initiates within the specimen surface and is not transmitted from the interface between specimen and ambient environment.
- The temperature variation is sustained more than 1 frame, which disqualifies those false positives caused by random flocculation in measured value of temperature.
- The temperature variation is not caused by mass transportation i.e. movement of disintegrated soil particle or water flow thawed from ice.

4.1 Crack in frozen clay

As shown in the load-time curve in Figure 4, the load peaks at 96.30 s after test started.

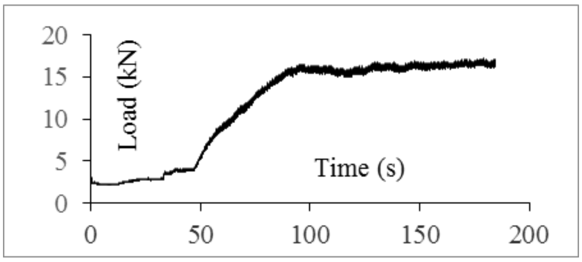


Figure 4. uniaxial load-time curve of clay specimen

After 96.30 s, temperature of certain points on the specimen surface appears to increase at a slightly higher rate than that of the rests. One example is indicated in **Error! Reference source not found.** as the crack point. A baseline point about 4 mm downwards of the crack point is selected to mitigate the effect of measurement error and the effect of heating from the ambient atmosphere on the variation of temperature.

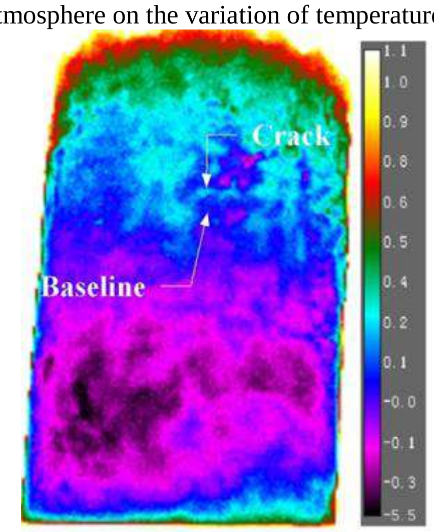


Figure 5. Temperature profile of clay specimen

The temperature-time curve for the crack point and baseline point are plotted in Figure 6. Disregarding the random flocculation, from 105 s to 123s seconds, the T increases from -3.02 °C to -2.41 °C. The temperature increase at crack point is further verified by the temperature profile along a line approximately perpendicular to the crack as shown in Figure 7. Temperature profile at the start of the test (0 s), immediately before the crack occurs (105 s), and after the crack forms (125 s), are plotted. Before the crack occurs, there is no significant difference in temperature between potential crack point and the rest. After the crack is formed, the temperature at the crack point is 0.57°C higher than those at points not influenced by the crack.

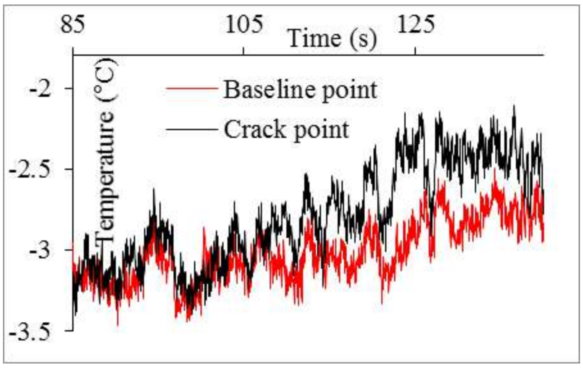


Figure 6. Temperature-time curve of crack point and baseline

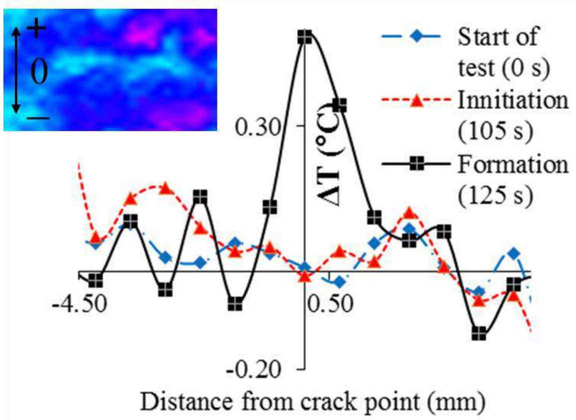


Figure 7. Temperature profile along a measurement line approximately perpendicular to the crack (the position of the measurement line is marked on the temperature profile attached on the top left)

4.2 Bulge effect in frozen sand

Although there is no individual crack observed in the sand case. As the frozen sand specimen is compressed, the. The expansion in radial direction, which we call bulge, becomes significantly visible after yield and the phenomenon can also be correlated to temperature variation. The temperature of three representative points located at upper part (U.), lower left part (L.L), lower right part (L.R), and average temperature of a square area (S.) are selected to demonstrate the effect of bulge on temperature. The locations are indicated in Figure 8.

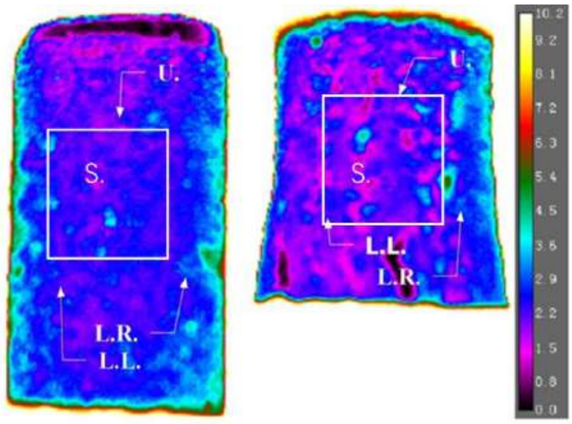


Figure 8. Temperature profile of frozen sand specimen at start (left) and end (right) of compression test

.

The temperature and load curves are plotted together in Figure 9. As the bulge of the specimen becomes obvious after yield (64.9 s), the temperature of every single point of specimen surface demonstrate 4 simultaneous impulsive increase initiating at 66.80 s, 88.30 s, 99.53 s and 110.30 s respectively. Impulses are not observed at points outside of the specimen surface, which means these impulses are not measurement error. The magnitude of ΔT for the impulses ranges from 0.37 to 0.95 °C.

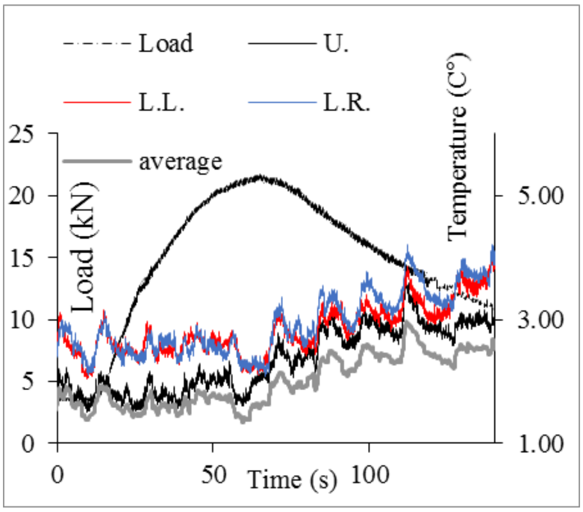


Figure 9. Load curve and temperature-time curve of sand specimen

4.3 Cracks in frozen gravel

Two types of cracks are observed during the compression test of the gravel specimen. The cracks, which occur in-between gravel particles, cause increases of temperature at crack point. Such cracks are noted as I1, I2 I3, and I4 following the initial of the word ‘increase’. Temperature decrease at crack point is observed for cracks occur within ice block. Such cracks are noted as D1, D2, D3, D4, D5 and D6 following the initial of word ‘decrease’. The ideal temperature variations for cracks of type I and D are illustrated in Figure 10. When cracks occur between gravel particles, the inter-particle friction generates heat. But those friction is relatively negligible between ice surfaces due to its smoothness. Even though there were heat generated around ice particles. The heat would probably be consumed by melting of ice rather than cause temperature increase. The temperature decrease is due to the temperature gradient from the surface to the inner core of specimen. When crack widens, the inner surface of the specimen, the temperature of which is lower comparing to the outside, is exposed to the camera. The location of these two types of cracks are indicated Figure 11.

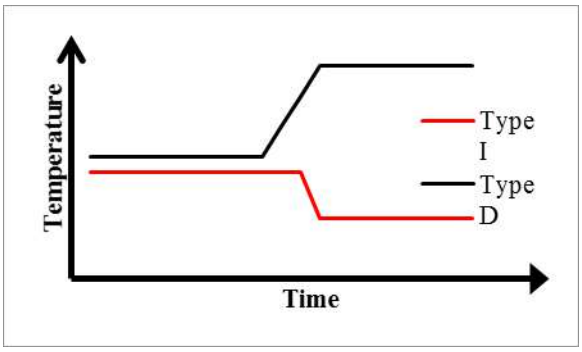
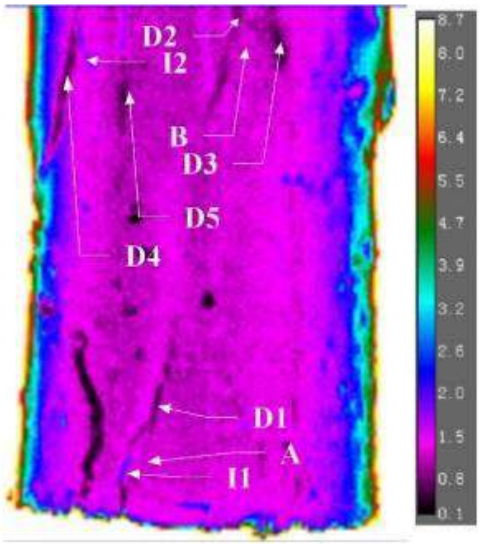
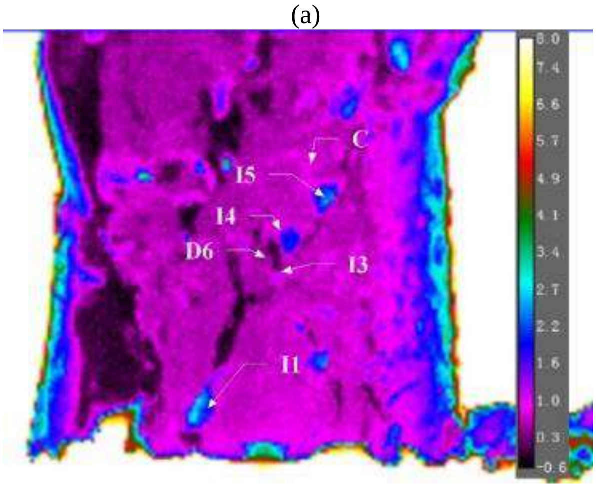


Figure 10. Ideal temperature-time curves of crack type I and type D



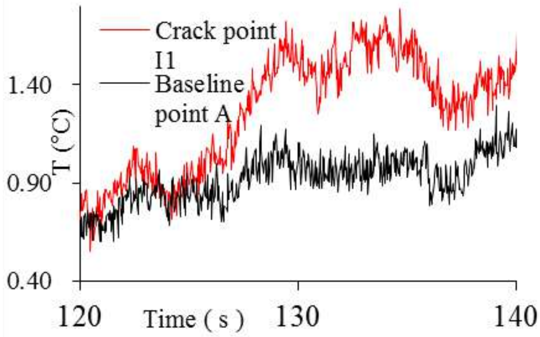
(a)



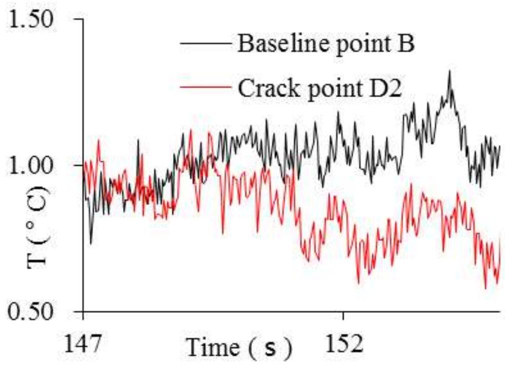
(b)

Figure 11. Locations of cracks before plastic deformation (a) and after plastic deformation (b)

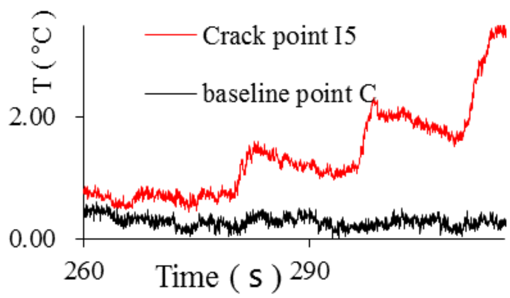
Temporal variation for crack I1, D2 and D5 are Shown in Figure 12. Crack I1 occurs at the time of yield. Before crack initiates, temperature of the crack point is relatively constant and approximately equals to the temperature of baseline. The T-t curve of crack point deviates from that of the baseline since t=126.33 s. From t= 126.33 to t=128.80s, the temperature at crack point increase by 0.6 °C while that at the baseline is relatively stable. After the crack is formed the temperature at the crack is relatively steady from 128.90 to 135.33 s but subsequently decreases due to the decrease of load. Crack D2 forms at the transitional point between stress softening and plastic deformation, which takes less time than the formation of crack I1. It is compatible with the common sense that the ice is very brittle and there was little friction. The magnitude of temperature decrease is not as important as the temperature increase for crack between gravel particles as the decrease only show how deep the crack develops into the specimen. The crack I5 occurs along the global failure surface during plastic deformation. The crack occurs at 265 s with a temperature increase of 0.51 ° C. After the relative movement between two parts of specimen on each side of the failure surface starts at 280 s the temperature increase takes 3 steps, which is corresponding to the steps of relative movement along the failure surface observed in the video. The load, and hence the stress within the specimen, is less than those previously during the elastic stage when I1 occurs. But the relatively movement along the global failure surface is more intense. Thus, both the rate of increase and total amount of increase in temperature is larger. From 280s to 315s, the temperature increase due to friction along the global failure surface is 2.66 °C.



(a)

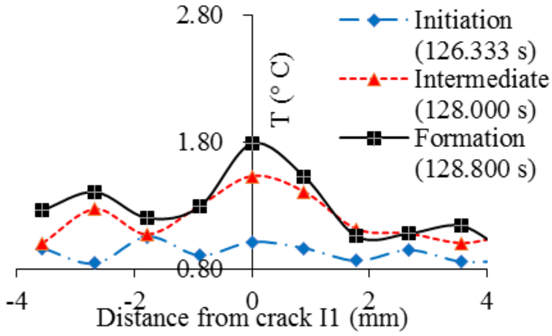


(b)

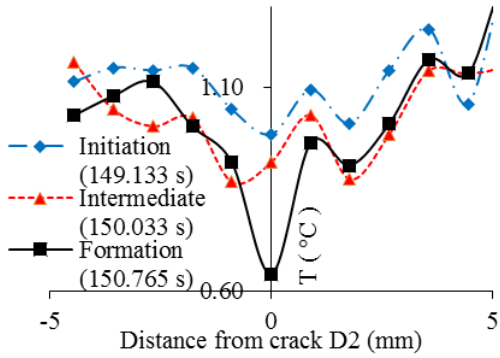


(c)

Figure 12. Temporal temperature variation at crack I1, D2, and I5 and their respective baseline A, B, and C.



(a)



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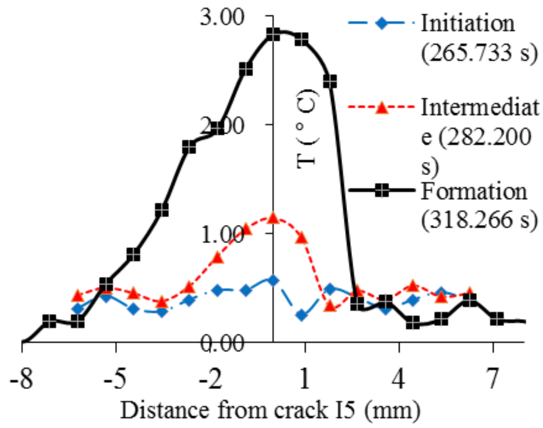

(c)

Figure 13. Temperature profile across crack I1, D2, and I5 during its formation

The spatial temperature distribution across I1, D2, and I5 are also plotted to demonstrate the increase during the formation of crack in Figure 13. ΔT_{I1} is defined as $\Delta T_{I1} = T_{I1} - T_{average}$,where T_{I1} is the temperature at crack I1 at formation and $T_{average}$ is the average at the immediate surrounding area of crack I1.In the same manner, the time t_i, when the crack is fully developed, and ΔT_i is recorded for cracks I2, I3, I5, D1, D3, D4, and D6. After a crack has formed, the temperature may still vary subjected to the change in stress-strain condition. Thus the ΔT for crack I1 at stress-softening stage (noted by the initial 's' as subscript in $I1_s$) and plastic stage (noted by the initial 'p' as subscript in $I1_p$) and ΔT for Crack I2 at plastic stage are also calculated.

The serie of $(t_i, \Delta T_i)$ are plotted together with load-time curve in Figure 14. During the elastic stage, only two cracks, I1 and D1, occur slightly before yield (128.9 s). As the load decreases during the stress-softening period, the ΔT at crack I1 also decreases. A series of crack consisting 4 type D and 1 type I occur just before the transition to plastic deformation at 162.0 s. Afterwards, the load is relatively constant as the compression reached its plastic stage and no crack occurs until t=265 s, when the cracks later forming the global failure line initiates. From t= 265 s to t 300s, the global failure surfaces gradually grow by connecting these individual cracks and the temperature along it generally increases. The total temperature increases at this series of cracks are all above 2.1 °C.

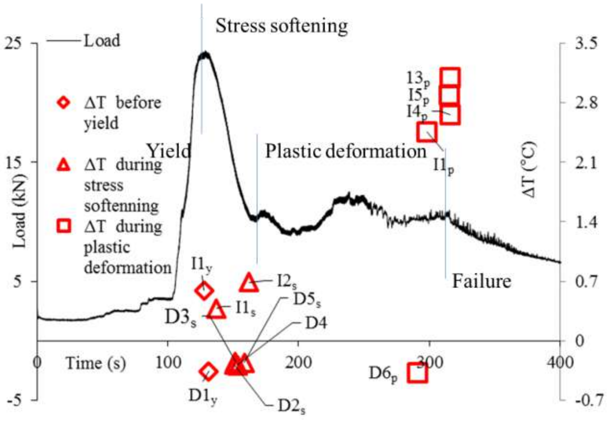

Figure 14. Load-time curve with magnitudes of temperature change at cracks

5 Conclusion

In this research, the thermographic profile of frozen soil specimen under uniaxial compression test is studied. For all 3 cases, abnormal temperature variations on specimen surface due to inter-particle friction occur are observed.

1. In frozen clay specimen, the temperature increases at cracks are identified only after plastic deformation occurs
2. For the frozen sand, simultaneous temperature increases are observed on the entire specimen as it bulges at plastic stage.
3. In frozen gravel, temperature change are observed at cracks before and after yield. For cracks in ice particles, temperature decreases due to change in geometry. For cracks in gravel particles temperature increases due to inter-particle friction.

6 outlook

In this research, the identification of temperature change induced by friction is achieved after the thermal-videos are manually examined for multiple times and the temperature variation at manually selected points are analysed. Such manual observation and analysis are time-consuming and not efficient enough for real-time monitoring. Thus, the application of this method for monitoring on-site requires significant improvement in efficiency in the future.

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A study of the influence factors on modular residential asset

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Abstract

There is a necessity to expand the supply apartment houses for the vulnerable classes. In addition, it is required to manage the assets for public rental housing to improve economic efficiency, such as improving the residential environment to prevent the surge of maintenance expenses due to deterioration. Therefore, it is necessary to supply modular apartment houses that can be constructed with low construction cost in a short period of time. This study aims to derive factors that have the greatest impact on assets in the maintenance phase, and determine the priority of them as part of basic research for efficient asset management of modular construction project. The optimum maintenance cycle and rate are applied as weight factors through a proper formula. As a result, wire rope & pulley, monitoring box, record device, CCTV and information signs are the highest priorities of long-term maintenance contents in economic aspects. In addition, mortar finishing has a high applicability.

Keywords –

Modular; Apartment House; Asset Management; Influence Factor; Maintenance

1 Introduction

1.1 The Background and Purpose of Study

In South Korea, the residence rate of domestic recipients of basic living is 40.2%, but the supply ratio of public rental housing is only 32.9% [1]. Therefore, it is necessary to expand the supply for the vulnerable classes. Also, the increasing number of one and two family members has led to a change in the area of the apartment house. In addition, it is required to manage the assets for public rental housing to improve economic efficiency, such as improving the residential environment to prevent the surge of maintenance expenses due to deterioration [2]. Therefore, it is necessary to supply modular apartment houses which can reduce life cycle cost, particularly in maintenance phase.

The ultimate goal of this study is to create a decision support model for optimal asset management of modular apartment housing. As a first step to achieve the goal, this study aims to derive factors that have the greatest impact on assets in the maintenance phase, and determine the priority of them as part of basic research for efficient asset management of modular construction project comparing to conventional (reinforced concrete) construction project.

1.2 The Scope and Method of Study

The subject of this research was limited to apartment houses constructed by modular construction method. The scope of this research was limited to financial assets except for other type of assets such as human assets and intellectual assets. The scope of period was also limited to maintenance phase. The reason was that the characteristics of modular construction are the most visible in maintenance phase. One of the influential advantage of modular construction is that the module or its components can be easily changed(repaired) and reused.

Figure 1. The sequence of this study

This research was conducted in the following sequence, as shown in Figure 1. First, the previous studies of modular apartment houses in asset management aspects involving domestic and overseas literature review were investigated. Second, general long-term maintenance items of apartment houses were derived. Following that, weight factors and importance factors for each item were assigned. Once this was done, priority for each item was derived. The final step is that long-term maintenance items between conventional and modular houses were compared and analyzed.

2 Literature Review

2.1 Previous Studies

The previous studies related to modular apartment houses in asset management aspects are shown as Table 1.

Table 1 Major research related to modular apartment houses

Author	Title	Main Content
Kim (2011) [3]	Economic Feasibility Study on the Unit Modular Fabrication Method According to the Life Cycle Costing Methodology	Proposing an economic feasibility forecasting model and to apply the model for method of unit modular construction
Kim (2013) [4]	An Economic Analysis of Modular Method for the Urban-type Housing	Conducting an economic analysis by calculating cost and profit by construction method in order to provide basic data for establishing directions for the projects in the future and making decisions
Bang (2014) [5]	An Economic Analysis of Steel Framed Modular Housing: Compared with Case of Urban Type Living Housing of Wall-slab	Analyzing the economics of modular house to vitalize the constructed residential building by modular method and to develop the modular method
Lee (2015) [6]	A Study on Comparative Analysis of Modular Architecture for Movable Accommodation	Proposing demand sensitized movable modular building in order to reduce the financial burden

In fact, one of the advantages of modular construction is reducing construction cost by fast construction. So many studies on the economic analysis of modular apartment houses have been carried out, but the majority of studies have only considered details of construction cost and indirect cost. However, it actually costs more than the conventional method since the infrastructure is not yet built up in South Korea. Therefore, LCC analysis including the details of the modular construction in maintenance phase is needed.

2.2 Introduction to Modular house

2.2.1 General Meaning of Modular house

Modular Construction can be defined as a construction system where volumetric components forming a completed part of a building are produced off-site and transported to the construction site for installation [7].

There are two types of modular construction. One is Permanent Modular Construction(PMC) and the other is Relocatable Buildings(RBs). Permanent Modular Construction “PMC” is an innovative, sustainable construction delivery method utilizing offsite, lean manufacturing techniques to prefabricate single or multi-story whole building solutions in deliverable module sections. PMC buildings are manufactured in a safe and controlled setting, and can be constructed of wood, steel, or concrete. The structures are 60% to 90% completed in a factory-controlled environment, and transported and assembled at the final building site.

A Relocatable Building(RB) is a partially or completely assembled building that complies with applicable codes or state regulations and is constructed in a building manufacturing facility using a modular construction process. Relocatable modular buildings are designed to be reused or repurposed multiple times and transported to different building sites. [8]

2.2.2 Characteristics of Modular Construction

There are four major characteristics of modular construction.

① Fast

The modular construction is based on the dry method, so it is possible to carry out the module production at the factory and the foundation work on the site at the same time [9]. Therefore, the modular construction can be constructed in the rainy season and the winter season, so the construction schedule can be reduced by 50-80% compared to the conventional construction method [10].

② Increasing profit

Compared to the conventional construction method whose labor cost is 50% of the total construction cost, the modular construction costs 20% for the labor cost and 80% for the material and equipment cost. Thus, it is expected that higher profitability as high-function and valuable products [11].

③ Eco-friendly

Since most of the housing materials are produced at factories, the effect of noise and dust reduction is outstanding by minimizing the site construction when it is constructed close to existing building [1]. From a lifecycle perspective, carbon dioxide and construction waste can be minimized during construction, use and disposal [9].

④ Improving quality

Modular construction is able to move and reuse due to the standardized design of materials and module [10]. It is also possible to maintain the uniform quality of the house as the materials are produced indoors [1].

Among these characteristics, the most effective properties in Korean construction industry is that materials or modules can be easily changed(repaired) and reused. It is because that there is less advantages of cost saving in construction period.

3 Influence Factors

3.1 Long-term Maintenance Items

According to the previous research, the LCC items of apartment house are largely classified into 'Planning Cost', 'Design cost', 'Construction Cost', 'Operation & Minor Maintenance Costs', 'Utility Costs', 'Long-Term Maintenance Costs', and 'Remaining Value & Removal Costs'. When considering the whole lifecycle, the most critical item is long-term maintenance costs.

Table 2 represents the criteria for establishing long-term repair plans according to Enforcement Rule of the Multi-family Housing Management Act in Statutes of the Republic of Korea [12].

Table 2 Criteria for establishing long-term repair plans

Category	Component	Content
Exterior building	Roof	Mortar finishing, Polymer coating waterproofing, Polymer sheet waterproofing, Metal shingle roofing, Asphalt shingle roofing
	Outside	Stitching, Water-based painting
	Outside window	Door (automatic door)
Interior building	Ceiling	Water-based painting, Oil-based painting, Synthetic resin coating
	Inside wall	Water-based painting, Oil-based painting, Synthetic resin coating
	Floor	Underground parking (floor)
	stairs	Non-slip stairs, Oil-based painting
Electricity, digestion, elevator and intelligent home network equipment	Spare power (self-generated) facility	Generator, Switchboard
	Substation	Transformer, Incoming panel, Switchboard
	Automatic fire detection system	Detector, Receiver
	Fire extinguishing system	Fire Pump, Sprinkler head, Digestion water pipe (steel pipe)
	Lift & elevator	Machinery, Wire rope & pulley, Control board, Governor, Door opening / closing device
	Lightning protection equipment & outdoor light	Lightning protection equipment, Security light
	Communicating & broadcasting facilities	Amplifiers & speakers, Broadcast receiving facility
	Boiler & machine room	Power tables
	Security facilities	Monitoring box, Record device, CCTV (closed circuit Television) camera & intrusion detection facility
	Intelligent home network equipment	Home network device, Complex common system equipment
Water supply, gas, drainage and ventilation equipment	Water supply equipment	Feed pump, High water tank (STS, synthetic resin), Supply pipe (steel pipe)
	Gas equipment	Pipe, Valve
	Drainage	Pump, Drain pipe (steel pipe), Waste water pipe (cast iron), Waste water pipe (PVC)
	Ventilation equipment	Extractor fan
(Water) Heating equipment	Heating equipment	Boiler, Water supply tank, Boiler pipe, Heating circulation pump, Heating pipe (steel pipe), Automatic control device, Heat exchanger
	Hot water supply facility	Circulation pump, Hot water tank, Hot water pipe (steel pipe)
Outdoor (welfare) facilities	Outdoor (welfare) facilities	Asphalt pavement, Fences, Children's play facilities, Paving block, Septic tank, Drain & manhole, Entrance, Roof at access road to underground

	parking lot, Bicycle storage, Parking breaker, Landscape facilities, Information signs

Each content has optimum maintenance cycle and rate. These two elements are applied as weight factors in this study on the assumption that the general maintenance period of apartment houses is approximately 50 years [13]. The method of applying weight factors is shown in the formula below.

$$\text{Result value} = Z \times \frac{y}{100}$$

$$Z = \frac{50}{x} - 1 \text{ (when } \frac{50}{x} \text{ is an integer value)}$$

$$Z = \text{natural number of } \frac{50}{x} \text{ using truncate function (when } \frac{50}{x} \text{ is not an integer value)}$$

When x : maintenance cycle (year)
y : maintenance rate (%)
Z : number of repair times

The maintenance cycle (year) is substituted to number of repair times in 50 years, and it is mulipied by the maintenance rate. Some of contents are classified into the method of repair such as partial repair (pr), full repair (fr), full replacement (fm), and full painting (fp). For easy understanding, exterior building category was an example, as shown in Table 3.

Table 3 An example of applied formula

Content	Maintenance cycle (year)	rate (%)	method	Z	Result value
Mortar finishing	10	100	fr	4	4
Polymer coating waterproofing	15	100	fr	3	3
Polymer sheet waterproofing	20	100	fr	2	2
Metal shingle	5	10	pr	9	0.9
roofing	20	100	fm	2	2
Asphalt	5	10	pr	9	0.9
shingle roofing	20	100	fm	2	2
Stitching	25	5	pr	1	0.05
Water-based painting	5	100	fp	9	9
Door (automatic door)	15	100	fm	3	3

3.2 Priorities of Long-term Maintenance

If all contents are analysed in the same way as above, they can be prioritized as shown in Table 4. It represents top 20 items among all the long-term maintenance contents.

Table 4 long-term maintenance contents ranked top 20

Ra -nk	Content	Result value	Mainte -nance method	Applic -ability in modular
1	Wire rope & pulley	9	fm	N
1	Monitoring box	9	fm	N
1	Record device	9	fm	N
1	CCTV (closed circuit Television) camera & intrusion detection facility	9	fm	N
1	Information signs	9	fm	N
6	External water-based painting	9	fp	N
6	Ceiling water-based painting	9	fp	N
6	Ceiling oil-based painting	9	fp	N
6	Ceiling synthetic resin coating	9	fp	N
6	Inside water-based painting	9	fp	N
6	Inside oil-based painting	9	fp	N
6	Inside synthetic resin coating	9	fp	N
6	Stairs oil-based painting	9	fp	N
14	Boiler pipe	5	fp	N
15	Underground parking (floor)	4.5	pr	N
16	Home network device	4	fm	N
16	Feed pump	4	fm	N
16	Extractor fan	4	fm	N
16	Drainage pump	4	fm	N
16	Mortar finishing	4	fr	H

If the result values are same, the maintenance method would become the standard of rank. The order is full replacement(fm) > full repair(fr) > full painting(fp) > partial repair(pr). Additionally, the applicability in modular houses was considered whether highly(H) or normally(N) applicable. Only ‘mortar finishing’ has a high applicability in modular construction. The reason is that it can be fully repaired or replaced as a module. It was difficult to find clear difference of long-term maintenance items between conventional and modular construction. However, table 4 is a result of fundamental research to derive influence factors on modular residential asset and represents top 20 long-term maintenance contents. As the research continues, the ranking items will support to decide the prior scope of economic analysis on modular maintenance asset. Since there are too many considering economic maintenance items, the prior influence factors are needed.

4 Conclusions

In this study, research was carried out to derive influence factors which are long-term maintenance items of apartment houses. Also, the priority of items was derived through assigning weight factors. However, most of prior items have little difference between conventional and modular construction.

On the whole, more considerations and weight factors are needed. The maintenance method should be weighted as a number and included in applied formula according to objective criteria. Also, construction materials or works should be repaired as a whole unit such as wall and floor itself, not separately. For instance, roof can be replaced as a module in modular construction if mortar finishing, polymer coating waterproofing and metal shingle roofing are needed to repair simultaneously. Even though a module is installed as one room at construction site, it is possible to replace each part in maintenance phase. This is because modules are made up of bundles of individual components such as exterior/inner wall, ceiling and window.

In addition, this study was focused on repair of long-term maintenance items. In order to highlight 'reuse' which is strong advantage of modular construction, considered period or phases should be increased. If the remaining value and removal phase are considered, there must be lots of items which have high applicability and strength to modular construction.

It was so hard to analyze influence factors on modular residential asset with scarce economic information. This study was the first step to manage modular residential asset. In conclusion, it was meaningful study as a leading research. Therefore, the results of this study will lead to a study on asset management of modular houses in the future.

Acknowledgements

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Automatic traveling method for the self-propelled Tunnel Inspection System

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In recent years, road tunnels in Japan with severe aging are obliged to check periodically. But there are problems such as lack of engineers and inspection cost.

In order to solve these problems, we are developing a tunnel full-section inspection system.

In this system, inspection devices are arranged at the upper and both side parts. The lower part is protective frame vehicle with portal frame shape secured space through which the vehicle can pass. Although this system travels in a limited space, the position of the inspection device in the tunnel transverse direction is particularly important. Moreover, tunnel is a special environment that the GPS cannot be used, and feature points are few.

Therefore, we examined the automatic traveling control method suitable for this system and carried out driving tests.

As a result, it is confirmed the automatic travel control method using the magnetic sensor and guide are effective for this system.

Keywords –
Automatic operation; Magnetic sensor; Road tunnel

1 Introduction

Approx. half of road tunnels in Japan are over 40 years from the construction and aging is serious. Under such circumstances, due to the collapse of the tunnel ceiling board that occurred in 2012, periodic inspection every five years was obliged. In road tunnels, there are problems such as the shortage of engineer and the inspection cost. This tendency is particularly noticeable in road tunnels in country areas.

In order to solve these problems, we are developing a tunnel full-section inspection system (hereinafter, called this system) aimed at efficiently inspecting road tunnels. The final goal is to use this system for inspection instead of engineer.

The concept of this system is shown in Figure 1. Inspection equipment is arranged at the upper part and both side parts, and at the lower part it consists of a self-propelled portal frame secured space through which the vehicle can pass. Then, these inspection devices are moved to a predetermined position for inspection. The target value of the traveling position accuracy depends on the clearance with the tunnel that the frame and inspection device can tolerate. In this system, the tolerance of traveling position is within ± 75 mm in the tunnel transverse direction. Also, it is desirable that the operation during traveling is as simple as possible. Therefore, we consider mounting an automatic traveling control method in this system. The method can travel along a tunnel linear shape with keeping acceptable traveling position.

The environments of inside the tunnel are follows. Global Positioning System (GPS) cannot be used, and there are relatively few feature points with relatively monotonic shape. Therefore, we compare and study the sensing technologies used for various automatic driving control currently in practical use. And we select a control method considered to be suitable for this system. Then we conduct driving test with control method, and evaluate traveling accuracy.

In this paper, we report on the results of examination of these automatic traveling control methods and the evaluation results of driving accuracy by driving test.

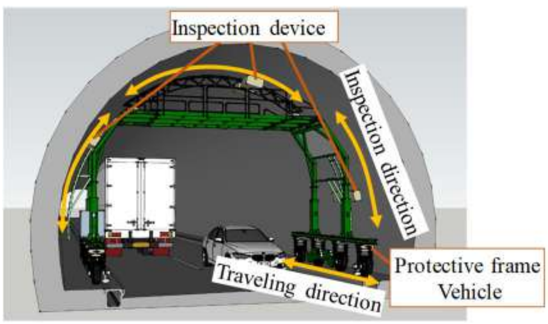

Figure 1 Concept of Tunnel Inspection System

2 Outline of Tunnel Inspection System

The actual machine of our system, which we produced, is shown in Figure 2, and the details of systems are as follows.

1. Crack inspection device: To replace the visual inspection from inspector. Automatic detection of cracks on concrete surface by light sectioning method with color image.
2. Hammering inspection device: To replace the hammering inspection from inspector. By hammering the concrete surface with the same force as inspector, the deformed of the surface layer is automatically found by the hammering sound.
3. Variable Guide Frame (hereinafter, called as VGF): Rail that moves the inspection devices in the transverse direction. In order to avoid an obstacle, it can be deformed into an arbitrary shape.
4. Protective frame vehicle: Travel the inspection system to a prescribed inspection position while securing a space through which the vehicle can pass. An inspector can ride on the upper stage, and it is effective when the inspector approaches the upper part of the tunnel. In turning traveling (minimum turning radius is R50(m)), it is assumed that the speed difference is given to the left and right driving wheels, and steering operation for adjusting the direction of the wheels is unnecessary. Since the device size can be adjusted by exchanging this frame, it is possible to deal with tunnels of various sizes. Table 1 shows main specifications of this system.

Figure 2 Actual machine of Tunnel Inspection system

Table 1 Specification of Tunnel Inspection System

Specification	
Inspection Speed (m/h)	25
Traveling speed (m/min)	Max 10
Turning diameter (m)	Min R=50
Weight (kg)	4.000
Length (m)	5.000
Width (m)	7.500 (Adjustable)

3 Automatic traveling of the protective frame vehicle

3.1 Travel accuracy and driving environment

This system aims to move the inspection device to a predetermined inspection position while traveling in the tunnel. In particular, the positional accuracy in the tunnel transverse direction is important. And its target tolerance is set to be within ± 75 mm that the frame and inspection equipment can tolerate.

On the other hand, the features in the tunnel are as follows.

1. It is not possible to grasp own position by GPS.
2. It is a relatively monotonous shape with few feature points.

Furthermore, since the vehicle width is large, the blind spot of the operator is large, and the traveling operation relying on the visual confirmation is high in risk. Therefore, we should consider automatic traveling control method to travel accurately in the tunnel.

3.2 Sensing method used for automatic traveling control

Currently, various sensing technologies for automatic traveling control exist. So we compare them and consider methods that are considered to be suitable for this system. The comparison result is shown in Table 2. From this result, it is considered that the magnetic guide sensing technology is suitable for the automatic traveling control of this system.

Table 2 Comparison of sensing method for automatic traveling control

Type	Technology	Issues	Cost	Eval
GPS	Positioning estimation by GPS	GPS signal cannot be received	Mid	Poor
SFM (Structure from Motion)	Positioning estimation from acquired image	Error due to few feature points	Mid	Poor
LiDAR	Measure the forward shape with electromagnetic waves	Need high-spec PC for calculation	High	Average
Laser ranger	Measure distance between tunnel wall and frame	Error due to equipment (ex. road signage, fire hydrant)	Low	Average
Magnetic guided	Scan the position of the magnetic guide and calculate the deviation	Magnetic guide installation required	Low	Good

4 Evaluation of Magnetic Guided Type Automatic Travel Control

4.1 System configuration of magnetic guided automatic traveling

As a result of 3.2, we decide the magnetic guided sensing technology is suitable for this system. This control method is installed in this system and we conduct driving test. The configuration of control system is shown in Figure 3, the mounting appearance is shown in Figure 4, and the specifications of control system are shown in Table 3.

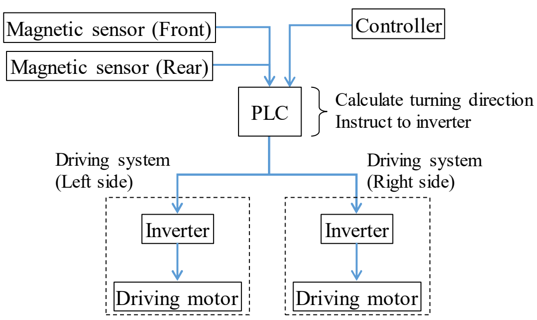

Figure.3 Control System Configuration

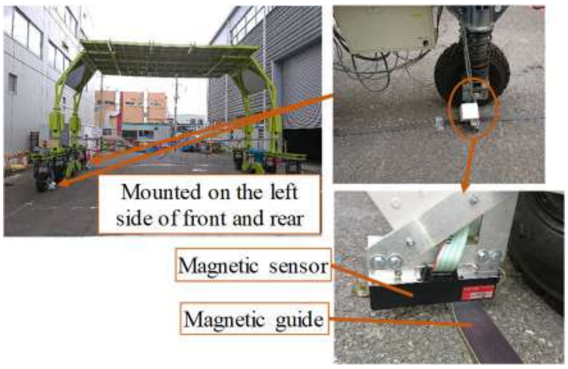

Figure 4 Appearance of magnetic guided sensor

Table 3. Specifications of control system

Equipment	Model	Manufacturer
Magnetic sensor	GS-115	MACOME
Magnetic guide	MGL-50-25	CORPORATION
PLC	KV-N14AT	Keyence

4.2 Driving Test with Magnetic Guided Automatic Travel Control

A driving test of a protective frame vehicle with a magnetic guided automatic traveling control is conducted. The results are shown as follows.

4.2.1 Conditions of driving test

The conditions of driving test are shown in Table 4. And the laying situation of the magnetic guide as the driving target is shown in Figure 5. The driving road is a flat asphalt pavement surface in a dry state.

Table 4 Conditions of driving test

Driving mode	Driving direction	Driving speed	Number of driving
Intermittent Every 40 cm	Forward / Backward	10m/min	Every 3 times
Continuance	Forward / Backward		

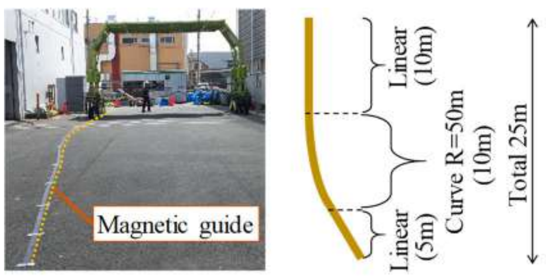

Figure 5 Magnetic guide laying situation

4.2.2 Measuring method of driving locus

In this test, automatic tracking type Total Station (hereinafter, called as TS/ST15P and ST16, Leica) is used for measurement of the magnetic guide position and the driving locus. Particularly the measurement of the driving locus, the TS target is located on front and rear of the magnetic sensor side. And the measurement is performed continuously using two TSs. This measurement method is shown in Figure 6.

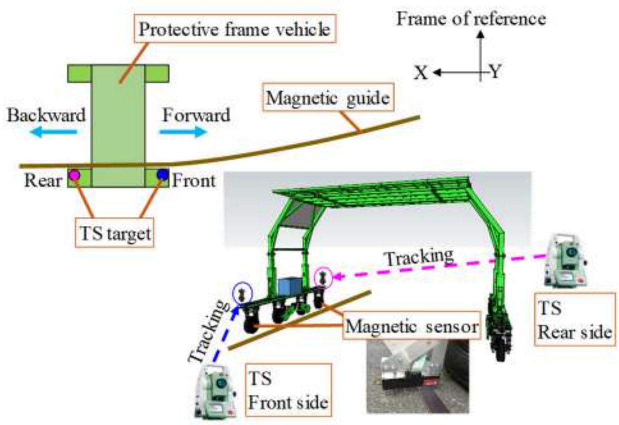

Figure 6 Measuring method of driving locus

4.2.3 Test results

Figure 7 shows the result of comparing the magnetic guide position and traveling locus in this test (excerpt of the first driving result). The numerical value in the graph indicates the maximum deviation amount (right and left with the magnetic guide position as the center) and its position.

Magnetic guide of this test is combining the linear part and the curve part (Turning radius R=50m). As a result of the automatic driving test with the magnetic guide control, the maximum deviation amount from the magnetic guide is 79mm. The large deviation points are before and after turning area. No difference is confirmed by running conditions (continuous driving / intermittent driving, forward / backward).

In this test, since the deviation amount is almost within the target. It is considered that the magnetic guided automatic travel control can be used for this system.

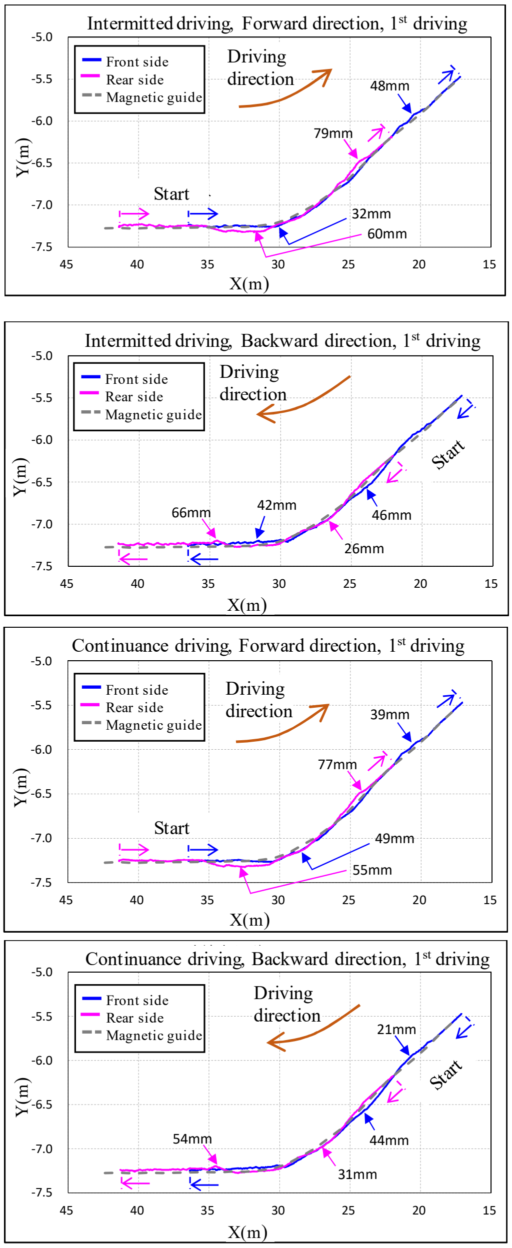

Figure 7 Comparison of magnetic guide and driving locus

5 Implementation of magnetic guided automatic traveling control system

Magnetic guided automatic traveling control system confirmed effectiveness is mounted on actual machine. Installed system configuration is shown in Figure 8, and detail of magnetic guide is in Figure 9. The main improvements based on test results are as follows.

1. Increase number of sensors (From one side to both sides): To improve the accuracy of traveling control by sensing magnetism on both sides.

2. Add the distance guide: This system should stop at every 40cm at inspection. Therefore, a marker is incorporated in the magnetic guide as a stop target.
3. Magnetic guide indicator: An indicator is added in operation interface. Operator can check the deviation amount of each magnetic guide.
4. Output of running position and deviation amount: For grasping position information, the position in the traverse direction is calculated from the deviation amount of the four magnetic sensors. The traveling distance is calculated from encoder count. And these information are output to inspection system.
5. Magnetic guide installation method: The magnetic guide is installed in the tunnel at the timing of inspection. The installation position is set to a certain distance from the tunnel wall surface, and it is installed simply and accurately with a JIG. Also, magnetic guides are connected by connecting 1 m straight lines. Since it is possible to handle all straight and curved sections, it is not necessary to prepare multiple types of magnetic guides.

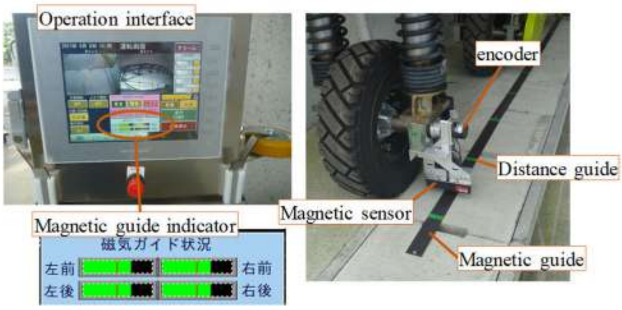

Figure 8 Installed system configuration

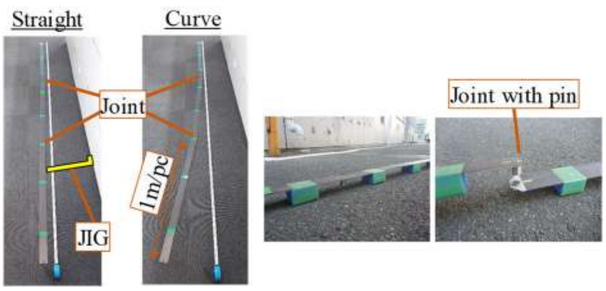

Figure 9 Detail of magnetic guide

6 Conclusion

In this paper, we evaluated the automatic traveling control method of the tunnel full cross section inspection system. As a result, it is found that the automatic traveling control method using the magnetic guided is effective and reasonable.

In the future, we will try to optimize the frame structure and the turning method by measuring the twist of the frame during turning and structural analysis.

In addition, it is now supposed to complement self-position information that is detected only by a deviation from the magnetic guide. Since we will study a system that measures the distance between the entire frame and the tunnel wall surface at several places.

With these improvements, we aim for practical application of this system.

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Mixed Reality Approach for the Management of Building Maintenance and Operation

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Abstract

Building Information Modelling (BIM) has been indicated as the right tool to provide the construction industry with the productivity boost that has been lacking in the last 40 years. This momentum finds its highest fulfilment in the support provided by BIM models to knowledge management and the automation of process. However, the management of information flow is still far from its automation breakthrough and, as far as operation and maintenance are concerned, knowledge about procedures is often incomplete. Moreover, processes are often do not undergo optimisation and the individual steps to be performed are not communicated, but in facility management (FM) the transmission of know-how is fundamental particularly because some operations are dangerous or risky. In this framework, Mixed Reality (MR) represents a powerful means to communicate the correct data concerning both geometric features to be considered and the standard procedure to be followed. The aim of this paper is to investigate the possibility of exploiting the benefits provided by these technologies to achieve automation in the transmission of information and optimisation of procedures, improving efficiency and productivity thanks to a better understanding of the operations to be carried out and the reduction of errors. With the support of a head-mounted display (HDM) device with a see-through screen capable of presenting 3D virtual objects, this research tries to combine information from a BIM model with reality to study the benefits for maintenance personnel.

Keywords –
Mixed reality, BIM, Operation and Maintenance

1 Introduction

Facility Management is the phase in the entire building life cycle with the highest costs and yet to date little attention is still being paid to it. Nevertheless, there would be plenty of room for improvement for various aspects of operations and maintenance. The possibility of performing assisted diagnoses, automatically detecting components, avoiding surveys for the collection of information are all scenarios that offer great opportunities for improvement, particularly in terms of automation, since the automation of procedures is the benchmark for the improvement of efficiency and productivity. This research starts from an analysis of the needs which are still not being satisfied in the maintenance industry. Once the goals are established, the aim is to test the effectiveness of a system that collects together some technologies that, when considered separately, have already been demonstrated to increase efficiency in the construction industry. The BIM paradigm, which is rapidly spreading and establishing itself as a guarantee of efficiency, cloud systems for data management and mixed reality, which is the most interesting version of virtual reality since it allows human interaction with the digital environment created. This work aims to demonstrate the feasibility of this system and lay the foundation for its implementation by analysing its architecture and identifying all its components. Finally, on the basis of the needs identified, three scenarios the system could be used to bring benefits to and improve efficiency by reducing time and costs are proposed.

2 Scientific Background

The operational phase of a building is the main contributor to the cost of the building's life-cycle. Studies show that this cost is five to seven times higher than the initial investment costs and three times the cost of construction [1]. It is, therefore, crucial to identify increasingly efficient methods for managing the life-cycle of buildings.

At the same time, Building Information Modelling (BIM) has become the new international benchmark for improved efficiency and collaboration in the different phases of the life- cycle of a building [2].

One of the first necessities when performing commissioning or preventive and corrective maintenance is to identify building components (equipment, materials and finishes) and related information for quick identification and solution of possible problems [3].

Several studies state that building maintenance requires a comprehensive information system that captures / retrieves information about those components that may need intervention [4].

But building inspections are time and cost consuming, both with regard to on-site surveys and, even more, the subsequent BIM modelling of the data collected. In this regard, several researches have been initiated to facilitate this task by finding faster methods to retrieve information and communicate results, while other studies are focusing on the possibility of reaching automated reconstruction of 'as-built' building models [5, 6, 7].

After the surveying phase, one of the biggest challenges in the construction industry today is information management, both in the construction phase and in the building management phase. In order to manage buildings a huge variety of information are necessary [3]. As regards variety, to take maintenance decisions, facility managers require the integration of various types of information and knowledge created by the different members of a construction team such as maintenance records, work orders, causes and knock-on effects of failures, etc. Moreover, when it comes to information, besides the data that can be collected or the individual technical specifications of the various components of the building, a further aspect that needs to be kept in mind is the knowledge created from maintenance operations such as the lessons learnt from the investigation of the causes of failure, the reasons for choosing a specific maintenance method, the selection of specialist contractors, ripple effects on other building elements [4]. This knowledge also includes the fundamental know-how to train new personnel and therefore should be captured/retrieved in sufficient details. However Building Information Modelling is not tailored to individual processes and this makes it very difficult to enter the aforementioned kind of information if not already considered by the IFC structure [5, 8].

Cloud database systems represent a tool for connecting information of different disciplines that is not placed in building models and information related to processes [8]. Furthermore cloud computing has the ability to support construction projects in the sharing of documents and information despite the fragmentation of the construction industry [9, 10]. In particular, the power of cloud computing lies not only in making the sharing of documents and information possible, but also in improving it and allowing it to be exchanged in real time. [11,12] In fact, one of key challenges in operation and maintenance processes is always the need to have sufficient information about products readily available.

The Cloud-BIM system not only provides an information display service, but also provides information manipulation services for users located anywhere and at any time [13]. A link from BIM models to FM databases could help detect and diagnose construction equipment based on the necessary information such as specifications and maintenance history, which could be automatically associated with the equipment located and delivered to the staff on site [2]. Effective and immediate access to information during operations minimises time and labour and helps avoid ineffective decisions made in the absence of information [14].

This system for the management of large information flows can also find the necessary support for on-site visualisation thanks to a head mounted display that supports mixed reality. Starting from the definition by Milgram and Kishino [15] of mixed reality as a "spectrum of reality" ranging from pure "reality" (seen by a user without computer intervention) and pure "virtual reality" (a computer-generated environment where the user has no interaction with the physical world), it can be said that MR is any environment that incorporates aspects of both physical reality and computer-generated reality, for example, by overlapping virtual objects over a user's field of view of a real space. As far as augmented reality (AV) is concerned, it is a predominantly real environment with some virtual elements. Milgram et al. also gave other details about MR, which is also defined as a special class of Virtual Reality-related technologies for creating environments wherein real world and virtual world objects are presented together in a single display [15].

Thanks to these characteristics, mixed reality has already found application in on-site support to operators, especially with regard to the need for a good training of operators and access to large amounts of information about equipment management . In these circumstances, in fact, the capability of AR to involve construction personnel in increased workspaces allows a user to work with the true 3D environment while visually receiving additional computer generated or modelled information about the activity in progress. Mixed Reality can improve the user's perception of the real environment, showing information that he could not directly acquire without help [16].

Despite the great successes of BIM-based VR and cloud computing in improving the performance of AEC activities, it is still necessary to examine methods and systems to integrate both BIM virtual reality and cloud computing for advanced project communication among remote project stakeholders with a shared immersive virtual experience [11].

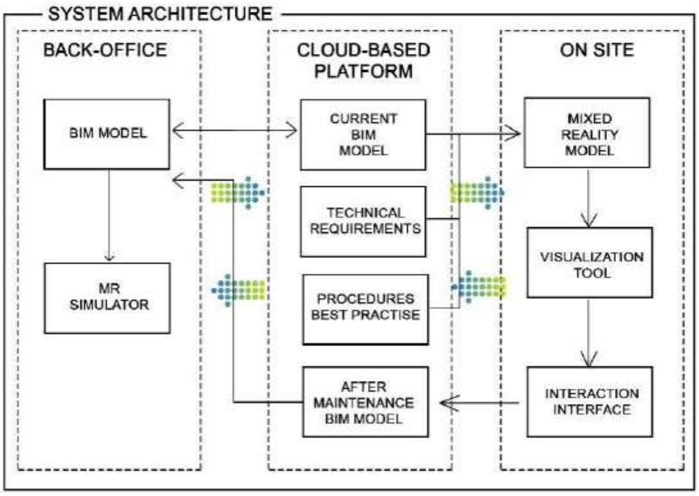

Figure 1. System Architecture

Indeed the research presented in this paper is mainly focused on:

- integrating the BIM virtual model, the real environment and operators;

testing the mixed reality approach in three novel scenarios (inventory/survey support, diagnosis, remote support to operations).

3 Research Methodology

This research starts from the study of FM needs. The identification of these challenges leads to a huge set of data requirement which become the starting point for the creation of a BIM model of the building. Following a survey with maintenance expert personnel additional information and procedures are collected. Since the management of all the maintenance data must be real time, therefore fast and efficient, the study foresees the use of cloud platforms for the management of large amounts of data and consequently the creation of interfaces between the model and virtual data. Finally to verify the proposed approach, simulations of the three different scenarios are carried out with both preliminary and real world test.

3.1 Requirement analysis

In literature it is widely recognised that FM includes and involves multi-disciplinary activities and, as a consequence, has extensive information requirements. [2] Operation and maintenance are a substantial part of the FM and can be related to structures or facilities which may be very different from each other. Many references about the most important needs to be met in order to best perform maintenance interventions can be found in literature.

In this research the analysis will be enhanced by also considering the opinions of experts in the maintenance sector.

In literature, requirements can be split into:

aided document/information retrieval

components localisation

procedure management automated support

personnel training

automated identification and modelling of components

Aided document and information retrieval is based on the use of BIM software for modelling buildings. The digital model of a building could, in fact, contain information on the maintenance operations carried out, the level of deterioration and technical specifications, making this data easily retrievable and providing an immediate localisation in the building. Furthermore, the digital model could be supported by cloud data storage systems for procedures or extended information that cannot be inserted into the model. [17,18,19]

In literature, research attempting to identify, in a more or less detailed way, the information needed for buildings maintenance management can also be found. This depends largely on the type of facilities and on the operations to be carried out. Among the necessary data, Hamledari et al. indicate the details associated with the inspection process, such as the person/organisation responsible, defects, as-built type, as-designed type, data capture tools, time/date of the inspection, the inspector's notes and the images captured [20]. Gao et al. begin, instead, from a more detailed analysis of the components to be detected on-site, starting from the OmniClass classification and integrating it with data fields in a COBie worksheet [21].

A further informative requirement concerns the localisation of the component which is an expensive activity in terms of time and effort. Conventionally, maintenance personnel on-site rely on paper-based blueprints or on their experience, intuition and judgment in finding and locating equipment,such as HVAC systems and electrical, gas and water lines, which are usually in places that are not easily visible, e.g. above ceilings, behind walls or under floors. This task becomes of great importance especially during an emergency, or when newly assigned personnel takes over responsibility for the facility or when the equipment has been replaced or removed. Also in this case, the BIM as-built model can be of great help, also considering the clear visualisation that the 3D model provides. [2,22]

It is crucial to organise and have information regarding also the procedures to be followed always available : which maintenance and repair works must be performed, when these works must be done, how work can be undertaken safely and which works are most needed. [17]

These initial information requirements are all included in the training of personnel, who are currently managed through presentations, on-site visits, hand-hand demonstrations and self-study, which requires intensive preparation, takes a long time and depends largely on the skills and experience of the trainers. [2] This would certainly benefit from organised data management and advanced visualisation and support tools. [23,24]

Lastly, the real geometry of buildings often differs from the original plans and for this reason the reconstruction of a precise 3D model is a common requirement. The efforts in automated modelling have so far focused on the segmentation and recognition of large structural components and more strongly for the exterior rather than for internal components. However, modelling should also include small-sized indoor items for different purposes (scheduled maintenance, storage and documentation, FM, security, feeding of building information models). In addition to this, recent research focused more on capturing geometric data rather than semantic representations of buildings and feeding point cloud data into BIM software [5, 25, 26, 27, 28, 29] This requires, on the one hand, a certain work of interpretation of the data collected, on the other hand, it omits a series of information that goes beyond the geometry of the elements and which is necessary for process management. In general, although this proves to be a demanding task, so far relatively few studies have turned their attempts to reduce modelling/ conversion efforts from construction data acquired into BIM objects with a high semantic meaning. [23,24,30]

3.2 System architecture

This research proposes a framework that integrates the information flow from office to operation site and vice versa. The architecture of the system proposed is actually composed of three different fields of action: the back-office, a cloud-based platform for big data management, and the operation site (Fig.1).

Starting from the back-office, this is the place where operators work. They have access to all the documents (BIM model, data sheet, etc.) and give support to the operators on site. The back office contains also the BIM model and the MR simulator necessary to enrich the virtual environment.

The cloud-based platform is the place where the BIM model updates are shared. At first, the model of the current state is shared, so that the information packages and procedures can be connected to objects. Then, following the maintenance operations, also the updated BIM model is shared to allow the back-office model to be updated.

The on-site part of the system makes available equipment to provide the technician with the MR view, the visualisation of the virtual reality on top of the real one and an interface that allows the interaction and transmission of information to the cloud system.

3.3 Cloud-based Platform

The BIM model of a building needs a deeper range of information in order to be usable for MR applications. All this information can be integrated through cloud systems for big data management. The choice of the use of a cloud based platform to support data flows depends on the need of having a schema that allows fast and efficient queries among data coming from different technologies or with different purpose and, as other researches have shown, IFC is not a suitable choice for real-time applications [3]. The maintenance operation data to be included in a cloud system concern, on the one hand, a specific in-depth analysis of the components, containing all the technical information necessary for the interventions, and, on the other, the procedures that the personnel must follow to complete the operations.

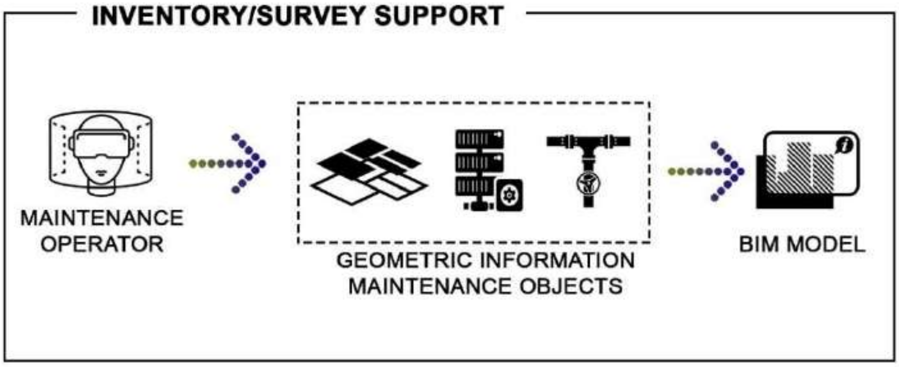

Figure 2. Inventory/survey support scenario

3.4 Design of workflow management

The information data will flow through the different components of the system by means of the cloud platform. Depending on the applications, it will be decided how and which interfaces to use to guarantee interoperability and allow the different users (back-office operators, designers, technicians) to collaborate. The flow will move in both directions, from the office to the site and vice versa, thus allowing a continuous exchange of data, which will make it possible to have continuously updated documents and the perfect knowledge of the asset status.

3.5 Development of on-site technology

The on-site part of the system proposed is developed with the support of a head-mounted display device with a see-through screen capable of presenting 3D virtual objects on top of existing physical surfaces. [31] This technology enables maintenance personnel to interact with the building and with virtual building objects, thus, pushing mixed reality towards a necessary goal so as to promote its widespread use [11].

The MR functions provided by this device include the possibility of displaying virtual objects and performing automated localisation in the building without markers.

This interaction brings also the possibility of capturing real-time data (e.g. updating maintenance operation results) which, in turn, allow constant updating of the model leading to having the updated version of the digital building all the time.

3.6 Preliminary and real world test

The tests to determine the reliability of the system will be performed, at first, in a predefined environment, the basis for the creation of the system itself. This experiment will have the purpose of calibrating the system and verifying the system's main functions based on the intervention scenario taken into consideration. Secondly, the test will be carried out in the real world, in a new environment. That is where the possible sources of interference will be evaluated and the remote support function will be tested.

4 Three interventions scenarios

Following the requirement analysis, as far as the management of maintenance operations, scenarios with criticalities only partially solved have emerged. These are the usage scenarios which are the basis of three frameworks that have been developed for information flow management and on-site support.

4.1 Inventory/survey support

Existing building data collection is the necessary basis for asset maintenance management and it is a challenging step. Recovering all the necessary information on all the elements of a building could indeed be difficult or sometimes impossible [19,24]. A series of new or more advanced technological applications are emerging to make information acquisition faster and more efficient (Scan-To-Bim for small building components), but often these applications are not related to the creation of a BIM model [30]. The first intervention scenario is therefore the automated acquisition of data on the status of fact (Fig. 2). To make the creation of a BIM 3D model of the building as automated as possible, this collection of data should be based not on point clouds or generic surfaces but on objects, which are the basic elements of BIM digital modelling.

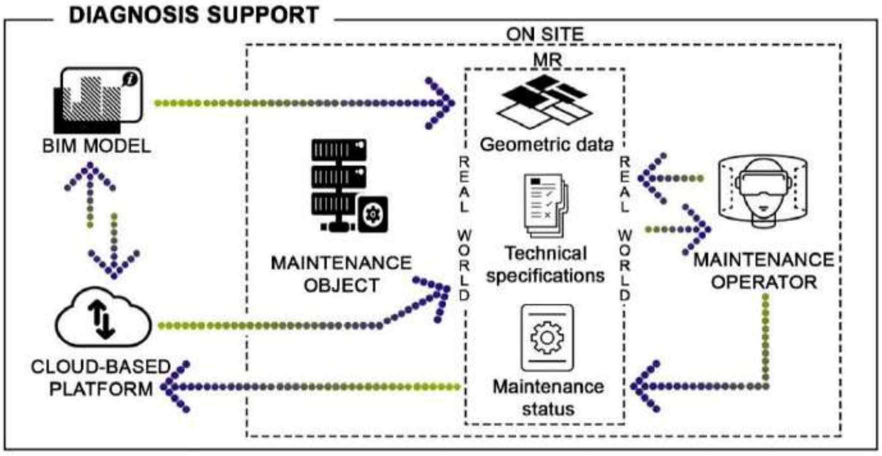

Figure 3. Diagnosis support scenario

In order to allow this type of recognition, it is essential to identify the objects' relevant features that will allow the operator to perform the recognition. This type of analysis involves the adoption of a precise and codified classification that makes it possibloe to detect all the elements involved in maintenance operations, at the same time collecting also the information necessary for the subsequent operations. The innovative contribution of this research work lies in its aim to provide a more efficient object inventory and a more rapid conversion of the elements identified during inspection into BIM elements by adding not only geometric but also semantic data and trying to minimise the post-collection work of the data acquired.

4.2 Diagnosis support

The second scenario this system could bring benefits to is that of diagnosis (Fig. 3). The prime set of information functional to diagnosis is undoubtedly the geometric one. Correct and immediate localisation of the objects on which it is necessary to operate certainly allows a reduction of possible misunderstandings, also thanks to the mixed reality display viewer that avoids having to rely on paper documents, thus making the possibility of error lower, keeping in mind that the overlapping of a virtual reality allows maintenance personnel to see hidden things (e.g.

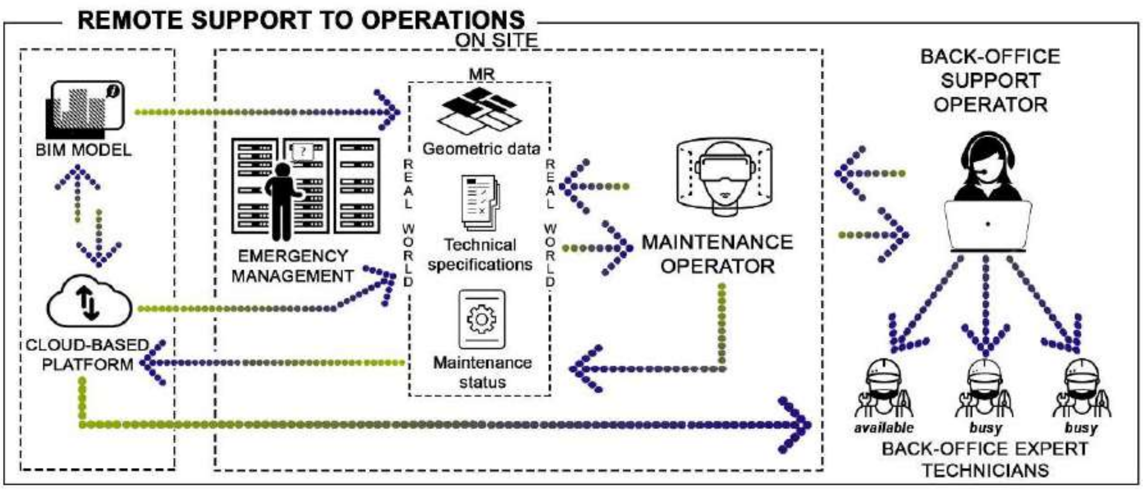

Figure 4. Remote support to operation scenario

steel in the concrete or cable paths in the walls or behind the floor). In addition to geometric data, there are also technical specifications and descriptions of components to be updated and stored and procedures to be followed in the operations. All these data start from BIM and cloud databases and can then be visualised thanks to a head-mounted display and be immediately available on site.

4.3 Remote support to operations

The last scenario taken into consideration is that of on-site operatios support from back-office (Fig. 4). Sometimes it is not possible to reduce maintenance operations to a standard procedure displayed as an object property. Therefore, in case of emergency, a standard procedure to be performed is not always available. These are the circumstances in which back-office support can be fundamental.

Moreover, sometimes not all information can be displayed automatically, because it would result in having a large amount of bulky data to be handled on site. In this case, remote support can be of great help for all the information that would be complicated/ difficult to find automatically, which is more efficient than asking a colleague working remotely (e.g. the pieces out of production in stock).

5 Conclusion

The aim of this research project is to provide support for the operation and maintenance phase during building life-cycle. This study focuses on the possibility of a combined use of three big technologies, the BIM paradigm for data management, a cloud-based system for managing information flows and mixed reality, to obtain an interaction between operators, digital model of the building and information flow.

A data set, not covered by this project, that could be developed in the future is that related to the building functional data and therefore the management of on-site safety, an issue that is always very important, since it aims at reducing risks at the workplace.

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Continuing Increasing of Quality Management Level in Construction Company using Excellence Model with Software Support

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Abstract

This contribution aims to increase quality level of organization applying the EFQM (European Foundation for Quality Management) excellence model. It provides analysis of current quality management trends, defines EFQM model structure a criteria and possibilities of its introduction in construction companies all over the world. The purpose of this contribution is also proposal of electronic manual and automated system of evaluation the criteria and sub-criteria of EFQM model by company management and also by external auditors.

Selected scientific methods of problem solution can be divided into two main groups: empirical and logic (scientific analysis and synthesis). An empirical method is applied to an electronic survey that aimed to determine knowledge of the EFQM model and its use in practice among organizations operating in Slovakia. The logical method was utilized for the problem solving analysis and synthesis. Methods of scientific analysis was used to evaluation of the current issue of quality management level and EFQM implementation in construction sector, analysis of criteria and sub criteria of the EFQM model, exploring the possibilities of applying the EFQM model in construction organizations and examination of existing systems of assessment under the EFQM model. Synthesis allows to know the object as a single whole and is the basis for correctly decisions. Scientific synthesis method was used during the process of definition of methodology for application of the EFQM model, creation of electronic manual for the development and improvement of the EFQM model in the construction, design an electronic evaluation of construction company quality management level, defining the benefits of the EFQM development and implementation in the organization, creation of documents and forms within the individual criteria of the EFQM model.

Research work results in the form of its own methodology and electronic manual allow to construction organizations effectively introduce and implement EFQM model requirements to practice in a relatively short period of time with aim to constantly improve its performance towards excellence. Defined methodology suggests and explains the sequence of steps towards EFQM model applying, the electronic manual describes all of EFQM model sub-criteria and provides concrete suggestions and solutions to meet them. In the manual there is also automated electronic assessment system for construction organizations included.

Application of the methodology and manual on concrete company enabled in a short time to evaluate its quality management level, identify opportunities for improvement and also implement concrete improvement steps in necessary areas. Theoretical results in terms of current state analysis will find its application in educational process, science and common practice. Created methodology and automated evaluation system can be applied in different construction organizations introducing EFQM model and to utilize acquired knowledge to further research this issue.

Keywords –

Management level; Model of excellence; Construction company

1 Introduction

The EFQM excellence model is an European model based on Total Quality Management – TQM. It is designed for all organizations that are interested in continuous improvement and progress towards excellence. The main purpose of the EFQM model is self-assessment of the organization in order to achieve continuous improvement of quality. It helps identify strengths and opportunities for improvement and encourages solutions. It allows for an independent view on the organization and its functioning. [1,2]

The EFQM model is a basis for assessment and evaluation of a business aspiring to receive the

European Quality Award (EQA), but also the National Quality Award of the Slovak Republic. In order to win the EQA, the model must be applied for at least three years and yield the corresponding results.

The EFQM model may be used in any business as well as any government organization (however, the Common Assessment Framework – the CAF model is specially designed for public administration) [8]. There are several literature sources, which describe the structure of EFQM model and offer methodology, how to implement and evaluate it, but for customers are very brief and hard understood. [2,4,5,6,7,8,11,12] Therefore we decided in our research work to propose integrated electronic manual, which will offer to construction company complex and total information concerning the implementation and evaluation of all criteria of EFQM model. Our electronic manual contains total 9 criteria, 32 sub-criteria and 121 sub-sub-criteria of EFQM model. [6,8]. Users of this manual can self-evaluate own activity in a given sub-criterion and using automated system (software) determine point value of quality level (see next chapters).

2 EFQM Model Structure and Features

The EFQM model was created by the European Foundation for Quality Management (EFQM), which was founded in 1988. Its establishment involved fourteen large European corporations. [5] The aim of the foundation was to create a model based on Total Quality Management (TQM) in order to achieve excellence in European companies and make them competitive in comparison with the U.S. and Japanese companies in the global market. Society-wide recognition of quality in the USA (Malcolm Baldridge National Quality Award) and Japan (Deming Application Prize) proved that the application of TQM models delivers measurable business results to organizations [9,10]. The EFQM model first appeared in 1991 and it was called The European Model for Business Excellence. [4] It was innovated in 1999 and it became more universal and applicable in a larger number of organizations. For public administration, the CAF (Common Assessment Framework) model was developed. It was launched in 2000 and revised in 2002. The EFQM model is based on 9 criteria: leadership, policy and strategy, people, partnerships and resources, processes, customer results, people results and key performance results [6,13]. The first 5 criteria are enablers (what the organization has got) and the remaining 4 criteria are results (what the organization achieves). All criteria are divided into sub and sub-sub-criteria. The structure of the model, together with score for each criterion is shown in Figure 1. The direction of arrows shows the dynamic nature of the model. Innovation and learning help improve enablers, which leads to improved results. This process is continuous. Criteria and sub-criteria of the model are very sophisticated and deal with all areas of the organization, even with the environment surrounding it. The model emphasizes the ethical principle crucial for those who are exceptional.

ENABLES (500 points)
1. Leadership (100 points)
2. People (100 points)
3. Strategy and Policy (100 points)
4. Partnerships and resources (100 points)
5. Processes, products and services (100 points)

RESULTS (500 points)
6. People results (100 points)
7. Customer results (150 points)
8. Society results (100 points)
9. Key results (150 points)

Figure 1. EFQM model structure

3 Survey concerning the EFQM Model Implementation

The survey concerning the EFQM model implementation has been carried out during three months in year 2017 by the form of electronic and anonymous questionnaire. There were surveyed 180 construction companies in Slovakia of all sizes. The questionnaire completed 36 of them.

The issues were identified about whether the model has been applied for excellence in the organization, the purpose of its application (or the reasons not to apply it), as well as interest of the construction company to introduce the EFQM model in the future. Graphical interpretation of some of the responses is shown in Figure 2.

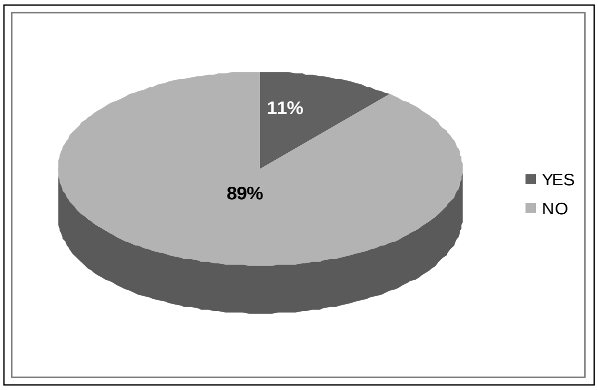

Figure 2. Application of the EFQM model at present or in the past in surveyed companies

The results obtained by survey shows that the EFQM excellence model and its application in practice in Slovakia are still relatively new, unexplored issues. Most companies do not exclude its application in the future, but they need much more necessary information about this model and effective training process. The solutions contained at this contribution can be helpful for the performance of the EFQM model to organizations, which have aims to continually improve their quality management level and implement maximum positive effects in future activities.

3.1 Analysis of EFQM model application in construction companies

The study of the EFQM model through consultations with trainers in the area of Quality Management and our own knowledge concerning this area of interest made us aware of areas for improvement and problems currently faced by Slovak companies striving for excellence when implementing the EFQM model. Application of the EFQM model in Slovak organizations is currently not a very frequent activity. Although the model seems simple, its application is a complex process in terms of time and resources. The EFQM model can be described as a higher form of quality management in organizations. It is starting to be implemented mostly by organizations, which have successfully passed the introduction and certification of the Quality Management System (QMS) according to ISO 9001 and look for other ways how to improve the quality of their products.

However, the management in most organizations fails to realize that this approach to improving the quality is not as simple as it seems at the first sight. Although the nine main criteria of the EFQM seem like they were encountered when building the QMS, the EFQM model contains a series of sub-criteria (32), which require a very detailed description of the functioning of the organization and many of the sub-criteria are often misunderstood by the management. Thus, the enthusiasm with which the management welcomes the introduction of the EFQM model begins to fade when the model is implemented in practice. A deeper study of the EFQM model makes directors come to conclusion that the whole process is too bureaucratic. Organizations often meet the EFQM requirements, but fail to record their results sufficiently and as required. When aspiring to the National Quality Award of the Slovak Republic or the European Quality Award, the company has to prepare a self-assessment report according criteria of the EFQM model. The preparation of the self-assessment report is an extremely complex and time-consuming process and requires involvement of key employees from all areas of business. Incorrect definition of processes and results in the self-assessment report may result in a low score of an otherwise successful organization from the professional EFQM auditors. This leads to disappointment, conflicts and rejection of the whole process.

The path towards excellence according to the EFQM model is a long-term process that must be upheld by the whole business from the top management to the last employee. If only the top management desires the introduction of the EFQM model and then delegates the application duties to employees – failing to properly explain its effects – it encounters resistance and the process is doomed.

The current competitive environment in the global marketplace requires organizations to continuously improve quality. This applies not only to products, but also to processes and management. Today, it is often not enough to satisfy customer needs, but it is necessary to exceed them. This requires excellence in organizations.

The EFQM excellence model understanding and effective implementation is one of the tools that can help organizations on their path of improving and achieving a lasting success.

4 The EFQM Model Application Methodology

During the research work in this area, we propose a methodology for application of the EFQM model, which is proposed especially for manufacturing organizations, which have developed and implemented Quality Management System (QMS) according to standards ISO 9001 and plan further development and improvement of the existing management system using the model EFQM. Steps of the methodology are illustrated in Figure 3.

The methodology is designed in conjunction with manual and automated self-assessment system to enable the organization to apply the EFQM model in less time and evaluate their performance level and effectiveness by more transparent way. The methodology enables to get an idea of what is necessary to do in the process of EFQM model application. The actual implementation of the methodology and the manual is designed to avoid confusion and unnecessary complexity requiring to start again and resulting in the time loss.

4.1 Used scientific methods

Selected scientific methods of problem solution can be divided into two main groups: empirical and logic (scientific analysis and synthesis). Empirical methods are applied to an electronic survey that aimed to determine knowledge of the EFQM model and its use in among organizations operating in Slovakia. The logical method was utilized for the problem solving analysis and synthesis. Methods of scientific analysis were used to evaluate the current issue of quality management level and EFQM implementation in construction sector, to analyse criteria and sub-criteria of the EFQM model, to explore the possibilities of applying the EFQM model in construction organizations and to examine the existing systems of assessment under the EFQM model.

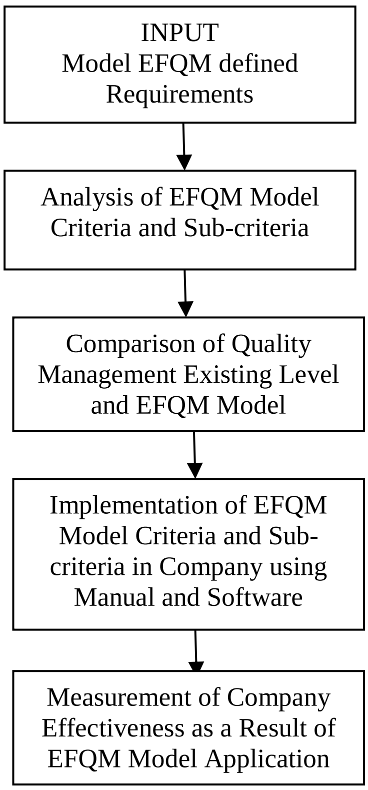

Figure 3. Steps to apply EFQM model in construction company

Scientific synthesis method was used during the process of EFQM model development and implementation including the creation of electronic manual and during the process of automated evaluation system of construction company quality management level.

5 Electronic Manual for the EFQM Model Application

Electronic manual is designed on the basis of the EFQM model criteria and sub-criteria requirements and helps organizations to understand and apply the EFQM model and evaluate their own performance and effectiveness in a shorter time. The structure of the proposed manual consists of these main parts:

- the analysis of EFQM model requirements defined by criteria and sub-criteria and determine the existing quality level of the organization and opportunities for improvement,
- self-assessment system of organization quality management level using the criteria and sub-criteria of the EFQM model by electronic automated system.

5.1 The Evaluation System of EFQM Model Criteria

The EFQM model consists of prediction and result parts. For each of them is in the manual suggested a specific method of evaluation. In this paper we provide an example evaluation of prediction part of the EFQM model. In the process of self-assessment of the organization is for each of the manual requirements of prediction part of the EFQM model selected phase of applications based on the Deming cycle - Table 1 and the performance level -Table 2.

Table 1. Evaluation of EFQM model application level in organization

Activity is:	Description	Evaluation %
P (planned)	Organization plans the activity to apply	10
D (done)	Activity is implemented	15
C (checked)	Organization checks the effects	20
A (acted)	In a case of positive effects activity is used in practice	25
B (benchmarked)	Organization compares the activity with best organization in market	30

Table 2. Level of EFQM model sub-criterion fulfilling in a given phase of application

Level of fulfilling	Description
0	There is no evidence to fulfil the requirements
0,25	There exist indicators of compliance requirements
0,5	Partial evidence of requirement fulfilling
0,75	Significant evidence of requirement fulfilling
1	Clear evidence of requirement fulfilling

The selected phase applications and performance levels are the basis for calculating the assessment for the achievement of the criterion and sub-criterion requirement. Position in the current phase of the application assumes management of the previous phases. If the company in meeting this requirement found for example in phase "act" with the degree to 0.5, the overall percentage achieved in meeting this requirement are:

$$\underset{\text{PLAN}}{1x10} + \underset{\text{DO}}{1x15} + \underset{\text{CHECK}}{1x20} + \underset{\text{ACT}}{0,5x25} = 57.5\ (\%) \qquad (1)$$

By this way is calculated the percentages evaluations for all requirements. The percentage evaluation of each sub-criterion is the weighted average of achieved percentage values for each of its requirements, and a set of weights represents the coefficients of importance.

$$P_{K_iS_j} = \frac{\sum_{r=1}^{n} P_{K_iS_jR_r} . d_{K_iS_jR_r}}{\sum_{r=1}^{n} d_{K_iS_jR_r}} \qquad (2)$$

where P_{KiSj} is achieved percentage evaluation of j sub-criterion in i criterion,
r = 1,2...n – number of requirements in criterion K_i and subcriterion S_j,
d_{KiSjRr} is coefficient of importance for r requirements of j sub-criterion in i criterion.

Each of the criterions of the EFQM model has a defined maximum point value which can be achieved. It is evenly distributed among the individual sub-criteria.

The resulting number of points for the sub-criterion we obtain by multiplying of the achieved percentage value by maximum number of points. Generally we can for any criterion express:

$$B_S = B_{max} \cdot \frac{P_s}{100} \qquad (3)$$

where B_S is achieved score in evaluated sub-criterion,
B_{max} is maximum score which can be in a given sub-criterion obtained,
P_S is achieved percentage evaluation for given sub-criterion

The resulting score for each criterion is the sum of achieved point value of its individual sub-criteria. The total achieved point value concerning the enablers is the sum of achieved points for criterion 1 to 5. The maximum possible score can be 500 points (see enablers - Figure 1).

5.2 Electronic Evaluation of the Proposed Solution

Electronic solution of proposed evaluation system is realized by using Microsoft Excel Program. The aim was to design and develop an automated system using computer technology, which would on the basis of defined requirements in electronic manual and in evaluation system allow easy, fast and comfortably realize evaluation of business performance and effectiveness, as well as clear and understandable display output of the evaluation process. Entering of inputs is handled through a questionnaire form, by selection of predefined options from "drop down menu" (dropdown list). The user does not perform any calculations, nor inscribe the input values. The results are updated immediately after any change in input data.

The selected values the user can change at all time during the evaluation process shown in Figure 4. Sheets “enablers” in Figure 5 and “results” in Figure 6 clearly show achieved percentage scores for each sub-criteria and requirements, and from these values is automatically calculated score for sub-criteria, and all criteria of “enablers” and “results” sections. Changes of point values are automatically transferred to the sheet EFQM - assessment, in which is a graphical view of the structure of the EFQM model with the nine criteria and the corresponding percentage and scoring for each of them for the “enable” and “result” part and also total assessment of all criteria.

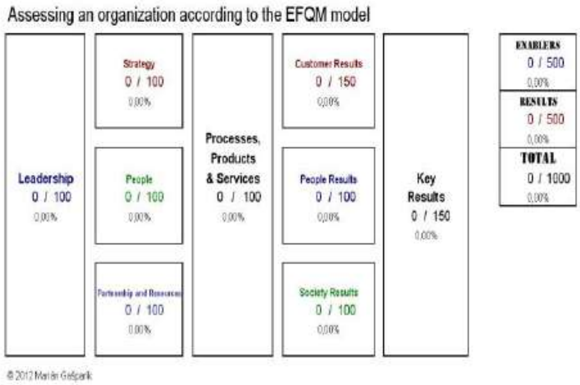

Figure 4. Software illustration of EFQM model basic structure (starting level of criteria evaluation)

5.3 Application of the Proposed Methodology and electronic Manual into Construction Company (2)

Application of the proposed methodology and the electronic manual was made for a construction company in Slovakia. During our cooperation we offered to the company basic training process concerning the EFQM model development and application and electronic manual for self-evaluation according to EFQM model criteria.

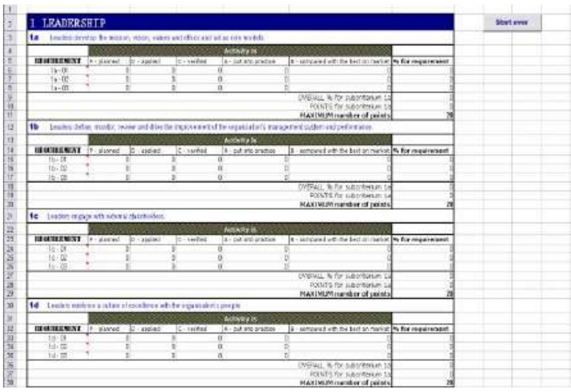

Figure 5. Software illustration of EFQM model part „enablers“

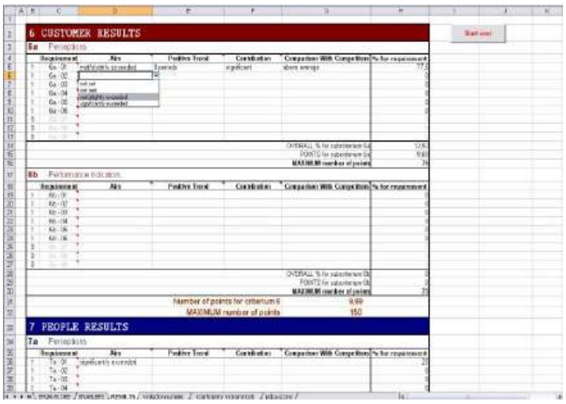

Figure 6. Software illustration of EFQM model part „results“

Process of self-evaluation was realized using our software for automated evaluation quality management level in company according to EFQM model criteria. By application of the higher described methodology and electronic manual and the company during 1 year showed improvement in all criteria of the EFQM model in Figure 7. Our cooperation will continue and we assume more dramatic improvement next 1-2 years after implementation next actions especially in production process. Quality of construction processes at this model company was increased by implementation of research activities described in [15, [16] and [17].

Model EFQM is useful to implement after development and implementation of Quality Management System (QMS) according to ISO 9001. QMS represents very good basis for application of higher quality management philosophy, like TQM, KAIZEN or model EFQM.

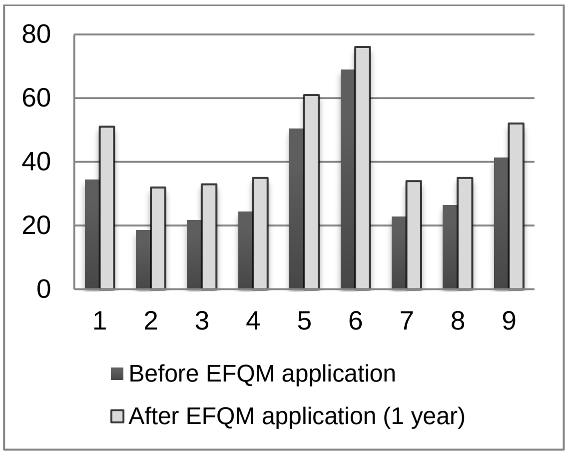

Figure 7. Evaluation of EFQM model in construction company before model application and after 1 year

Legend to Figure 7:
1 - Leadership
2 - Policy and strategy
3 - People (employees)
4 - Partnership and resources
5 - Processes, products and services
6 - Customer results
7 - People results
8 - Society results
9 - Key results

6 Conclusion

Research work described at this contribution results in the form of its own methodology and electronic manual allows to construction organizations effectively introduce and implement EFQM model requirements to practice in a relatively short period of time with aim to constantly improvement its performance towards excellence.

Defined methodology suggests and explains the sequence of steps towards EFQM model applying the electronic manual describes all of EFQM model sub-criteria and provides concrete suggestions and solutions to meet them. The part of manual there is also automated electronic assessment system for construction organizations which was verified in real company. Application of the methodology and manual enables in a short time to evaluate company quality management level and to identify opportunities for continually quality improvement.

The main results of our research activity are:

- creation of a new electronic manual for implementation and evaluation of EFQM model criteria and sub-criteria in construction company,
- the definition of mathematical models for automated evaluation of EFQM model criteria,
- the proposal of own software for automated evaluation of quality management level for company using EFQM model,
- continually improvement of construction company quality management level in all areas of its activities.

Model EFQM is an effective tool for continual improvement of organization quality, which leads not only to higher level of quality management, but also to customer satisfaction, success at national and world market and to increasing the culture of whole organization.

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Concrete Inspection Systems Using Hammering Robot Imitating Sounds of Workers

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Abstract -
In Japan, deterioration of many tunnels and bridges have become a serious problem. Moreover, engineers that manage them are insufficient due to aging. Therefore, we developed an under-actuated hammering robot that can imitate hammering sounds of inspection workers. When we use this robot, workers can detect concrete defects by using their experiences. For example, if we attach a video camera or microphones to this robot, they can detect defects as before at remote locations. Furthermore, it can contribute building high accurate automatic inspection systems by learning hammering sounds of inspection workers. Therefore, we developed an under-actuated hammering robot that can imitate hammering sounds of inspection workers. In this paper, we described these systems using this robot. To verify usefulness of these systems, we conducted experiments using a concrete test block and compared the results of an inspection worker with this robot. As a result, we confirmed that this experiments showed the results of this robot is similar to its of an worker.

Keywords -
Concrete inspection; Hammering robot; Under-actuated; Defect; Nondestructive

Figure 1. The hammering test by inspection workers

1 Introduction

In Japan, deterioration of many tunnels and bridges have become a serious problem. Moreover, engineers that manage them are insufficient due to aging. For this reason, it is desired to develop innovative inspection techniques such as robots and implement on site.

Inspection of the concrete structure are using nondestructive test mainly. There are visual inspection and hammering test and so on in that test. Visual inspection is useful to inspect cracks of the concrete surface. For example, systems that find out concrete cracks using a CCD camera or others are actually implemented on site[1][2].

Hammering test is useful to find out defects inside the concrete. For example, the hammering test by workers as shown in Figure 1 is a popular method. In this method, the worker hammer the concrete surface and assesses condition of the concrete from hammering sounds. Another method is that the Schmidt rebound hammer is widely used in the concrete inspection[3]. However, the method takes much time to inspect a wide range. To improve the efficiency of these work, there are researches to find out defects inside the concrete. There are a robot named "Sonic Meister" using an industrial manipulator and impact unit with five hammers[4][5]. This system can obtain hammering sounds at 0.2 s intervals by controlling these hammers successively. However, this system is large and requires eight-ton truck. There are a inspection method using the non-contract laser measurement technology[6]. This technology enables high speed inspection and automation. However, the technology requires high position accuracy in order to irradiate the concrete surface with the laser. The laser may hurts the eyes of workers.

To consider these results, we examined a mobile hammering robot based on the hammering testing method. When we use hammering robot that can imitate hammering sounds of inspection workers, they can detect concrete defects by using their experiences. For example, if we attach a video camera or microphones to this robot, workers can detect its at remote locations as before. Furthermore, it can contribute building high accurate automatic inspection systems by learning sounds of inspection workers.

Therefore, we developed an under-actuated hammering robot that can imitate hammering sounds of inspection workers[7]. This robot and a example of the system as-

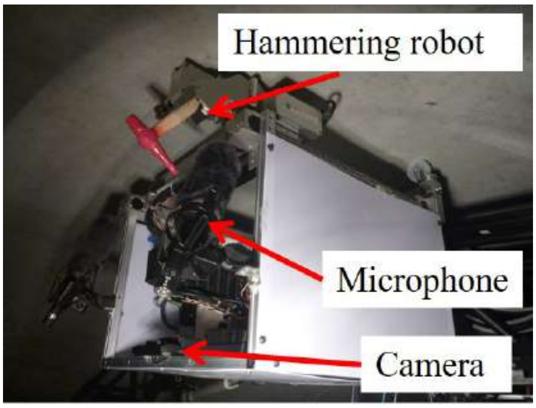

Figure 2. The hammering robot

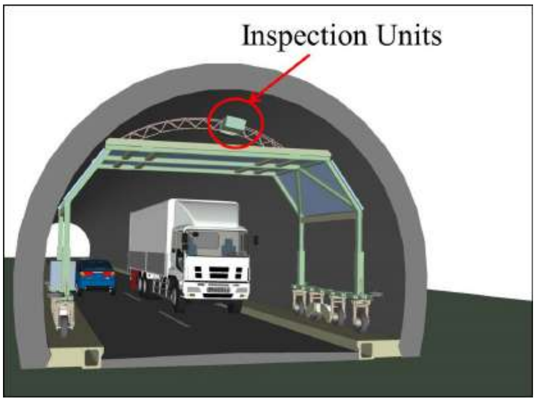

Figure 3. An image of the tunnel inspection system using the hammering robot

sumed to mount it are shown in Figure 2.

In this paper, we described systems using the hammering robot and the results of experiments to verify usefulness of them.

2 Concrete inspection system

There are concrete inspection systems using the hammering robot. For example, we have assumed a tunnel inspection system such as Figure 3. This system will equip the robot and can inspect tunnel automatically by using vehicles. This robot has a camera and microphones and can record image of concrete surfaces and hammering sounds. As a more simple system, you can attach this hammering robot to the tip of a pole.

In this system, we have thought that there are two ways to detect concrete defects. The first way is that inspection workers use measured data "Type-A". For example, inspection workers can detect concrete defects at remote locations by using data sent from this inspection system. The second way is that systems learn this data by the

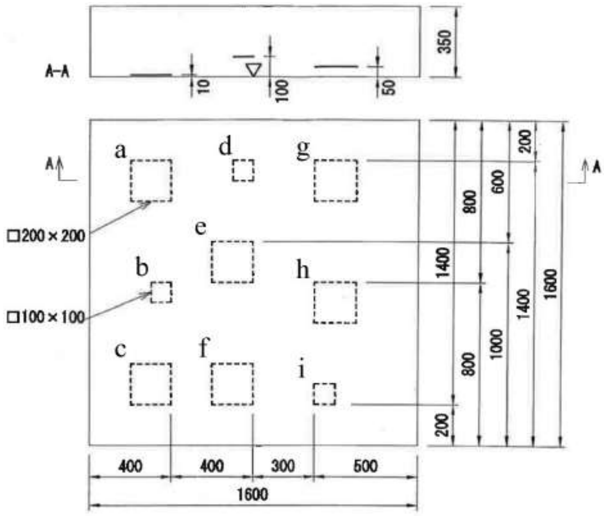

Figure 4. Drawing of the concrete test block

ensemble learning method to detect automatically "Type-B"[8]. If hammering sounds of this robot is similar to inspection workers, we can collect reliable learning data by using hammering sounds of inspection workers. To verify usefulness of these systems, we conducted hammering experiments assuming these systems.

3 Hammering experiment

In this experiment, we verified usefulness of these systems comparing the results of assuming Type-A with the results of previous works by expert inspection workers. If Type-A is useful, we can verify that sounds of the robot are similar to inspection workers. Therefore, this robot is also useful with Type-B.

3.1 Concrete test block

The concrete test block which is used in this experiment is shown in Figure 4. In this block, there are some artificial cavity which are shown as Table 1 simulating defects.

Table 1. Specification of the defect

Defect	Area[mm2]	Depth[mm]	Thickness[mm]
a	200×200	10	1
b	100×100	10	1
c	200×200	10	20
d	100×100	100	1
e	200×200	100	1
f	200×200	100	20
g	200×200	50	1
h	200×200	50	20
i	100×100	50	1

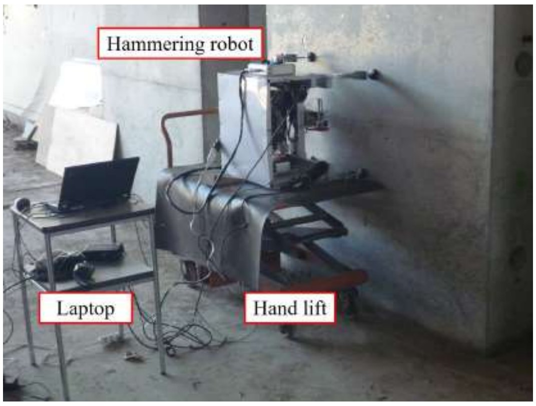

Figure 5. Appearance of a test using the robot

Figure 6. Appearance of a test by an expert

3.2 Hammering device

Figure 5 is a device with the hammering robot we developed. This device can hammer the concrete surface at equal intervals because it can move a hammering robot at the same speed. When this device fixed, the robot can move within 300[mm]×300[mm] area. This device has a camera and microphones and can record images of concrete surfaces and hammering sounds. This hammering robot have equipped with a hammer weighing 100g using by many inspection workers.

3.3 Experimental method

First of all, we described about hammering tests by the robot based on Type-A. In this tests, we used a device such as Figure 5 and hammered the surface of a concrete test block. The hammering interval was set to 25mm. The height of this device was adjusted using hand lift. We recorded images of concrete surfaces and hammering sounds by this device. Furthermore, we prepared an expert inspection worker who had not know the position of defects. An expert detected defects using this data at a later date. In this process, an expert had not know where these image are on the test block.

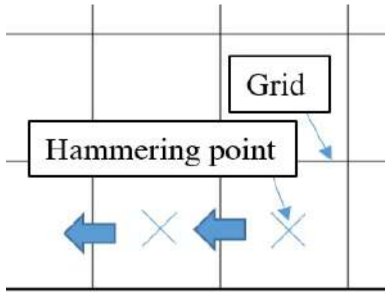

Figure 7. Hammering points

Secondly, we described about hammering tests by inspection workers. An inspection worker was the same as an expert who detected defects in Type-A. He used a hammer weighing 100g that he always use. We displayed grid which size is 25mm on the concrete test block by the projection mapping such as Figure 6. He hammered at the center of each grid such as Figure 7. To compare quantitatively, we adjusted the position of grid to hammer the same place as Type-A.

3.4 Evaluation method

We recorded positions detected defects and qualitatively compared. Furthermore, we recorded the number of grids $P[points]$ detected defects, and quantitatively compared by detection rate of defects $R[\%]$. When inspection interval is $D[mm/points]$, defect area $S[mm^2]$ is written by,

$$S = P \times D^2. \tag{1}$$

If defective area in a concrete test block (Figure 4 or Table 1) is $S_0[mm^2]$ and it detected in this experiment $S[mm^2]$, detection rate R is written by,

$$R = \frac{S}{S_0}. \tag{2}$$

We compared the results of the robot and an expert using this detection rate.

3.5 Experimental Results and Consideration

The result of defective area by the robot based on Type-A is shown as Figure 8. An expert were able to detect defects a, b, c, g, h from images of the concrete surface and hammering sounds of this robot. This experimental result showed that it is difficult to detect defects of depth is 100mm. Moreover, it is difficult to detect defects of area is 100[mm]×100[mm] even if depth of defects are 50mm. Similarly, the result of defective area by an expert is shown as Figure 9. As shown in Figure 9, he were able to detect

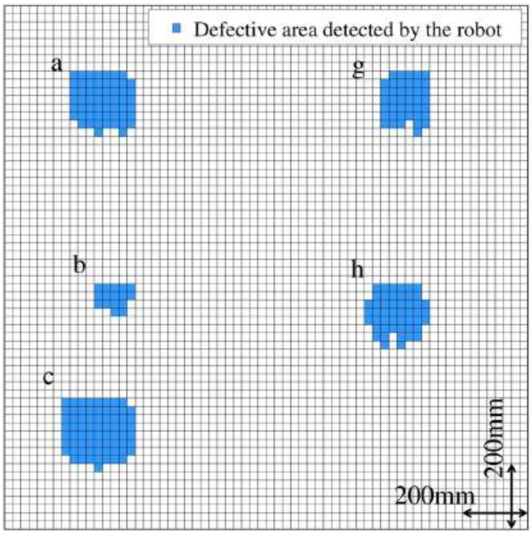

Figure 8. Defective area by the robot (25mm)

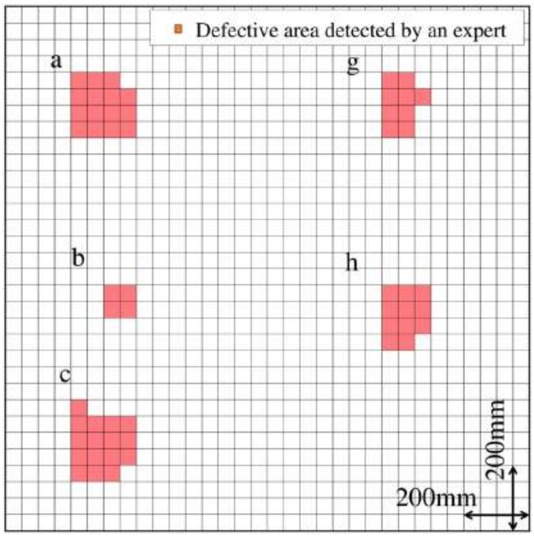

Figure 11. Defective area by an expert (50mm)

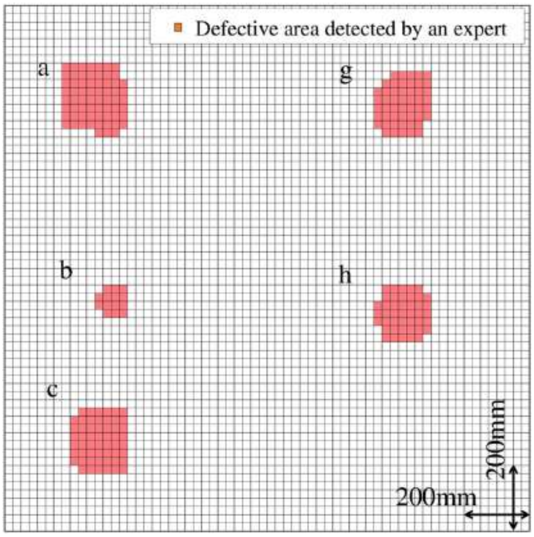

Figure 9. Defective area by an expert (25mm)

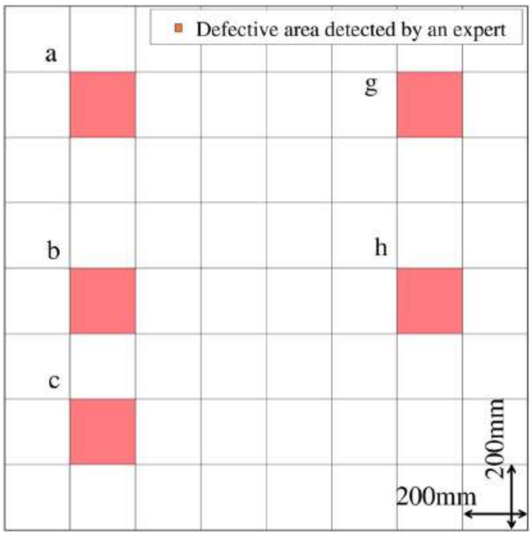

Figure 12. Defective area by an expert (200mm)

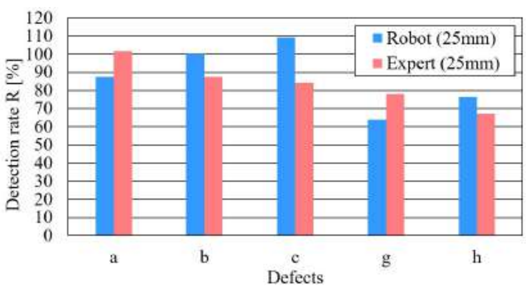

Figure 10. Detection rate

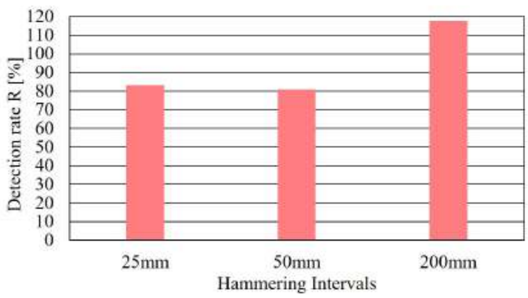

Figure 13. Detection rate of an expert

the same position of defects as the robot. As a result of qualitatively comparing, the results of defective area by the robot and an expert are similar. Therefore, we verified usefulness of our concrete inspection systems using the hammering robot.

We compared these results quantitatively using Equation (2). As shown in Figure 10, the robot can simulate an expert within ±15% at defects of a, b, g, h. We think that it is not a problem although there is a difference of about 25% at a defect of c. Because the robot detected a defect wider than an expert of it.

In this paper, we conducted hammering tests at 25mm interval. In fact, the more this distance larger, the more inspection speed large. Therefore we conducted hammering tests 50mm interval and 200mm interval by an expert. This result is shown as Figure 11 and Figure 12. Both tests could be detected a, b, c, g, h as in the Figure 9. Moreover, detection rate at whole defects is shown as Figure 13. As shown in Figure 10, the difference between 25mm and 50mm was within 3%. However, 200mm detected defects about 35% wider than 25mm and 50mm. This experimental results showed that hammering inspection at 50mm intervals is useful for accurate defective area. We think that it is useful to inspect at 200mm intervals and then inspect a detailed at 50mm at the defective area.

4 Conclusion

In this paper, we described usefulness of the way to detect concrete defects by an expert inspection worker using sounds of the robot. To verify usefulness of this system using the hammering robot, we conducted hammering experiments using a concrete test block at 25mm interval. As a result of the experiments, the results of defective area by the robot and an expert are similar. Moreover, the experimental results showed that the robot can simulate an expert within ±15% at almost defects. Therefore, we think that inspection workers can detect concrete defects using data sent from this robot. In addition, we think that they can automatically obtain inspection results using this robot that adopted the ensemble learning. method.

We also conducted hammering tests at 50mm, 200mm intervals by an expert to improve inspection speed. As a result of the experiments, the difference between 25mm and 50mm was within 3%. However, 200mm detected defects about 35% wider than 25mm and 50mm. We think that it is useful to inspect at 200mm intervals and then inspect a detailed at 50mm at the defective area.

5 Acknowledgements

In this work, advice and comments given by Japan Construction Method and Machinery Research Institute (CMI) besides permission to use test fields. We thank them very much. This work was in part supported by Council for Science, Technology and Innovation, “Cross-ministerial Strategic Innovation Promotion Program (SIP), Infrastructure Maintenance, Renovation, and Management” (funding agency: NEDO).

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A Numerical Model for the Attitude Manipulation of Twin-Hoisted Object

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Abstract –

Hoisting an object with two crane hooks is sometimes applied when the pitch attitude of the hoisted object is necessary to be adjusted. The pitch attitude can be manipulated by changing the length difference of the two crane cables that connect the object with two hooks at two different positions. However, this twin-hoisted approach is impractical for crane operators who must be highly experienced and capable of adjusting the crane based on their visual measurement. This implies that the safety of workers and operation efficiency may rely on the physical and mental state of the operator. Furthermore, for the automation of the hoisting process, the method to precisely adjust attitude is required. In this research, a numerical study is carried out by a model that enables the attitude manipulation of a twin-hoisted object. By specifying a pitch attitude and lifting height of the object, the model can take the geometrical limitations of hoisting process into consideration and then determine the lengths of the two crane cables in real-time. In this study, the developed model is validated using a mobile crane both through a virtual environment and a lab-scale experiment. The proposed model not only can be implemented with a guiding interface established to guide crane operators in real time but also contributes to the development of automated crane control method.

Keywords –

Twin-Hoisting; Attitude Manipulation; Crane Control; Authors; Automation

1 Introduction

Conventionally, if the manipulation of the pitch attitude of a hoisted object is necessary, three approaches can be applied. The first approach is to hang the object with one crane using one single cable. This requires nearby workers adjusting the pitch angle of the hoisted object. The second approach is to hang the object by two cranes. These cranes hang each sides of the object and adjust its pitch angle through changing the length of their cables. The last approach hangs the object with two cables on one crane. By using both cables of the main boom and the auxiliary jib, adjustment can be achieved similarly to second approach. However, the former two approaches are limited in many ways. The first approach requires space for workers to adjust the attitude of the object. This may be hazardous when the attaching point is located high where there are only uncomplete structures for workers to stabilize themselves. Moreover, the object hanging in the air can also pose dangerous to nearby workers by striking them [1]. As for the second approach, requiring an additional crane implies that extra space and rent are needed. This may increase the total cost of the project and hinder its progress as well. Moreover, the coordination of the two cranes may be troublesome when attempting to reach the desired attitude by respectively changing the length of their cables.

While the first and the second method face those issues, the third method avoids them. As a result, demands on controlling the pitch attitude with the third approach is reported to be rising [2]. Furthermore, similar approaches in the field of manufacturing have been developed. Sawano et al. proposed a power-assisted attitude control system that hangs an object with one cable and a linear cylinder. In their study, the attitude of the object can be controlled through expanding and contracting the cylinder [3]. Hence, we aim to further improve the third method for a better controlling of the pitch attitude of the object hung by a crane.

Although the third method has some advantages over other methods, it still has a few disadvantages. This practice relies heavily on the experience of the crane operator. Also, the operator has to estimate the angle of the object by sight, which is not intuitive and precise. In the case that the operator cannot see the object, a voice guidance from other workers is needed. However, this may be sometime confusing to the operator. In addition, if an autonomous crane control system is to be developed, a precise approach to determine the pitch attitude will be necessary.

Therefore, we propose a numerical model to aid the manipulation of the pitch attitude using one crane and two cables. The telescopic boom of crawler cranes and a beam-type object are selected in this model. Formulas are also developed basing on the geometry of the crane and the hoisted object. By specifying the desired attitude, the corresponding lengths of the two cables can be obtained. Then, the cables of the crane are adjusted without changing the posture of the crane. An assigned attitude includes the pitch angle and the height of the hoisted object. As a result, a desired pitch attitude at a certain elevation can be reached. Finally, we inspect the validity through a virtual experiment and a lab-scale experiment.

2 Numerical Model and Formulas

The model considers the geometry of a crane to calculate the proper length of the crane cables to achieve specified pitch attitude of the object hoisted. In our study, A mobile crane with a telescoping boom and an auxiliary jib attached on the top of the boom is considered. A simplified mobile crane is illustrated in figure 1 with a set of parameters representing the geometry of the crane. As the figure shows, l_1, l_2, a and b respectively represents the length of the main cable, the length of the auxiliary cable, the distance between the left hooked point on the object to the center of mass of the object and the distance between the right hooked point on the object to the center of mass of the object. The distance between the sheaves of the main boom and the auxiliary jib is assigned as D. The angle of elevation of the auxiliary jib, main cable, auxiliary cable and the object are respectively defined as φ, α, β and θ. Furthermore, we defined a set of constraints to these angles. That is, $0° \leq \varphi \leq 90°$, $0° \leq \alpha \leq 90°$, $90° \leq \beta \leq 180°$ and $-90° \leq \theta \leq 90°$. This is to prevent unreasonable attitudes of the system.

The aim of the model is to obtain the length of the cables, l_1 and l_2, when a certain pitch angle θ and the vertical length $l_1 \sin\alpha$ of the main cable are assigned. Here we assume that the height of the main boom sheave is readily known, thus setting the vertical length of the main cable is equivalent of setting the height of the object. In this regard, we view D, a, b and φ as known parameters. On the other hand, the angle of the two cables, α and β will be calculated in the process as well. Therefore, a set of attitude calculation formulas are proposed.

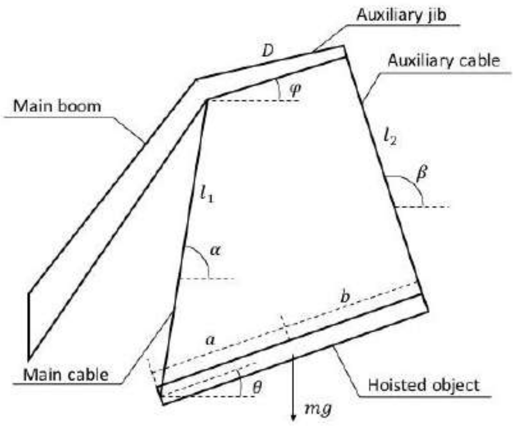

Figure 1. Simplified crane geometry

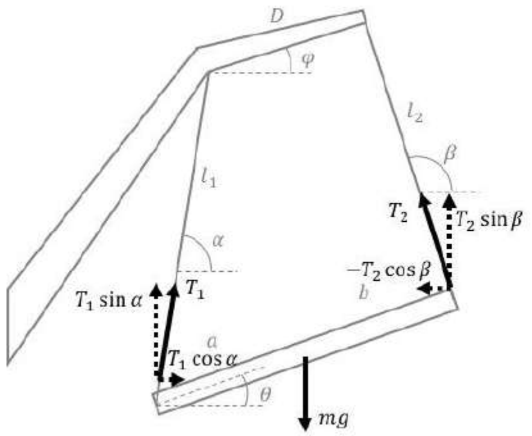

Figure 2. Forces acting on the object

Here we illustrate the formulation of the attitude calculation formulas of the model. The forces acting on the hoisted object in mechanical equilibrium are shown in figure 2. T_1 and T_2 are the tension of the main cable and the auxiliary cable. mg is the gravitational force acting on the hoisted object. Since the object is in mechanical equilibrium, vertical and horizontal forces in the system balance each other. Therefore, we can yield:

$$T_1 \sin\alpha + T_2 \sin\beta = mg \text{ and} \tag{1}$$
$$T_1 \cos\alpha + T_2 \cos\beta = 0. \tag{2}$$

In addition, the hooked points on the left and right side of the object are free to spin. This indicates that the moment on both side should be zero in mechanical equilibrium. Therefore, we can yield:

$$T_1 = m \cdot \frac{b}{a+b} \cdot \frac{\cos\theta}{\sin(\alpha-\theta)} \text{ and} \tag{3}$$

$$T_2 = m \cdot \frac{a}{a+b} \cdot \frac{\cos\theta}{\sin(\beta-\theta)}. \tag{4}$$

From Equation (1), (2), (3) and (4), we obtain a relationship between α and β:

$$\tan\alpha = \frac{a+b}{a} \cdot \tan\theta - \frac{b}{a} \cdot \tan\beta. \tag{5}$$

From the geometry relationship between the vertical distance of the upper and lower ends of D, l_1, l_2 and $(a+b)$, we get:

$$l_1 \sin\alpha = l_2 \sin\beta - D\sin\varphi + (a+b)\sin\theta. \tag{6}$$

Similarly, from the geometry relationship between the horizontal distance of the upper and lower ends of D, l_1, l_2 and $(a+b)$, we get:

$$l_1 \cos\alpha = l_2 \cos\beta - D\cos\varphi + (a+b)\cos\theta. \tag{7}$$

Finally, through Equation (5), (6) and (7), we yield:

$$\begin{aligned} & l_1 \sin\alpha \\ & = \Bigg((a+b)\sin\theta - D\sin\varphi \\ & + \big((a+b)\cos\theta - D\cos\varphi\big) \\ & \cdot \left(\frac{a}{b}\cdot\tan\alpha - \frac{a+b}{b}\cdot\tan\theta\right)\cdot\sin\alpha \Bigg) \\ & \div \left(\sin\alpha + \cos\alpha\cdot\left(\frac{a}{b}\cdot\tan\alpha - \frac{a+b}{b}\cdot\tan\theta\right)\right) \end{aligned} \tag{8}$$

By inputting a set of known value of D, a, b and φ and assigning a set of $l_1 \sin\alpha$ and θ, a set of αs satisfying the constraint of α can be obtained through Equation (8). In addition, the corresponding l_1s can also be calculated. Through Equation (5), a set of corresponding βs can be obtained. By checking if β meets its constraint, we can get the only set of α and β. With the particular set of α and β, l_1 and l_2 can be calculated through Equation (6) or (7). In this study, the process of finding l_1 and l_2 is carried out by Matlab.

3 Experiment and Result

To examine the validity of the proposed model and formulas, we conducted several tests with a virtual crane. In the tests, we specified 6 different attitudes of the hoisted object. Which are, respectively, 1. $\theta = 30°$, $l_1 \sin\alpha = 30cm$, 2. $\theta = 45°$, $l_1 \sin\alpha = 30cm$, 3. $\theta = 60°$, $l_1 \sin\alpha = 30cm$, 4. $\theta = -30°$, $l_1 \sin\alpha = 30cm$, 5. $\theta = -45°$, $l_1 \sin\alpha = 30cm$ and 6. $\theta = -60°$, $l_1 \sin\alpha = 30cm$. First, we calculated the corresponding set of α, β, l_1 and l_2 basing on the formulas through Matlab. Then, we adjusted the l_1 and l_2 of the virtual model according to the result of the previous calculation. Finally, we compared the resulting αs, βs, l_1s and l_2s. In addition, tests are also conducted with a lab-scale crane shown in figure 3. The feasibility of applying our method was expected to be inspect through these tests.

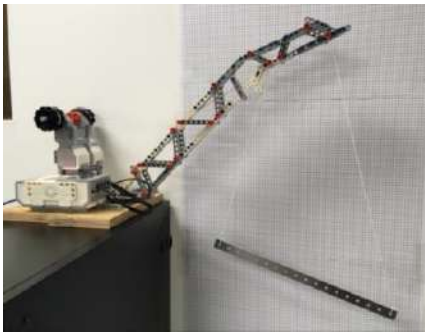

Figure 3. Lab-scale crane

In both virtual and lab-scale tests, the geometry parameters of the crane models are set identically as follows: $D = 9.7cm$, $\varphi = 26.04°$, $a = b = 13.65cm$. The corresponding αs, βs, l_1s and l_2s calculated basing on our formulas are listed in table 1.

Table 1 The calculated corresponding αs, βs, l_1s and l_2s

Attitude	$\alpha(°)$	$\beta(°)$	$l_1(cm)$	$l_2(cm)$
1	75.8	109.6	30.9	21.9
2	79.0	107.7	30.6	15.7
3	84.0	99.5	30.2	10.8
4	97.7	99.9	30.7	48.6
5	81.6	96.5	30.3	53.9
6	86.4	93.0	30.1	58.0

In the virtual crane test, we built a crane in Unity 3D, which is a physic engine as well as a game engine. We adjusted the length of the cables to the calculated l_1s and l_2s of the six specified attitudes in the virtual environment. Then, we measured the resulting θs and $l_1 \sin\alpha$s as well as αs and βs. Noted that we did not precisely set the lengths to the precise numbers but manually adjust them to simulate the crane operating process. Thus, slight difference of l_1s and l_2s between the calculated result and experimental result can be noticed. The result of the virtual test is list in table 2.

In the lab-scale crane test, we built a crane boom and an auxiliary jib attached on its top with LEGO Mindstorms EV3. We also adjusted the length of cables l_1 and l_2 and measured the resulting θs and $l_1 \sin\alpha$s as well as αs and βs. Similarly, we did not precisely set the length but manually adjust their lengths. Thus, slight difference of l_1s and l_2s between the calculated result and experimental result can also be noticed. The result of the lab-scale test is list in table 3.

Table 2 Result of virtual test

Attitude	$\theta(°)$	$l_1 \sin\alpha\,(cm)$	$\alpha(°)$	$\beta(°)$	$l_1(cm)$	$l_2(cm)$
1	29.4	29.8	74.8	108.6	30.9	21.8
2	46.1	30.3	79.1	106.4	30.8	15.5
3	59.6	30.1	83.7	99.1	30.3	11.0
4	-29.3	30.4	97.4	99.8	31.1	48.7
5	-45.4	29.9	80.4	95.8	30.3	53.9
6	-59.6	30.1	86.6	93.3	30.2	58.1

Table 3 Result of lab-scale test

Attitude	$\theta(°)$	$l_1 \sin\alpha\,(cm)$	$\alpha(°)$	$\beta(°)$	$l_1(cm)$	$l_2(cm)$
1	26.9	26.1	74.1	108.7	30.2	22.0
2	43.2	26.6	77.6	107.0	30.0	15.4
3	55.5	26.9	81.2	101.9	29.2	10.6
4	-32.4	26.4	77.5	99.0	29.9	48.2
5	-51.5	27.0	83.0	94.6	29.9	54.8
6	-66.2	27.0	87.7	90.9	30.0	58.7

Table 4 Gap between test results and calculated results

Attitude		Gap ($\lvert 1 - TestResult \div CalculatedResult \rvert \times 100\%$)			
		θ	$l_1 \sin\alpha$	α	β
1	Virtual Test	2.1%	0.6%	1.3%	1.0%
	Lab-scale Test	10.3%	13.1%	2.2%	0.8%
2	Virtual Test	2.4%	0.9%	0.2%	1.2%
	Lab-scale Test	3.9%	11.4%	1.8%	0.7%
3	Virtual Test	0.6%	0.5%	0.3%	0.4%
	Lab-scale Test	7.6%	10.2%	3.3%	2.4%
4	Virtual Test	2.5%	1.2%	0.3%	0.1%
	Lab-scale Test	7.8%	12.1%	20.6%	0.9%
5	Virtual Test	0.8%	0.4%	1.5%	0.7%
	Lab-scale Test	14.5%	10.1%	1.7%	1.9%
6	Virtual Test	0.6%	0.5%	0.2%	0.3%
	Lab-scale Test	10.4%	9.8%	1.6%	2.3%

4 Discussion

The gap of the geometry parameters between the results calculated through the formulas and the results obtained through the tests is listed in table 4. The gaps between the θs of the virtual tests and the calculation are less than 2.5%. Also, $l_1 \sin\alpha$s, αs and βs of the virtual tests also show matching results with gaps no more than 1.5%. This indicates that the corresponding l_1 and l_2 calculated through proposed model and formulas are able to form the specified attitude. On the other hand, the results of the lab-scale tests show larger gaps. However, since the main purpose of the lab-scale tests are not evaluating the formulas, precise measure methods were not applied. Therefore, we believe this is because of the errors of the measurement of these parameters. Also, deformation of the crane boom caused by weight was noticed and may also lead to the inaccuracy of the attitude of the object.

We observed several facts during the lab-scale tests. 1. Some geometry constraints are necessary to be added into our model. 2. The swaying pattern of a twin-hoisted object is complicated. 3. Physical factors are necessary to be considered. For the first observation, we noticed that the hoisted object may strike the crane boom in certain critical condition. This is especially likely to occur when the length $(a + b)$ of the object is sizable or the object is close to the boom. Therefore, geometry constraints are needed to avoid collisions between the object and the boom. For the second observation, we noticed that the swaying of the twin-hoisted object is apparently different from single-hoisted objects.

Referring to the study of Maleki et al., a two-mode oscillation occurs when a motion perpendicular to the boom is performed with unequal cable lengths [4]. Reduction of the oscillation may be needed to allow more rapid operation and further applications. Finally, for the third observation, we found that deformation of the boom caused by weight can affect the accuracy of the resulting attitude. This issue should also be considered to allow a precise control of the hoisted object.

Although several problems were observed in the tests, the proposed method is still able to provide useful indication to adjust the cable lengths for an assigned pitch attitude of the hoisted object. Also, we believed that allowing users to assign the height of one side of the beam-type object is considerably convenient. In a case of attaching a beam to the structure, the operator may first lift the beam horizontally to the desired height near the attaching point on the structure. Then, he or she can adjust its attitude without changing the height of the attaching point on the beam. Consequently, the effort and time of readjusting the height of the beam can be saved.

5 Conclusion

A numerical model of a twin-hoisted beam-type object hoisted by a crane is proposed. In the model, the object is hoisted by a main boom and an auxiliary jib attached on the boom with two cables. Formulas are also proposed to calculate the corresponding cable lengths which can lead to specified attitude of the object under certain conditions. Furthermore, several issues were observed in lab-scale test, which indicate several necessary enhancements to further improve the safety and precision of such practice. Finally, the results of our tests suggest that the proposed model and formulas are capable to aid the manipulation of the pitch attitude of the hoisted object using one crane and two cables. Future works can be focused on implementing the proposed method on real cranes, while simultaneously addressing the observed issues.

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Design for manufacture and assembly in off-site construction: Advanced production of modular façade systems

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Abstract – Product development for commercial façade systems is a complex procedure. Since the Grenfell Tower disaster in London in June 2017, the import, use and sale of polyethylene core Aluminum Composite Panels (ACP) has been reduced. This encourages research on development of new façade systems using advanced production techniques such as additive manufacturing and CNC milling. The aim of this paper is to analyze the two techniques considering principles of design for manufacturability and assembly (DfMA). Results show that in advanced manufacturing of façade elements, a large percentage of project budget is related to acquisition costs for equipment such as CNC machins and 3D printers. Despite these high costs, non-traditional manufacturers are likely to see return of investments over future development projects for the modular façade systems.

Keywords –

3D printing; Additive Manufacturing; CATIA and DELMIA software; Design Optimization; Industrialized Buildings; Moulds; Prefabricated Structural Element; Primavera P6; Project planning and management; Rapid prototyping

1 Introduction

Complex façade systems are increasingly used in construction of iconic buildings. Such façade systems often utilize hyperbolic paraboloid surfaces to maximize aesthetic attraction. While traditional site-built construction is unable to deliver such levels of complexity, off-site prefabrication of façade modules provides an optimal alternative [1].

Modern manufacturing techniques such as 3D printing and CNC milling can further increase the efficiency of façade prefabrication [2]. Coupled with principles of design for manufacture and assembly (DfMA), such manufacturing-led initiatives have the potential to optimize product development in modern construction.

The focus of this research is on production of modular façade systems with hyperbolic paraboloid surfaces. Such façade production includes off-site prefabrication of modular corner façade surfaces, modular straight façade surfaces, and modular curved façade surfaces (see Figure 1). The elements are to be held together by interlocking mechanisms. The aim of modular prefabrication is to allow the production of robust combinations of various façade patterns for clients.

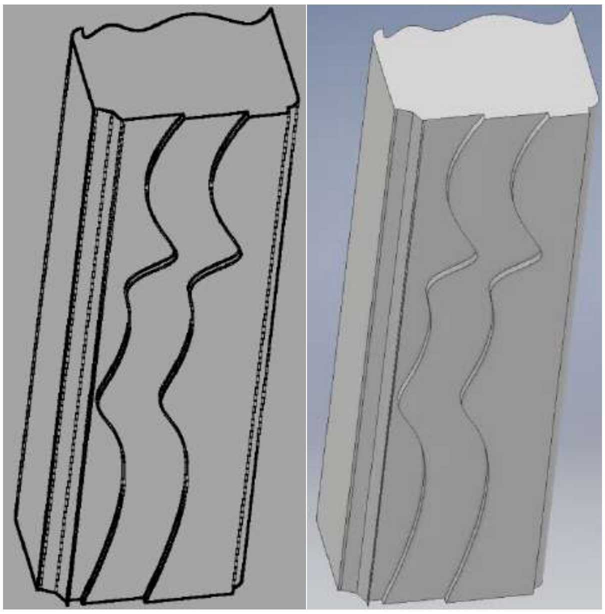

Figure 1. Sketch illustration and realistic view of

a complex façade system with hyperbolic paraboloid surfaces

The current paper explains principles of DfMA in modular prefabrication of complex façade systems. Then it reviews the advantages of using advanced production techniques of CNC milling and additive manufacturing. In the remaining part of the paper, a case study approach is used to analyze the cost and time requirements. At the end, concluding remarks are presented.

2 Modular prefabrication of complex façade systems- Design for manufacture and assembly

Modular prefabrication of Principles of complex façade systems is optimized by adopting principles of design for manufacture and assembly (DfMA). This is due to adoption of manufacturing-led and advanced processes in product development [3]. Furthermore, DfMA encourages multidisciplinary collaborations in product development where manufacturing and resourcing constraints are considered in designing parts and assemblies [4].

Successful implementation of DfMA requires parametric modelling software that supports collaborative work of designers, engineers and manufacturing teams [5]. Strong software such as CATIA and DELMIA have assisted off-site manufacturers of building elements to increase efficiencies and productivity [6]. CATIA is a software suite with multiple platforms for product lifecycle management (PLM), computer-aided design and computer-aided manufacturing [7]. DELMIA is also a software suite developed by Dassault Systems and focuses on manufacturing simulation [8].

The construction literature identifies most important principles of DfMA, including:

- Interdisciplinary collaborations in the early-stage design. Previous research shows that at least 80% of total project costs are committed during concept design stage [9, 10]. Project cost, time and quality of delivery will be optimised by involvement of design engineers, off-site manufacturers, assembly and on-site teams in early concept decisions [11]. This involvement also minimises the amount of rework or re-entrant flow, which is a key source of waste in construction projects [12, 13].

- Addressing past issues related to manufacturability and assembly. Design attributes in future projects are informed by challenges in previous projects. This way, issues that have caused difficulties for manufacturability and assembly will not be repeated [14, 15]. Past issues should be recorded in DfMA and CE knowledge repositories and properly addressed in future designs [16-18].

- Considering constraints in off-site and on-site construction. This DfMA principle optimises product design and process development so that both off-site and on-site limitations are satisfied [19]. Previous research has observed and analysed many cases in which desig of building components has been problematic in terms of transportation [20], crane operations [21], and safety of operations [22].

- Standardisation of design attributes. Excessive variation in design complicates manufacturing and assembly [12, 23, 24]. Some initiatives can minimise errors in assembly and installation such as designing paired parts instead of left/right hand parts [25]. Furthermore, paired-part designs support economy of scale in the supply chain by doubling purchasing volume when compared to mirror image parts [26, 27].

3 Prefabrication of complex façade systems- CNC milling

CNC milling can be used to produce required moulds for prefabrication of façade modules and panels, as well as the panel interlocking mechanisms [28]. The primary justification of using CNC milling at the prototyping stage is the ability to use CNC milling while transitioning from prototyping to final production [29]. Essentially, the ease to scale from prototype size to production size makes CNC milling an attractive approach. Furthermore, the basic skill sets required by CNC machining allows for cost-effective workers to be employed [30].

To enable the optimal production of façade systems using CNC milling, the workflow and product requirements must be understood and implemented. In order to determine the necessary activities for the project and the activity sequence, the following workflow needs to be analyzed and evaluated:

The workflow for CNC production includes design, program, setup, manufacture, assemble and evaluate.

- **Planning:** Throughout the planning process, product development teams identify the objective, specifications and requirements for the project. It is within this stage that risks, challenges and restrictions are identified, as well as establishment of scheduling and product plan outline.

- **Design:** The Design process for CNC requires the use of a 3-dimensional design definition that is constructed in CAD. Generated data can be complex and requires the time and labor of a CAM programmer. However, to initiate the design phase detailed engineering drawings must be provided to the CAM programmer and also CAD data must be reviewed considering DfMA requirements.
- **Program:** The program phase is the process of defining the machine operations. At this point, CAD data is imported into CAM programs, so the manufacturing process can be manually defined. The main components of the machine that must be defined are parts interlocking mechanisms, required number of machine passes, necessary cutters, and feed rates. As each façade design is unique, these decisions are made on a feature-by-feature basis.

- **Setup:** For CNC façade moulds, the set-up process is reasonably quick for machine operators. However, when there are multiple setups because of holes or pockets in moulds, processes need to be constantly repeated that will add time implications to the project. The setup process, however, requires machine operators to load required cutters onto machines and then fixture work pieces.

- **Manufacture:** Using 3-axis CNC, work pieces are repositioned to cut upon faces that are not in the original orientation for facilitating access by cutters. In order to reposition, the operator has to reorient and re-fixture the work piece. Due to the nature of CNC production, time is impacted by the volume of materials subtracted and the removal rate. Such rates are then impacted by specific tolerances and part thicknesses.

- **Assemble:** Depending on the required form of façade moulds, there are mandatory secondary operations after the CNC milling.

- **Evaluate:** Production process is reviewed by the evaluation process when comparisons to the initial design plan is conducted. Evaluation analyses the efficiency of time, cost and quality to determine if the CNC system will be substitute for the production of moulds in manufacturing façade modules.

The activity selection process in this research is based on the aforementioned stages to identify the sequence and flow of detailed project activities. The activity sequence has been identified below in the work breakdown structure illustrated in Figure 2.

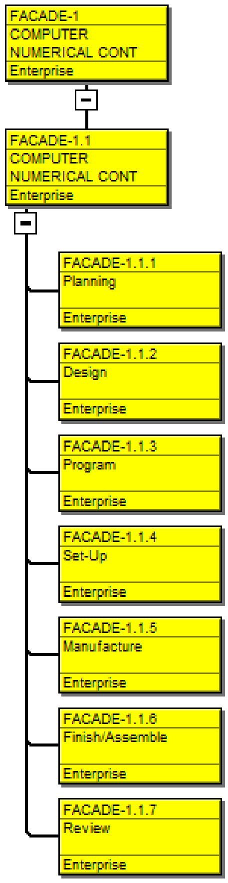

Figure 2. Workflow for manufacturing façade moulds using CNC- Developed in Primavera P6

4 Prefabrication of complex façade systems- Additive manufacturing

Additive manufacturing or 3D printing can be used to create prototypes of façade elements such as small interlocking mechanisms for modules. The applications of 3D printing generates benefits over standard processes during the production of curved elements façade modules where expertise and time are required to form materials into hyperbolic paraboloid surfaces [31].

To further mimic the characteristics of real material, different filaments can be utilized to create similar forming processes. Filament typically utilize a mixture of plastic (usually PLA) and other fibres. As such, they can undergo similar finishes to façade materials such as sanding and staining. The risk of utilizing commercial fibres in 3D printing is reduction of strength and flexibility compared to real-life scenarios. However, as the prototypes are primarily used for design validation and not for structural or endurance testing, this risk can be retained.

Key 3D printing considerations include but are not limited to printing speed, thickness of printed layers, extrusion process, retraction setting, variable speed setting, and printing temperature.

5 Case study- Time and cost analysis

Towards the aim of this study and in a similar approach to Liu, et al. [32], a case study method was adopted as it allows retaining a holistic approach towards the research problem at hand [33]. Selected façade production projects in Australia were deemed suitable to analyze time and cost within off-site project settings. A purposeful selection of case studies targeted maximum level of complexity in project production flows. Main factors contributing to project complexity included the hybrid production mode (on-site and off-site), the complex hyperbolic paraboloid surfaces in facade, and complicated design and construction processes across several project modules.

The average durations of the selected projects were calculated using Primavera Project Planner and is equal to 37 working days. The average total cost for a project is $108,240. The project cost has been calculated based on human resource costs and equipment hire. The resources have been distributed amongst activities to reduce costing. Resource costs have been identified in Figure 3.

Resource Name	Resource Type	Price / Unit
Machine Expertise	Labor	$60.00/h
Product Development Team Memeber	Labor	$35.00/h
Product Development Team Leader	Labor	$45.00/h
Designer	Labor	$45.00/h
Engineer	Labor	$65.00/h
Programme Technician	Labor	$60.00/h
Machine Operator	Labor	$42.00/h
Senior Management	Labor	$60.00/h
CNC Machine	Nonlabor	$110.00/h
CAD Software	Nonlabor	$50.00/h
Spindle	Nonlabor	$20.00/h
Cutters	Nonlabor	$5.00/h

Figure 3. Resource costs for manufacturing façade modules- Developed in Primavera P6

Cumulative cost for each WBS level can also be calculated. As can be seen in Figure 4, majority of project cost incurs during the program and set up stages. This is due to engagement of specialized resources in the two stages. These resources include but are not limited to engineers, designers, program technicians and machine operators. The labor intensive nature of aforementioned stages increases the total cost associated with human resources.

Layout: Resource Cost Profile — Filter: All Activities

Activity ID	Activity Name	Start	Finish	Budgeted Labor Cost
FACADE	COMPUTER NUMERICA	09-Oct-17	29-Nov-17	$108,240.00
A1010	Start Milestone	09-Oct-17		$0.00
A1000	Start	09-Oct-17	09-Oct-17	$0.00
FACADE.1	COMPUTER NUMERIC.	09-Oct-17	29-Nov-17	$108,240.00
FACADE.1.1	Planning	09-Oct-17	13-Oct-17	$12,000.00
FACADE.1.8	Design	12-Oct-17	31-Oct-17	$19,750.00
FACADE.1.3	Program	31-Oct-17	15-Nov-17	$21,950.00
FACADE.1.4	Set-Up	08-Nov-17	14-Nov-17	$21,000.00
FACADE.1.5	Manufacture	14-Nov-17	23-Nov-17	$12,120.00
FACADE.1.6	Finish/Assemble	23-Nov-17	27-Nov-17	$7,520.00
FACADE.1.7	Review	27-Nov-17	29-Nov-17	$13,900.00

Figure 4. Cost and duration analysis for different stages of façade prefabrication

6 Conclusions

Previous work has documented the effectiveness of using prefabricated façade elements in complex construction projects [34, 35]. Such studies, however, have not analyzed the use of modern production techniques such as additive manufacturing and CNC milling for prefabrication of complex façade modules.

Results of the current study show that multi-platform software such as CATIA and DELMIA are capable of increasing effective collaboration amongst product development teams and supporting design for manufacturability and assembly. Product development teams for prefabricated façade projects should be kept fairly small to reduce cost and increase efficiency. To save costs, a single Plant Operator (PltOp) should handle setups for both 3D printing and CNC milling.

In advanced manufacturing of façade elements, a large percentage of project budget is related to acquisition costs for equipment such as CNC machins and 3D printers. Despite these high costs, non-traditional manufacturers are likely to see return of investments over future development projects for the modular façade systems.

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Framework of Automated Beam Assembly and Disassembly System for Temporary Bridge Structures

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Abstract –

Temporary bridges play an important role in disaster relieving operations. However, available workers and limited time are precious resources during a disaster event. The requirement of not only human resource but also construction safety creates a barrier for completing the temporary bridge construction within expected time, which may result in the delayed subsequent rescue operation. To address these issues of worker safety and the worker shortage during a disaster event, an automated beam assembly approach for temporary bridge segment is proposed in this study. The approach includes a framework for temporary bridge construction to be automated assembled by a crane and a construction process based on the framework. The framework and the construction process are examined with both virtual and small-scale models.

Keywords –

Automated construction; Construction safety; Mobile crane control; Autonomous structural connector; Disaster relief

1 Introduction

Temporary bridge is recognized as being considered to be the approach of disaster relieving operation, when a bridge structurally loses its workability. Russell et. al. classified temporary bridges which were portable and rapidly-deployable into four types in 2013 [1]. Those bridges remain the span length and maximum load-carrying capacity of a bridge as a key issue. Therefore, Yeh et. al. in 2015 applied glass-fiber-reinforced-plastic (GFRP) material in a segmental temporary bridge design making it light-weight and reusable [2]. The live load capacity of the GFRP bridge was 5 tons, and the span was 20 meters. However, when taking actual working environment into consideration, the assembly of the GFRP bridge may be difficult. The reason is that not only the weather may not be suitable for construction but also it is hard to recruit sufficient workers on-site.

To clarify the main reason of these problems, we analyzed the video of the process of constructing the GFRP temporary bridge. The hoist and assembly process has been found to be so critical that it majorly controlled the construction progress and the worker safety of the bridge construction. This process put emphasis on the technique of beam assembly.

2 Background

Many attempts have been made with the purpose of automated steel beam assembly. A research team focused on automated construction of high-rise building with a construction factory covering at the top of the building [3, 4]. They developed robotic bolting and robotic transport of steel beam, and tested beam assembly in real construction site. This application created the constraint of architecture design because of the geometrical limitation caused by the working space of the construction factory. In 2016, a research developed an approach helping construction workers assemble steel beam with an automated wire control machine [5]. The research protected workers from assembling steel beams at height, although the pre-installation of the guiding ropes for automated assembly may be risky for workers. Another research tried to remotely achieve steel beam assembly by means of structural connector design and controllable rotation of crane hook [6]. The rotating hook would trigger the opposite rotation of the attached steel beam to finish beam assembly. However, object avoidance during the beam rotation was a challenge for the research.

To address worker safety and shortage during disaster event as well as comprehensive consideration of steel beam assembly using a crane, an automated beam assembly framework for segmental temporary bridges is proposed in the research.

3 Automated Beam Assembly Framework

The automated beam assembly framework identified critical elements for research development and proposed a construction process providing an automated approach utilizing a mobile crane to build up a temporary bridge.

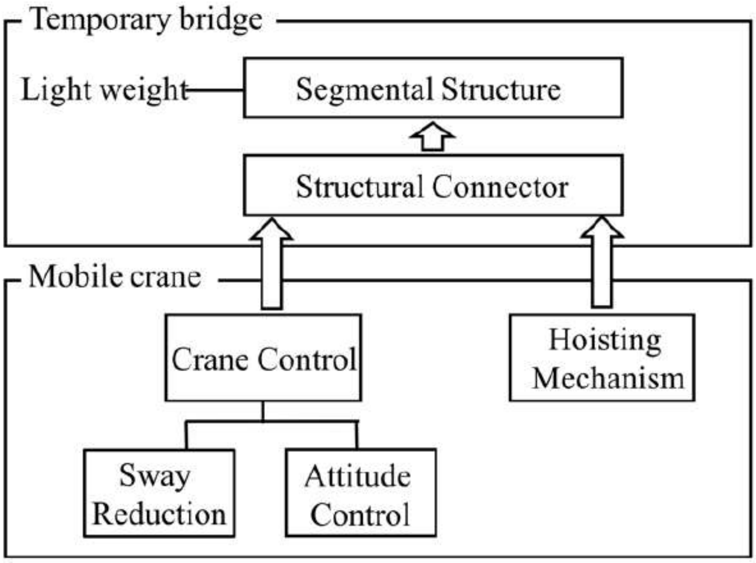

Figure 1. The framework of automated beam assembly

3.1 Elements of the Framework

The critical elements were categorized into two parts: structure and automated process. The structure part, also named Temporary bridge in Figure 1, including segmental structure, light weight, and structural connector, defines the requirement of the material and structural geometry to be used in a construction. The automated process part, also named Mobile crane in Figure 1, considers technical requirement on how a mobile crane finishes hoists and assembly tasks without any worker on site.

3.1.1 Segmental Structures (SS)

The temporary bridge for disaster relieving needs to be constructed within limited time. Therefore, segmental structure becomes an option to satisfy the requirement. Before a disaster occurs, each segment of the temporary bridge can be compactly stored in a container for shipping. The container can be placed near the potential damaged area.

3.1.2 Light Weight (LW)

To have a longer span of a temporary bridge, light weight is one of the important properties. According to the information from officers in Taiwan Directorate General of Highways, 30 meter at least is the common span of the bridge to be repaired after the bridge has been devastated by a disaster. Additionally, lighter weight of the bridge makes more convenient for shipping to the proximity to a valley or a river in a mountain where is often not easily accessible.

3.1.3 Structural Connector (SC)

A structural connector allows two segmental structures to be assembled with each other. The structural connector to realize automated bridge construction focuses on the beam design for autonomous assembly. The designed connector should also consider the construction feasibility when using a crane. In the research, we utilized the connector from our previous research for autonomous beam assembly [7]. The previous research demonstrated the feasibility of the hook-shaped structural connector for autonomous assembly. The design concept was to use a male connector and a female connector to lock themselves autonomously.

3.1.4 Crane Control– Sway Reduction (SR)

Sway reduction is necessary to reduce the magnitude of a sway of a payload. The payload such as a beam with designed connector should be stabilized to a suitable level to execute position control. Finally, the automated attachment of the male connector and the female connector can be executed afterwards.

3.1.5 Crane Control– Attitude Control (AC)

When a connector is at the targeted position, attitude control of the structural component may rotate the male connector to attach the female connector. Taking advantage of the sway reduction and the attitude control, the automated assembly of these two structural components becomes easier.

3.1.6 Hoisting Mechanism(HM)

Before the beam transportation using a crane, the beam should be firmly attached to the crane hook. After the transportation, the beam needs to be conveniently detached from the hook. Without human operation to attach and detach the beam, the automated mechanism of attaching and detaching is necessary.

3.2 Construction Process

The construction process defines each step of the beam assembly and disassembly.

3.2.1 Assembly process

- Step 1: Connect the crane hook to the beam.
- Step 2: Lift up the beam.
- Step 3: Transport the beam to the selected position for assembly.
- Step 4: Adjust the attitude of the male connector to attach the female connector on the bridge.
- Step 5: Release the beam for assembly triggered by gravity.
- Step 6: Lock the beam on the bridge structure.
- Step 7: Disconnect the beam from the crane hook.

3.2.2 Disassembly process

- Step 1: Connect the crane hook to the beam to be disassembled.
- Step 2: Unlock the beam.
- Step 3: Lift up the beam.
- Step 4: Detach the male connector from the female connector on the bridge structure.
- Step 5: Transport the beam to the storage area.
- Step 6: Release the beam.
- Step 7: Disconnect the beam from the crane hook.

4 Experiment & Result

The framework and the construction process were validated by the experiment described in this section. Three assumptions were made in the experiment. (1) If the assembly steps are feasible, the disassembly steps are also feasible. (2) Attitude control rotates the beam in the longitudinal direction. According to the research by Lee et. al. in 2012, the attitude control of a beam is probable to be implemented [8]. In the experiment, we rotated the beam by human operation. (3) Hoisting Mechanism was assumed that it connects to the end of a beam and can be remote controlled. The experiment was tested on-site and also in a virtual model using a commercial physics engine.

4.1 On-site experiment

The first four steps of the proposed assembly process were validated by an on-site experiment. The experiment measured the placement deviation from the targeted position of the hoisted structural component for assembly (Fig. 2). A crane with hydraulic retractable boom with the maximum load capacity of 3.4 tons was used in the experiment. The payload was an approximately 80kg and 1.45m beam. The crane operation was executed by a graduate student in the experiment. The student learnt crane operations from a professional crane operator, and practiced the required operation of the sway reduction before the experiment.

The result of X deviation was 3.03cm in average, and the result of Y deviation was 1.37cm. Figure 3a-1 shows the environment of the experiment. We placed a short beam which is around the center of the picture as the targeted position for beam assembly. The overview of the crane we used and the test environment is represented in Figure 3a-2. Figure b recorded the first four steps of the assembly process. In the experiment, we connected the end of the beam to the crane hook using steel cables (Figure 3b-1). The beam was lift up with an approximate distance of 50cm from the ground (Figure 3b-2). The crane operator transported the beam only by slewing the crane (Figure 3b-3). Figure 3b-4 is the state that the beam was already at the targeted position, the crane operator reduced the sway by manual crane operation, and the operator manually rotated the beam in the longitudinal direction for the attitude control. After the position and the attitude of the beam were stable, the crane operator placed the beam on the ground to measure the placement deviation (Figure 3b-5).

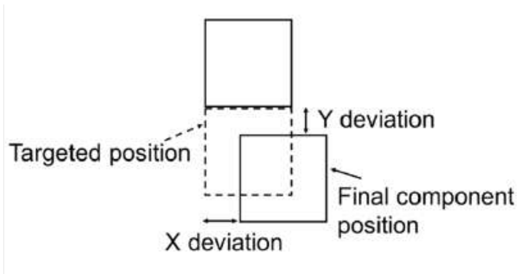

Figure 2. Measurement of structural component deviation from selected target.

Table 1 Placement deviation from selected target

Test	X deviation [cm]	Y deviation [cm]
1	4.0	2.9
2	1.9	0
3	3.2	1.2

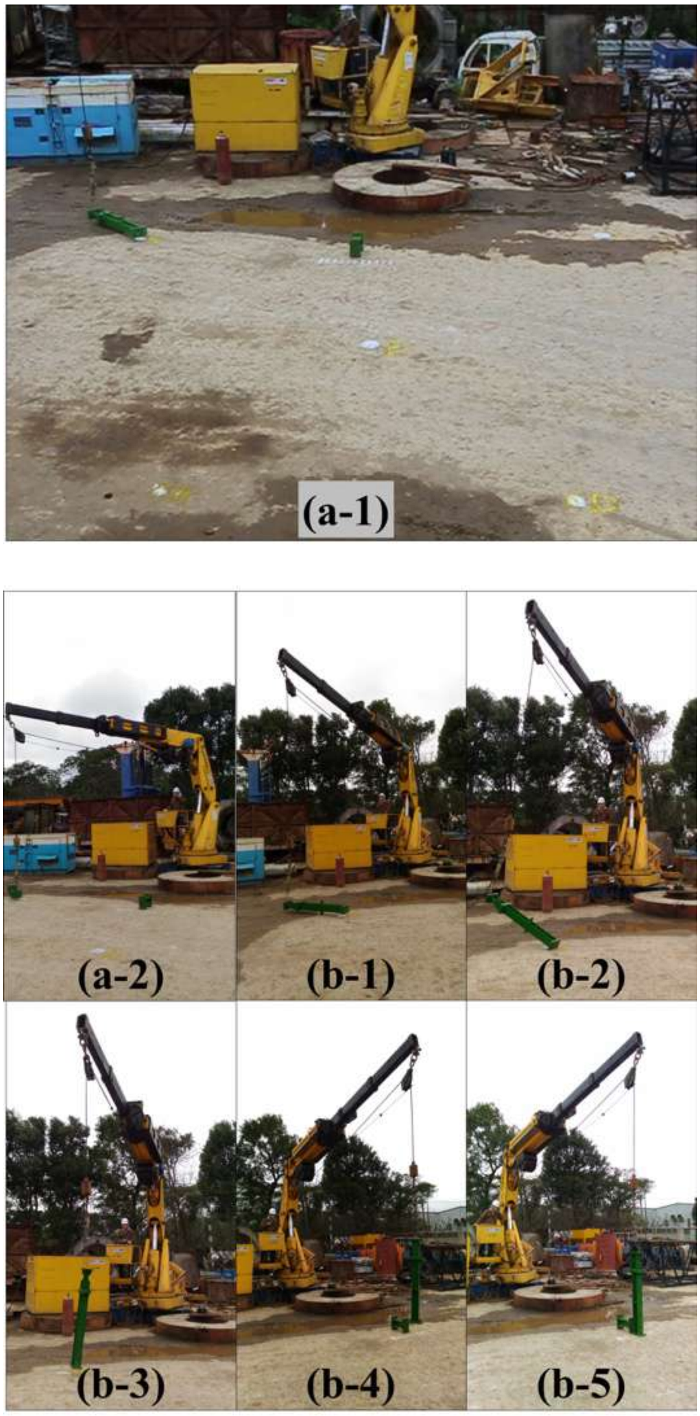

Figure 3. (a) On-site experiment environment. (b) The results of the automated process.

4.2 Virtual model experiment

To validate the step 5, “Release the beam for assembly triggered by gravity”, of the assembly process, we created a virtual structural component and used a virtual mobile crane to simulate the rotation of the structural connector. The virtual model was created on a commercial physics engine, Unity3D. The virtual model successfully demonstrated the step 5 (Fig. 4).

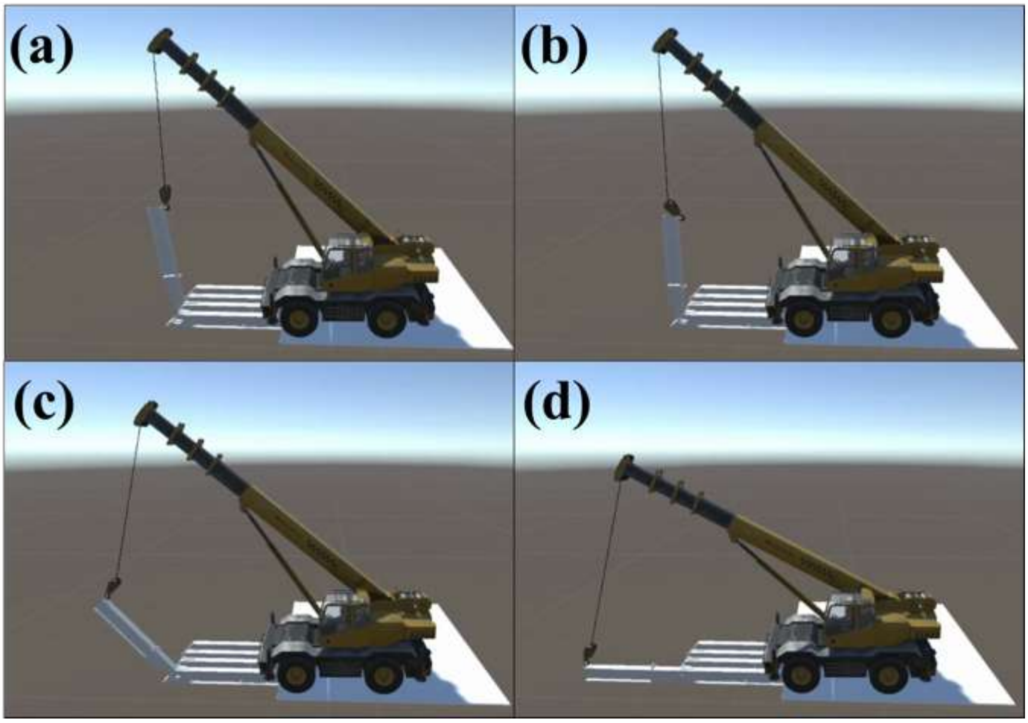

Figure 4. The results of virtual beam assembly by a mobile crane.

4.3 Discussion

The placement deviation from selected target showed the sway reduction made by the student crane operator an unstable performance. The unstable slewing torque generated by the hydraulic system of the crane was the main reason. The hydraulic control system could not keep the same angular velocity of slewing during the transportation of the beam, even the control stick of slewing remained the same inclination level. Another crane control issue was the control limitation of degree of freedom. Only one degree of freedom could be controlled at one time, indicating that the hoisted beam could not move as smoothly as we expected. To minimize the sudden change of the transportation path, we only applied slewing rotation in the experiment.

5 Conclusion

This research tried to clarify the construction process of automated beam assembly and identify key elements for the automated assembly for temporary bridge by a crane. The key elements including structure part and automated process part form a framework presented in the article. We conducted an on-site experiment and a virtual simulation to validate the construction process. The beam placement deviation from the targeted position was found, which can be the reference for autonomous structural connector design. The results showed the feasibility of the proposed framework and the construction process which may contribute to the development of automated beam assembly approach using crane operations. Future research can be focused on crane control including sway reduction and attitude control. It is suggested that the sway reduction for crane operation can be executed after the hoisted beam arrives the expected position. Since it is difficult for the crane hydraulic system to apply stable output force on the hoisted beam, it is easier to apply the sway reduction by controlling the crane boom to follow the motion of the beam. To control the beam attitude for connection, the benefit of controlling two crane hoist lines may be taken into consideration.

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Influence of automated building construction systems on vocational education and training

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Abstract

Robotic systems are increasingly becoming a relevant factor for so-called "made to order" production, as is the case in the construction industry. The aim of this contribution is to provide a basis for a cross-disciplinary discussion on the topic of robotics in the construction industry, in which both technical issues regarding the technical challenges of robotics in the construction industry and how automated building construction can be practically addressed in education and training. Based on case studies and lab experiments, the authors investigated upcoming transformations in shell production by comparing the conventional construction process with proposed processes involving cable-driven parallel robots. The focus is on bricklaying and working methods for the installation of pre-fabricated elements. Based on the prospective changes in construction the impact on vocational education and training will be discussed and influences in current educational frameworks based on automation and robotics will be introduced.

Keywords –

automated building construction, cable-driven parallel robot, bricklaying, site logistics, human-machine interaction, social effect, technology dissemination, vocational education and training, VET

1 Introduction

The Internet of Things and Building Information Modeling (BIM), which has already been used in some construction organizations, are two major areas of digitization in the construction industry [1]. Due to the increasing digitalization in the context of industry 4.0 and the current increasing spread of BIM in the construction industry as well as the constantly growing technical possibilities and the increasing computing power, the application and use of automated building construction systems is currently being pushed forward. Such systems can ultimately include both digital planning and autonomous construction of a building. The changes resulting from digitization will create new jobs, change existing ones, or make existing ones disappear [2]. In the context of this article, the study by Dengler and Matthes (2015) deserves to be considered. The authors discuss which professions could (partially) be replaced today due to the current state of digitalization. It should be emphasized that the current status of digitalization has a similarly high substitutability potential for assistant and specialist occupations. The study concludes that the ongoing digitalization process should be taken more into account in the training of skilled workers in order to counteract the loss of professional groups [3]. It does not deal with the question of whether only a shift in the areas of activity in the occupational groups takes place through digitalization and to what extent possibilities can be created with which the occupational groups can be supported or to what extent current training standards would have to be adapted. This paper aims to provide a first qualitative basis to answer these questions in the context of vocational education and training (VET) in the construction industry. It is not the aim to present new curricula for VET in this field, because setting up new curricula involves a lot of red tape which in turn costs a lot of time. Developments in automation and robotics are currently happening very fast, and therefore the construction industry needs solutions that can be implemented within a short period of time. Therefore, at this stage, the authors are more interested in identifying how new requirements from automation and robotics can be integrated into existing ordinances and framework curricula on short notice. Preferably directly at vocational schools or at the workplace.

2 Methodology

Based on an existing prototype of a cable-driven parallel robot at the University of Duisburg-Essen, the authors used for this research a) simulations and data analysis, b) qualitative case study, c) comparative analysis. The authors carried out analyses regarding the operation of the cable-driven parallel robot within the body shell construction. Based on this, possible influences on existing material and work processes up to changes in the construction site layout are identified (detailed results are published in [4][5][6]).

Consequences for VET are derived from technology, work organization, tasks and responsibilities, work environment and safety, materials management and site logistics. Based on the (partially) new boundary conditions identified in this way, general influences on the technical personnel are worked out in a qualitative analysis and the effects on the field of activity are illustrated exemplarily within the following three occupational profiles.

1: Construction equipment operator - Currently, this occupational group is responsible for the operation and maintenance of construction equipment. It is assumed that this profession will take over the operation of an automated building construction system in the future.

2: Bricklayer - This professional group is massively influenced by the use of an automated building construction system due to a shift of work in their activity areas. In order to counteract the loss of this professional group, it is assumed that further qualification is necessary and advisable.

3: Draftsmen - This professional group is involved in the conception and planning of a building project from an early stage. By using the BIM method draftsmen can have one or more of the following roles depending on their qualification, project size and responsibility: BIM author, BIM user, BIM coordinator. Due to the use of automated building construction systems, the (digital) construction drawings, especially for execution, must be aligned to the use within such a system.

The results of the analysis are compared with the corresponding ordinances and framework curricula of the professions selected as examples, to identify points of contact in relevant learning fields. Finally, it proposes options for the implementation of these options in construction technology education, which could already be implemented in the current situation at the educational institutions (e.g. VET schools).

3 Changes on the construction site using the example of a cable-driven parallel robot

The development of cable-driven parallel robots allows to create large manipulators that even cover the volume of a construction site [4]. It first carries out masonry works, later on other trades, partially autonomously in the structural work. As the cable-driven robot is covering the volume of a complete masonry building, it is potentially suitable for a wide range of construction processes and thus a superior concept to currently existing specialized systems like bricklaying robots. Therefore, the cable robot technology might have a broader impact on the automation of nearly all construction steps and serves as an example of future automated construction and the potential changes in the involved professions. Since December 2016 we are using a demonstrator with the dimensions L/W/H = 12.0 m/1.5 m/5.0 m which is able to assemble bricks into simple wall panels. The capabilities of the prototype will be continuously expanded in the planned follow-up projects, e. g. with automated mortar application (e.g. high-performance adhesives).

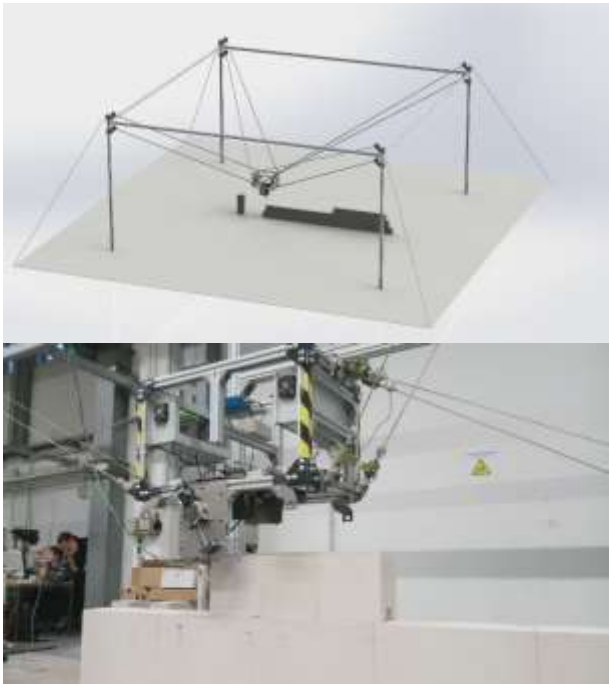

Figure 1. Cable-driven parallel robot for brickwork construction (upper illustration [5], illustration below own picture)

Figure 1 shows the desired long-term concept and a detail of the retractor of the current prototype. The prototype can already be used to investigate many interdisciplinary research questions. Due to the increasing digitalization, the construction industry is changing. Current buzzwords include Industry 4.0, Cloud Computing and Building Information Modeling (BIM). To assess the effects on VET, the changes resulting from the use of a cable-driven parallel robot in brickwork construction are identified below and significant adaptations to the construction site are derived from this. In principle, it must be stated that an automated building construction system is highly sensitive concerning the working process. Changes are common on construction projects and disruptive to labor productivity, in turn leading to increased costs and delayed projects [7][8]. Hence, early recognition of change is important, especially in automated processes. Faulty process sequences or wrong materials, which people must compensate (until now), lead to immediate downtimes during automated building construction. The construction process of the entire shell will be interrupted in the event of disturbances and additional (high) costs will be incurred.

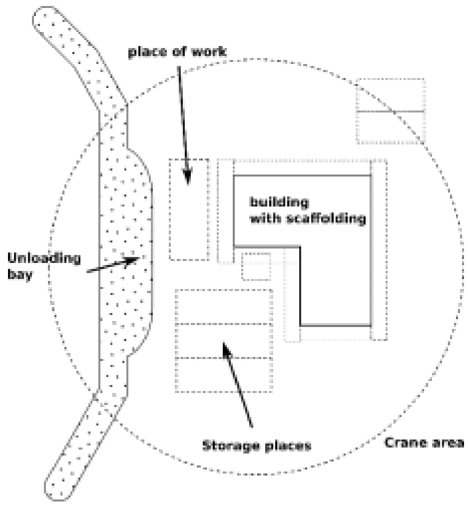

Figure 2. Example of a current construction site layout (based on [6])

Figure 2 shows an example of a current construction site layout without a cable-driven parallel robot and Figure 3 an exemplary construction site with a cable-driven parallel robot. Without a cable-driven parallel robot, a classic layout with tower crane, material storage areas, workshop, scaffolding and construction road is displayed. The construction site with a cable-driven parallel robot (Figure 3) is divided into 3 zones. Zone 1 is the material delivery zone. Here, trucks with the required materials arrive and are unloaded by forklift trucks. Zone 2 is the so-called pre-zone. The materials are stored here and pre-assembled into processable units for the robot. Zone 3 is the working area of the robot. Here, the construction process is largely autonomous. The personnel should not enter this zone while the robot is running as there is a considerable risk of injury. High loads are transported at speeds of several meters per second (the prototype currently transports 6-DF sand-lime bricks at a speed of approx. 0.5 m/s, the current maximum speed is approx. 4.0 m/s). For further details of the technical background of the cable-driven parallel robot refer to [6].

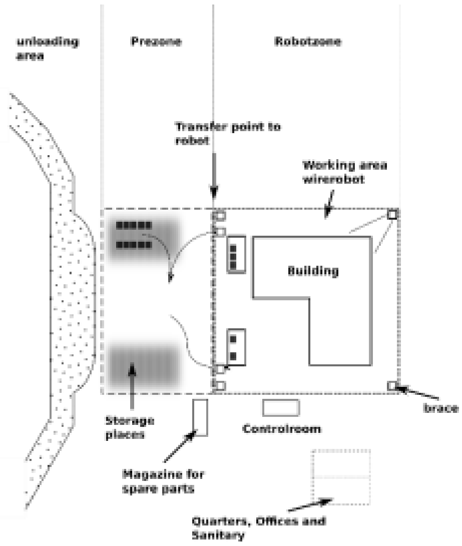

Figure 3. Changes on the construction site (based on [6])

4 Effects on the considered professions

Six different dimensions are considered to assess the effects on the technical personnel:

A: Collaborative working - Change of cooperation through interconnected working towards collaboration.

B: Support through technology- Support of many work steps by (partially) automated systems.

C: Modified construction processes - Changes in processes and office workflows, both in planning and by the introduction of ICT and robotics, especially in execution on the construction site.

D: Interaction with machines - Additional employment in man - machine and machine - machine interaction. The latter must be monitored by humans.

E: Virtual working - Increasing visualization of virtual objects in the real world.

F: Overflow of data - Increasing data must be handled, also in manual work processes.

The dimensions show, that there will be a shift from originally increasingly executive work towards cooperation and collaboration through interconnected working. Besides the other dimensions, which are mainly related to information and communication technology (ICT) issues, the first dimension takes foremost the social effect of automation and robotics into account and therefore the impact of automation on individual and collective level of human interaction. Hence, it investigates mainly the social outcomes of the innovation processes introduced by building automation in construction and workers re-skills effects. These effects are an important influencing part of the human capital, which is one of the basic factors of economic growth in the information, knowledge-based economy as its level of usage determines the innovation component [9]. The influence of automation on social aspects has been addressed since the 1930s (e.g. [10]) and has also become a relevant topic in the ICT community in the 1960s (e.g. [11],[12]) as well as in qualification and training of workers in the 1970s (e.g. [13]), probably driven by the beginning of the personal computer era with the founding of companies such as Apple, Microsoft and others. Nevertheless, the influence of automation in the construction industry seems to be predominantly discussed on technical and economic levels. Even if social aspects impact the whole social structures and changes working culture (e.g. on construction sites or in design teams) this paper deals as a first step mainly with direct changes and impacts on an individual level in exemplary professions. To be able to examine the effects on VET in a first step, the occupational profiles selected exemplary are identified on the basis of the essential activities and influences are localized in the context of automated building construction. The dimensions A-F are related to their effects on the following highlighted fields of activity of the considered occupational profiles ([14],[15],[16]), which are influenced in particular using an automated building construction system.

1: Construction equipment operator - **Set up construction machinery (cm); operate; transport and maintain cm**; carry out repair work on cm; observe safety and environmental regulations; **operate stationary equipment**

2: Bricklayer - **Execute preparatory work**; carry out scaffolding, formwork, erection of scaffolding, formwork, **structures and parts of buildings**; **produce masonry**; produce interior and exterior plaster; install insulation and insulation materials; erect lightweight walls; produce screeds and floor coverings; refine masonry; **produce exterior wall coverings**; carry out demolition and piling work; **operate, maintain and service construction machinery and equipment for building construction**; **quality check of the work carried out**; create measurement of finished work for billing.

3: Draftsmen - **Planning and coordinating work processes; preparing construction drawings for construction planning and execution**; carrying out surveying work; preparing documentation and drawings for presentations; **participating in the preparation of tender documents**; working out building applications in compliance with construction regulations; calculating simple static proofs; preparing accounting drawings and contributing to construction accounts.

As already shown in Figure 2, the construction site layout in particular will significantly change the field of activity of construction machinery operators. This includes the modification of construction processes and the interaction with machines. Recent developments show that construction machines with assistance systems and machine controls are increasingly being used [17]. In earthworks, for example, GPS data and inclination sensors are used to control the guidance of the excavator bucket along a digital terrain model. Other assistance systems, some with 3D control, make it easier, for example, to produce an exact level in road construction. Additionally, there are developments in surveillance, inspection and analysis of the construction progress [18], in the fabrication of wooden structures [19][20][21][22] and steel construction [23][24], too. Current research is also concerned with the unification of real and digital worlds (Augmented Reality Technologies [25][26][27]). To prevent existing underground pipelines and cables from being damaged during the excavation work, they are faded into a display or data glasses, for example. The use of these technologies is increasingly changing the way construction machines are operated on site as well as the planning of their deployment. Hence, the operation of an automated building construction system represents a further change in machine control and is therefore one of the most massive changes which includes almost all considered dimensions. The same applies to the operation of stationary systems. In contrast, transport is also subject to change. However, these are not to be assumed to the same extent as the other activities considered. Overall, it can be stated that in the dimensions "modified construction processes" and "interaction with machines" the strongest influences are to be expected. Since this paper looks at the effects of automated building construction on VET in the light of automated building construction using a cable-driven parallel robot, it is obvious that masonry construction will have a variety of effects. This means that the preparation as well as the construction of the building or parts of it and in particular the construction of masonry is influenced by almost all considered dimensions. A special focus will also be given to the examination of the executed quality. In the future, the bricklayer will be given the task of checking the performance and quality provided by the automated building construction system in a qualified manner and, if necessary, of adapting it by hand. Moreover, it will be necessary to understand, plan and organize the automated production process. Due to the sensitivity of the automated building construction system in the building process (everything depends on the faultless operation of the robot as the leading device), decisions must be made directly on site. Therefore, it is evident that in this field of activity more dispositive work has to be carried out and that, as a result, more and more management tasks will be assigned to this field. In the field of activity of draughtsmen a general approach seems to make sense, since this professional group is involved in the conception and planning of a building project from an early stage. Already in 1986, a modernization of the training content regarding computer-aided drawing and design was implemented in the reorganization of training according to the Vocational Training Act. Other technological innovations in electronic data processing (EDP), such as the incorporation of modern ICT, were included in 2002. Although the above-mentioned amendments go further than in the other two occupational groups considered, further changes can be expected in the observed dimensions. Since, for example, the BIM method considers the project ideally as a multi-professional and collaboratively planned building within its lifecycle, the planning and coordination of work processes is influenced by all dimensions. Due to the use of automated building construction systems, the (digital) construction drawings, especially for execution, must be aligned to the use within such a system for both the construction itself and the validation of the plans regarding the faultless implementation on the building site (e.g. operational aspects as well as data exchange and security issues). This presupposes that knowledge about the changed building processes during the practical implementation of the building construction must be available. The validation of the planning is done advantageously in a virtual building model. In addition, it should be pointed out that technical support for the preparation of tender documents is already integrated in a collaborative manner and therefore an ever-increasing amount of data has to be organized.

4.1 Intermediate results

Based on the qualitative analysis carried out, it can be concluded that the dimension "modified construction processes" has the greatest influence on the considered occupational profiles, followed by the dimensions "collaborative working" and "support through technology". On average, when comparing the considered occupational profiles, the highest influence of an automated building construction system is identified in the group of draftsmen, followed by bricklayers and construction machine operators. Nevertheless, the professional field of bricklayers will experience one of the most massive upheavals through automated building construction systems. For the construction machine operators, it could be assumed that the operation of the new technology could be handled in a similar way as it is currently the case with GPS-controlled construction equipment, for example, in which an introduction/ training takes place. On the other hand, however, it must be noted that an automated building construction system is a comparatively complex system whose operation and maintenance will probably require more far-reaching skills.

5 Consequences for VET

The results of the qualitative analysis are compared with the corresponding ordinances and framework curricula of the professions selected as examples. The German directives on training are structured in specific learning fields (LF) which were examined one by one to identify points of interest. As already introduced above, there is a lot of research on innovations in building construction regarding the use of assistance systems for construction equipment, but these new trends and developments have not yet been incorporated into any amended ordinance or the framework curriculum, especially in the profession of construction equipment operators. Using the example of construction equipment operators [28], five connecting points can be identified in the corresponding learning fields on which the use of an automated building construction system would have an influence leading to additional learning objectives.

LF 1: Setting up a construction site

Knowing automated workflows and processes, ability to plan and evaluate parking and traffic areas for automated building construction.

LF 2: Building a masonry wall

Ability to plan construction of masonry with automation technology (especially planning and checking of relocation plans).

LF 7: Handling of electrical systems

Understand the basic interrelationships and safety in automated electrical systems, integrate data and adapt programming if necessary.

LF 8: Maintenance of engines

Know the tasks and functions of automated technologies.

LF 9: Maintenance of trackside trolleys

Knowledge and ability to implement maintenance and servicing of automated technologies.

In LF 1, further learning objectives must be defined which deal with the changed workflows and processes. Because the construction site layout is fundamentally modified, it is important to be able to plan and evaluate parking and traffic areas for automated building construction. The production of masonry using automation technology should be addressed in LF 2. In this context, it is particularly important to follow on from the already known implementation plans, since the correct planning of an installation sequence is also an essential success factor for the rapid construction of the building when it comes to the automated building construction. When handling electrical systems in LF 7, construction equipment operators should be familiar with the basic interrelationships and safety aspects of automated electrical systems and should be able to integrate the corresponding data into the system.

Furthermore, it makes sense to be able to adapt programming on site, if necessary, as well as to know the tasks and effects of automated technologies in LF 8, and to know and to be able to implement maintenance and servicing of automated technologies to avoid or minimize longer downtimes (LF 9). For bricklayer [29] the modified workflows and processes resulting from the changed construction site layout leads to additional learning objectives similar to construction equipment operation.

LF 1: Setting up a construction site

Similar to construction equipment operator

LF 3: Building a wall of a single-shell building structure, knowledge of the basics of robot-compatible brickwork, e. g. wall connections and masonry connections and the ability to carry them out (e. g. for adaptation and repair work).

LF 7: Masonry walls of a single-layer

Ability to plan, test and optimize masonry of large formats for automatic construction (as a new installation technique), ability to work with digital layouts

LF 16: Fabrication of special wall components

Knowledge about measures for adjusting irregular masonry constructions (e. g. angled brickwork) and ability to implement it manually.

In relation to the specific handicraft activity, LF 3 should deal with the basics of robot-compatible execution of masonry in order to gain knowledge about wall connections and wall integrations which have to be implemented in the context of adaptation and repair work during the construction process. In addition, the bricklayers should be able to plan, test and optimize the masonry made of large-format masonry for automation (as a new installation technique). For this reason, it is recommended to work with digital installation plans in LF 7. As not every brickwork geometry can be created when using an automated building construction system, measures for the adjustment of irregular brickwork constructions (e. g. angled brickwork) should be known in LF 16 as well as the manual implementation in the context of an automated construction site should be taught. With reference to the automated construction site, the group of draftsmen [30] have six essential points of contact.

LF1: Participation in construction planning

Knowledge of data organization and data management in relation to collaboration platforms, planning and implementing data storage

LF 3+4: Development/ planning of foundation

Ability to create 3D/xD models for automated execution and validate third-party models.

LF 5: Planning a basement

Knowledge of the fundamentals of robot-compatible brickwork execution, creating, testing and optimizing installation plans for automated execution.

LF 10a: Preparation of a building permits application

Knowledge about data exchange between different stakeholders, ability to plan and implement data exchange strategies for automated execution, validate data, identify interface problems and propose countermeasures.

LF 11a: Designing an exterior wall

Ability to design external wall constructions for automated execution.

Due to the expected increase in digitally generated and processed data, important aspects that need to be addressed already arise in LF 1. Here, draftsmen should know forms of modelling and design, data organization and data management regarding collaboration platforms as active (and in practice to a large extent responsible) persons. Here, basic types of data transfer, information flows and interfaces should already be addressed to be able to plan and implement data storage and security strategies in practice. In LF 3 and 4, it is possible to extend digital modelling to automated building construction and implement it using practical examples. Furthermore, draughtsmen should be able to understand foreign models and validate their content. In this case, similar to the previous professional profiles, it is also imperative to know the fundamentals of robot-compatible brickwork execution and to have the ability to create, check and optimize installation plans for automated execution. This can be addressed in LF 5. Following on LF 1, the planning and implementation of data exchange strategies for automated execution, the technical validation of data as well as the identification and, if necessary, the first steps to solve interface problems should be considered when creating a building application (LF 10A). Finally, in learning field 11A, the automated execution can also be considered as a topic in the design of an outer wall construction.

6 Conclusion

This study shows that the use of an automated building construction system will lead to far-reaching changes in the entire work organization in the socio-technical field. The investigation provides a first ground for increased consideration of social aspects due to building automation in construction in a variety of areas. It is strongly recommended to conduct further investigations on the social impact of automation and robotics in construction in the social and psychological spheres on different sub-topics and levels. Such research is essential to avoid the development of a parallel and in a long term incompatible workforce. Indications for this are given through current research and development work, which shows that companies are increasingly considering how they can (fully) automate their work, which will lead to further significant changes in all areas of the construction industry in a relatively short period of time. For example, the object-related construction work is almost exclusively carried out by the automated system in the future, which will lead to the following positive causal relationships:

The productivity of the execution performance is increased by the automated building construction system. At the same time, this reduces the physical workload of the site personnel. This in turn leads to an increase in the physiological motivation of the workforce. Furthermore, the changed working conditions lead to more safety at work, which in turn will increase psychological motivation. In addition, the entire construction site organization has to be rethought, both at operational and management level. This means, for example, that tasks, responsibilities and competencies will be transformed due to changed work processes.

The examination of the potential changes within the operative production factors shows that there will be a shift from the executive work on the building itself towards dispositive work (planning, management and organization). The changed roles mean that skilled workers must acquire additional skills, competences and responsibilities as well. As a result, the training concepts and content in VET must be adapted to the new circumstances. The curricula for the operative construction staff must be redesigned in order to increase dispositive work. This paper gives some indications about additional learning objectives related to recent learning fields of existing regulations. To achieve a comprehensive understanding of technology and new working methods, further topics must be included in the curricula, depending on the characteristics of the specific occupation. These are topics from the ICT field as well as management. Although current ordinances or framework curricula do not yet cover such effects in terms of content, it should already be possible to address further learning objectives within the existing learning environments that are necessary for the profession in terms of content and methodology. The results of this study are intended to provide guidance in this respect.

The analysis carried out shows that the incorporation of automated building construction into the various learning fields of the considered occupational profiles appears potentially possible. As the amendment of training guidelines cannot be achieved at short notice, the authors are currently examining options which can be implemented immediately in the current situation in VET schools and companies to address the additional learning objectives independent of existing regulations. First promising approaches are (ICT-supported) group-oriented teaching/learning projects, across-school projects in cooperation with companies or even game-based concepts.

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Adaptive Perception and Modeling for Robotized Construction Joint Filling

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Abstract –

Construction robots must perceive and model their surroundings to compensate for uncertainties in their workpieces. This research investigates a technique to enable the autonomous sensing and modeling of construction objects and features so construction robots can adapt their work plans and perform work. To that end, the Generalized Resolution Correlative Scan Matching (GRCSM) construction component model fitting technique is presented, which registers BIM models to point cloud sensor data. The registration results enable the robot to update its workpiece models to reflect their actual condition. An experiment was conducted in which virtual sensor data was generated for a virtual construction joint, and joint profile models were registered to form a model of the joint. It was found that the GRCSM construction component model fitting technique can be used in combination with a low precision sensor to estimate the pose and geometry of a virtual construction joint with a mean norm positioning error of 1.7 mm. The GRCSM construction component model fitting technique appears promising for the geometric estimation of construction objects, especially for situations involving full automation, detailed construction work, incomplete sensor data, and complex object geometry.

Keywords –

Construction Robotics; Robot Perception; Model Fitting; Construction Joints; GRCSM

1 Introduction

The construction industry is often considered one of slow change, hazardous conditions, old technology, and stagnant productivity levels. Robotics offers the potential to change that by reducing construction project cost, shortening project lead time, improving construction quality, and improving worker safety [1]. However, the construction industry's adoption of robotics has proven slower than other industries, such as manufacturing. This is largely attributable to technological challenges arising from the unique characteristics of the industry [2].

One such challenge is the construction robot's need to perceive its workpieces and adapt its plan in order to reliably perform quality work. In contrast with construction robots, many manufacturing robots are able to perform work with little or no sensing of their workpieces. This is made possible through tight control over the manufacturing robot, its environment, and its workpiece. Such control enables the robot to neglect stochastic variation and leverage a simple a kinematic chain to estimate its pose (i.e., position and orientation) relative to the point of interest on its workpiece.

However, such control is generally much looser for the construction robot. For example, far greater uncertainty exists in the pose of the construction robot relative to the jobsite due to the robot's need for mobility and the high uncertainty inherent in mobile robot pose estimation methods. Similarly, greater uncertainty exists in the pose of the construction robot's workpieces relative to the jobsite due to loose construction tolerances and high process variation. Additionally, uncertainty exists in the actual geometry of the construction workpiece due to such factors as material variation, material deflection, and process variation. Given the high uncertainties present, the construction robot cannot reliably determine its pose relative to the workpiece through a kinematic chain like the manufacturing robot, but rather, must perceive the workpiece in place.

The objective of this research is to develop a means by which a construction robot can perceive and model the workpieces in its immediate environment so it can ultimately adapt its plan and autonomously perform detailed construction work.

2 Related Work

Past research has been conducted in the sensing and modeling of construction objects and environments. Such researchers employed various sensing and modeling techniques for the purposes of project progress monitoring, as-built documentation, material quantity estimation, material tracking, obstacle avoidance, and object manipulation.

To circumvent the challenges and computational burden associated with fitting models and extracting meaning from dense point clouds, Cho et al. [3] proposed leveraging human cognition to assist in the modeling of a construction environment. In this approach, a human selects a geometric primitive (e.g., cuboid or cylinder) or a complex model (e.g., excavator or bridge) from a database and manually aims a laser rangefinder at strategic points on the physical object to obtain individual point measurements. The selected model is then fit to the sparse point cloud. McLaughlin et al. [4] used the same approach, but developed three additional construction workspace model types: partitions, convex hulls, and tight-fitting bounding boxes. Kim et al. [5] applied the aforementioned partition and convex hull methods for such purposes as obstacle avoidance, accident prevention, and material tracking. However, all such variations of this sensing approach rely on human operation, which is not suitable for autonomous applications.

Kim et al. [6] later demonstrated that convex hull modeling could be used in combination with a more automated form of sensing, flash laser distance and ranging (flash LADAR), in which a 2D array of measurements can instantly be obtained by pointing a flash LADAR sensor in the general direction of interest. The approach was only demonstrated with large objects and coarse models for such purposes as obstacle avoidance, and did not include semantic recognition of the objects it detected. Thus, the approach is not suitable for the autonomous recognition and manipulation of detailed construction components.

Stentz et al. [7] developed an autonomous excavator for excavating soil and loading it into a parked truck. The excavator used laser rangefinders for sensing the soil terrain and a nearby truck. A 2D grid of height values was fit to the terrain data and a parametric truck model was fit to the truck data. The terrain model was used to determine where to remove soil and the truck model was used to determine where to dump soil. The approach reportedly worked well, but was only demonstrated with large objects and coarse models. The approach may not be suitable for the manipulation of detailed components.

Work has also been done in the sensing and modeling of small, targeted construction components. Kim et al. [8] scanned individual stones with a combination of projected laser beam and charged-coupled device (CCD). However, the highly irregular stones were simply modeled as cuboids of corresponding principle dimension (i.e., tight-fitting bounding boxes). Kahane and Rosenfeld [9] used a similar projected laser and CCD to measure the gap width between adjacent wall tiles to aid in the placement of tiles by an autonomous tiling robot. Although the gaps were targeted and measured accurately, they were only modeled by a single parameter: gap width. Such simple models may not be sufficient for detailed construction manipulation tasks.

Authors like Sicard and Levine [10] and Kim et al. [11] employed a method called polygonal approximation and syntactic analysis to extract 2D models from weld joint data obtained from a projected laser beam and CCD. In this approach, data points were evaluated one by one and combined into linear segments via polygonal approximation. The segments were then merged according to prescribed syntactic rules used for describing weld joints. However, the syntaxes developed in such studies were only capable of handling a handful of simple joint types because the complexity of segmentation and syntactic rules tends to increase with increasing component complexity. Furthermore, such methods are susceptible to failure under conditions of partial object occlusion and incomplete sensor data.

All of these studies suffer from limitations which inhibit their employment in the robotic perception and manipulation of detailed construction components. Such limitations include the need for human intervention, the lack of semantic object recognition, the lack of modeling detail necessary to perform detailed work, the inability to handle a variety of complex components, and the susceptibility to modeling failure under partial object occlusion and incomplete sensor data. The research described herein seeks to address such limitations by enabling a construction robot to autonomously perceive its workpieces through the fitting of geometrically complex models to sensor data with sufficient fidelity to ultimately adapt its plan and perform detailed construction work.

3 Research Contribution

This paper offers three central contributions. First, this paper introduces a modified search algorithm for such purposes as fitting a geometric model to a point cloud, fitting a point cloud to another point cloud, or fitting a point cloud to a map. Specifically, the modified algorithm is called Generalized Resolution Correlative Scan Matching (GRCSM) and is a generalization of Multi-Resolution Correlative Scan Matching (MRCSM) [12]. Second, this paper introduces a construction component model fitting technique, also referred to as GRCSM, in which the GRCSM algorithm is applied in order to fit a model of a construction component to a robot's sensor data. Lastly, this paper provides an initial investigation into the capabilities and limitations of the GRCSM construction component model fitting technique as a model fitting tool for construction robot perception via experimentation.

4 Technical Approach

This work focuses on the detailed modeling of targeted workpieces for robotic manipulation. Specifically, this work employs a model fitting technique whereby complete models of construction components are fit to point clouds so that contextual meaning can be directly applied to the data. Although the technique can be applied to either 2D or 3D models and sensor data, 2D models and sensor data are used here.

Despite the existence of numerous construction tasks to which such modeling techniques could be applied, construction joint filling is used as an example application in this work due to its commonality across a range of construction activities. Activities such as welding, caulking, drywall finishing, tile grouting, spray insulating, and pipe soldering may be classified as joint filling. In this paper, joint filling refers solely to the placement of filler or sealant material into the joint, although the full treatment of an actual construction joint might require additional tasks such as scraping, cleaning, masking, priming, backing, tooling, and cleaning.

4.1 General Setup

Many interdependent technological advancements must come together to support the successful operation of a construction robot on a real-world construction project. Rather than attempting to address all aspects of the problem at once, this research focuses on a portion of the problem, leveraging the assumption that the other supporting components are also in place. The general setup is described as follows.

First, it is assumed that the construction robot has access to a Building Information Model (BIM) containing the designed geometry of the construction project, which is reasonable considering the rapidly expanding use of BIMs in architecture, engineering, and construction [13]. Second, it is assumed that the robot has been placed, tele-operated, or autonomously navigated in such a manner that it has reached the near vicinity of the object of interest. Furthermore, it is assumed that the robot's pose estimation error is small enough that it can aim its sensor in the direction it expects to find the object, and despite pose errors, still detect the actual object within the sensor's operational window. This is a reasonable assumption considering that today's indoor mobile robots are able to localize themselves on the order of several centimeters and a single degree [14]. Lastly, it is assumed that the sensor is capable of adequately sensing the object of interest. In reality, highly reflective or transparent materials tend to degrade the data quality of many sensors, and specialized sensing modalities may be necessary for such cases. In the experiments described here, materials were intentionally chosen based on sensor compatibility.

4.2 Modeling

In order for a robot to identify or manipulate a construction feature, a feature model is first needed. Construction joints are used as an example here to demonstrate feature modeling. For most construction joints, the majority of the feature's descriptive information lies transverse to the joint. Thus, one modeling strategy would be to model the feature in thin 2D slices and assemble the slices to create a 3D model. Such an approach is employed in this work. Given that the square butt joint is arguably the simplest and most common joint type, it is used as the illustrative example.

The techniques presented in this paper tend to be best suited for situations in which modeling accuracy requirements permit the fitting of fixed models to the data. Given that a joint's primary feature of interest is the gap formed by two construction components, a model in which each of the two component models is free to translate and rotate offers considerable descriptive capability for the gap. Since each of the two individual components has three degrees of modeling freedom, and the gap is defined by a combination of those two components, the gap model has six degrees of freedom. The square butt joint model is shown in Figure 1, where it has been decomposed into an individual component model, a combined component model, a separated component model, and a gap model.

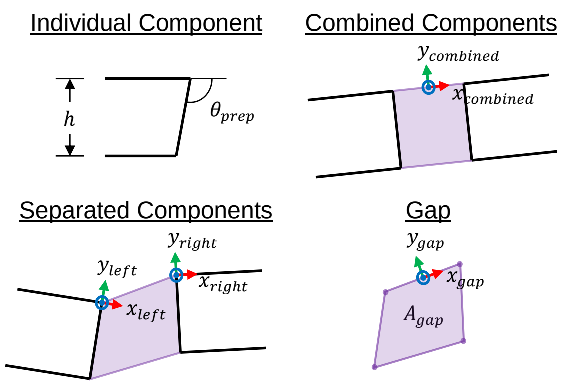

Figure 1. Square butt joint model decomposed into individual component, combined component, separated component, and gap models

4.3 Sensing

A wide range of sensors could be used for the sensing of such construction components. In addition to various modalities (e.g., optical, ultrasonic, laser, etc.), sensors can output data in a range of dimensions (e.g., 2D, 3D, etc.). Since laser data can easily or directly be converted to spatial data, and because the majority of a joint's descriptive information lies in its transverse plane, the authors chose to use a 2D laser rangefinder in this work.

4.4 Model Fitting

In this paper, the authors take the approach of fitting complete models to sensor data so that any contextual meaning associated with the model can be directly related to the data. One of the benefits of this approach is that it does not require sophisticated rules for segmenting data, regardless of the complexity of the model. Another benefit of this approach is its robustness to incomplete sensor data.

The technique presented here for fitting models of construction components to sensor data is referred to as the Generalized Resolution Correlative Scan Matching (GRCSM) construction component model fitting technique. It employs a search method called the Generalized Resolution Correlative Scan Matching (GRCSM) search method, which is a generalization of Olson's Multi-Resolution Correlative Scan Matching (MRCSM) search method [12]. Like MRCSM, GRCSM is a brute force search method that uses multiple resolution levels to quickly narrow a search. However, the two methods differ in that MRCSM performs a search over two resolution levels, while GRCSM searches over any arbitrary number of resolution levels. GRCSM automatically determines and implements the appropriate number of resolution levels based on the specified search window size and desired fit tolerance.

One particular benefit of the GRCSM search method is its immunity to local minima entrapment, which is a well-known issue for search methods like Iterative Closest Point (ICP) [15]. The GRCSM construction component model fitting technique can be generalized to 3D data and 3D models, but is presented here in the context of 2D data and 2D models.

The GRCSM construction component model fitting method is comprised of three primary stages: determining the appropriate number of resolution levels, building a component model lookup table for each resolution level, and fitting the sensor data to the component model by searching for a best fit. The first step in determining the appropriate number of resolution levels is to determine the search-range-to-tolerance ratio r for each degree of freedom (e.g., x, y, and θ), as shown in Eq. (1), where w is the search window size and t is the loosest allowable fit tolerance.

$$r = w/t \tag{1}$$

The number of resolution levels L is then determined as shown in Eq. (2), where s is the search test quantity per level for each degree of freedom and *ceil* is a function that rounds a number up to the nearest integer.

$$L = ceil\left(\frac{\ln(r)}{\ln(s)}\right) \tag{2}$$

The second step in the GRCSM method involves building a component model raster lookup table for each resolution level, starting with the highest resolution table. The table and its entries can be thought of as a uniform grid of cells. The dimensionality of the table corresponds to the dimensionality of the search (e.g., 2D, 3D). The size of the high resolution table is determined along each dimension as shown in Eq. (3), where c is the number of high resolution grid cells. Margins can be added to the high resolution table in integer multiples of s^{L-1}, but c should still refer to the expression shown in Eq. (3).

$$c = s^L \tag{3}$$

The scale q (e.g., $1\ mm/grid$) of a cell along any dimension is given by Eq. (4).

$$q = w/c \tag{4}$$

The component model is then projected onto the high resolution lookup table. If the model already exists as a bitmap representation, or can easily be converted to such form, then it can be directly inserted into the table, provided appropriate scaling. Alternatively, the model's vertices can be projected onto the lookup table and intermediate points can be interpolated between the model's vertices. After a bitmap representation of the model has been established, a probabilistic distribution is applied to the model to reflect the stochastic nature of the sensor, as suggested by Olson [12]. For simplicity, the authors employ a radial Gaussian distribution with standard deviation equivalent to that of the sensor. The bitmap representation and stochastic counterpart for an arbitrarily shaped object profile are shown in Figure 2.

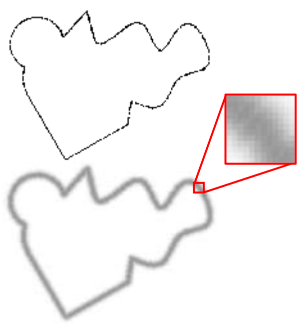

Figure 2. Bitmap (top) and stochastic (bottom) representations of an example arbitrary profile

After the high resolution lookup table is complete, lower resolution lookup tables are produced by iteratively employing Olson's [12] technique for generating a low resolution lookup table. To generate a lower resolution table, the first cell of the lower resolution table is set to the maximum value found in the first $s \times s$ block of cells in its high resolution counterpart. Similarly, the second cell of the lower resolution table is set to the maximum value found in the second $s \times s$ block of the high resolution table, and so on. As such, each new table becomes $1/s$ the size of its higher resolution counterpart. This process continues until L tables, including the high resolution table, are obtained. The lowest resolution table then becomes of size $s \times s$. An example set of lookup tables for an arbitrarily shaped object is shown in Figure 3, where dashed lines have been superimposed on the lowest two resolution levels to help illustrate the process.

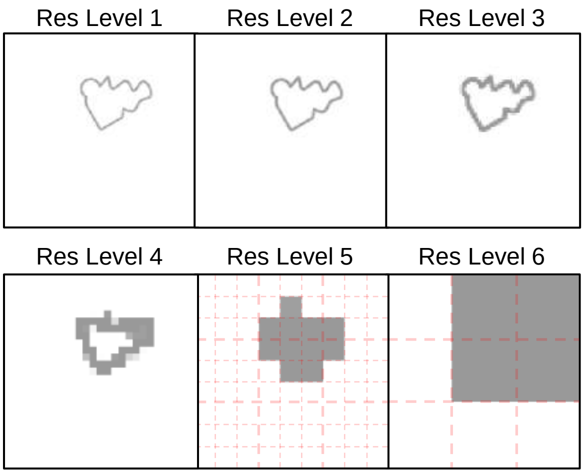

Figure 3. Model lookup tables at various resolution levels for an arbitrarily shaped object

It is expected that such lookup tables may only need to be built once for a construction feature if it possesses a uniformly designed cross section, as is the case for most construction joints.

The third step in the GRCSM method involves fitting of the sensor data to the component model by searching for a best fit between the data and the lookup tables. Using the expected sensor-to-joint pose as a reference, the data points are projected onto the lookup table and the corresponding values are summed to provide a fit score. To start, the data points are transformed and projected onto the lowest resolution table using various pose combinations. For each degree of freedom, the immediate search window i is given by Eq. (5), where v is the current resolution level.

$$i = \frac{qc}{s^{L-v}} \tag{5}$$

The immediate search window is divided into s uniform intervals, such that test points lie at the center of each interval. Similarly, s test points are also created for the other degrees of freedom. The data is then projected onto the table for each of the f^s pose combinations. The table values are summed, and the total fit score is recorded for each combination. The scores are then added to a list, and the pose of highest score is removed from the list and explored at a new resolution level. This process is repeated until the highest scoring pose found on the list coincides with the highest resolution level (Level 1). Such pose is then selected to represent the best fit between the data and the model. An example search process is shown in Figure 4.

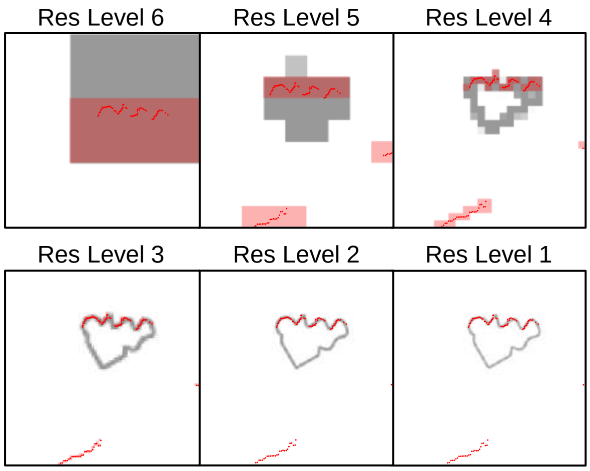

Figure 4. Example GRCSM search process showing the best fit results at each resolution level leading to the final fit result

It should be noted that during the process, it is possible to move bi-directionally along the resolution spectrum and jump more than a single level, given that search transitions are dictated by the highest score found in the score list. Furthermore, it should be noted that the scores in the score list have both an associated pose and resolution level. That is, the same pose can be explored at more than one resolution level.

For the case of a single construction component, the GRCSM model fitting process is straightforward. However, for the case of a construction joint, which is comprised of two components, the process occurs differently. First, a combined model is built from the two component models such that their relative pose matches the BIM. The GRCSM method is applied to the combined model. The pose corresponding to the fit of smallest error is selected as the combined pose estimate. The process is then repeated for each component individually, using the combined pose estimate to initialize the search. Furthermore, the search window for the individual components is limited to a fraction of the designed gap width in order to avoid erroneously fitting a model of one component to the sensor data of other components. The resulting pose estimates are then adopted as the component pose estimates, and the joint gap is modeled directly from the transformed component models.

5 Experiment

An experiment was conducted in a virtual environment to evaluate the ability of the GRCSM model fitting approach to estimate the geometry of a square butt joint that deviates from its expected, i.e., designed, geometry. A randomized square butt joint was generated by specifying information about the gap and the two components that comprise the joint. The transverse parameters of the expected joint are listed below, where a, b, and c are counterclockwise rotations about x, y, and z, respectively.

- Gap width (top corner to top corner): 25 mm
- Workpiece thickness: 25 mm
- Workpiece width: 200 mm
- Expected pose in world frame:
  $\bar{x} = 0\ mm, \bar{z} = 50\ mm, \bar{a} = 0°, \bar{b} = 0°, \bar{c} = 0°$

The joint was extended along a third dimension by uniformly spacing two-dimensional cross sections, or slices, along the world y-axis. The joint was made continuous by interpolating between particular slices designated as transition slices. The joint was generated by randomizing various geometric joint parameters. The joint was comprised of 83 cross-sectional slices and took the form shown in Figure 5. Dashed lines denote the joint's 83 cross-sectional slices, and solid lines denote the joint's 12 transition slices.

A virtual sensor was used to generate virtual sensor data of the joint. The virtual sensor was modeled after a 2D scanning laser rangefinder that outputs range and bearing measurements. Loosely modeled after the Hokuyo URG-04LX-UG01, the sensor was assigned bearing increments of 0.352° (10 $bits$) and a range standard deviation of 3 mm. Uncertainty in the sensor's bearing measurement was neglected. The sensor's scan window was set to $\pm 30°$. The virtual sensor scanned the joint while translating along the world y-axis, 250 mm directly above the expected center of the joint. The virtual sensor data was generated by projecting a beam onto the incident joint face, finding the point of intersection, and adding a normally distributed random range error corresponding to the sensor's standard deviation. The resulting virtual sensor data is shown in Figure 5.

The GRCSM construction component modeling fitting technique was then applied to estimate the poses of the two workpieces at each slice along the length of the joint. For the GRCSM search, the fit tolerances for x, y, and θ were set to $\pm 0.5\ mm$, $\pm 0.5\ mm$, and $\pm 0.3°$, respectively. The test quantity per level was set to three, and the search windows for x, y, and θ were set to $\pm 121.5\ mm$, $\pm 121.5\ mm$, and $\pm 45°$, respectively. All computational processing was performed in MATLAB using an Intel® Core™ i7-4900MQ 2.80 GHz central processing unit.

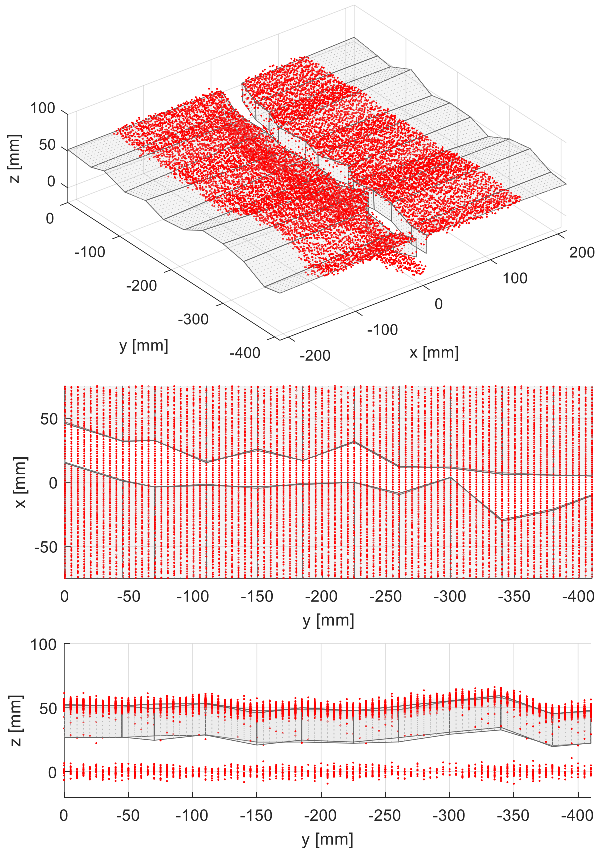

Figure 5. Virtual square butt joint and sensor data

The dataset was processed a second time to provide a comparison between the MRCSM and GRCSM search algorithms. MRCSM was simulated in the experiment by restricting the number of GRCSM resolution levels to two, with an equal number of tests for each resolution level.

Because the gap is defined by the two workpieces, the gap's pose and geometry was extracted directly from the workpiece model results. The 2D gap geometry (e.g., cross-sectional area) was converted to 3D (e.g., differential volume) by projecting the information half the distance between slices in both directions.

6 Results

The gap modeling results for the GRCSM model fitting technique are shown in Figure 6, where the results are represented as a collection of gap pose estimates and differential gap volumes estimates, and the gap origin is defined as the midpoint between upper corners of the workpiece models.

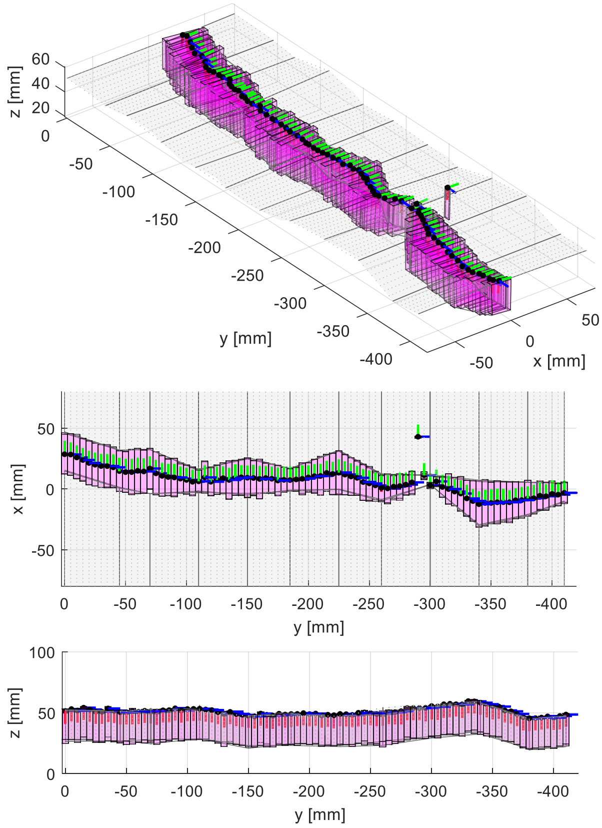

Figure 6. Model fitting results using the GRCSM construction component model fitting technique

The model fitting pose estimation error statistics for the virtual joint are shown in Table 1, and a plot of the estimated poses and differential volumes are shown in Figure 7.

Table 1. Absolute gap pose error statistics

	Min	Max	Mean	Std Dev
$\lvert err_x \rvert\ (mm)$	0.0	37	1.6	4.0
$\lvert err_z \rvert\ (mm)$	0.0	2.2	0.6	0.5
$\lVert err_{pos} \rVert\ (mm)$	0.0	37	1.7	4.0
$\lvert err_\theta \rvert\ (deg)$	0.1	10	2.3	2.0
$\lvert err_V \rvert\ (cm^3)$	0.0	1.3	0.3	0.2

The mean processing time was found to be 0.082 $s/scan$ for the GRCSM component model fitting technique. Additionally, the mean processing time was found to be 630 $s/scan$ when using MRCSM to perform the search, suggesting that the GRCSM search algorithm executed the search an average of 3100 times faster than the MRCSM implementation.

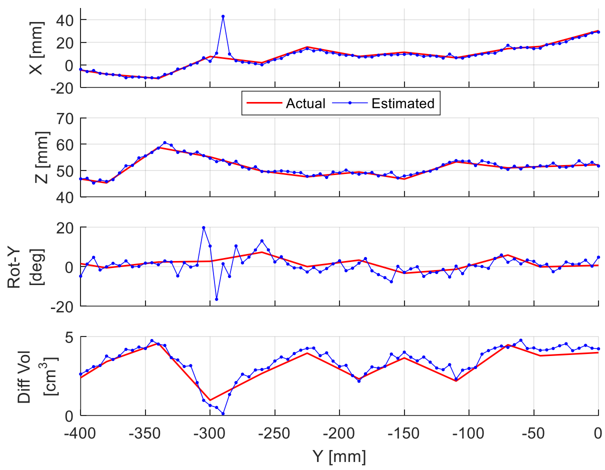

Figure 7. Gap pose estimates using GRCSM

7 Discussion

GRCSM was explored as an alternative model fitting approach to ICP that is free of local minima entrapment. Although ICP is sufficiently robust and accurate for many coarse model fitting applications, the authors anticipate that an entrapment-free approach will be critical for detailed construction tasks, such as welding.

As indicated by the experimental results, the GRCSM model fitting technique appears capable of estimating the geometry of a virtual construction joint. At a rate of 0.082 $s/scan$, the processing time for the entire joint was found to be 6.8 s. This appears reasonable for a real-time scan-and-plan procedure in a real-world construction operation. With further algorithmic and hardware improvements, it is not unreasonable to expect that processing times can continue to be reduced.

This research provides a construction component model fitting technique which enables a construction robot to perceive and model the workpieces in its immediate environment so it can ultimately adapt its plan and autonomously perform construction work. Despite the large uncertainties in robot pose, workpiece pose, and workpiece geometry, this framework enables the robot to perceive the workpiece directly and perform quality work. As opposed to past construction component modeling techniques, this technique eliminates the need for human involvement, provides a level of semantic recognition, offers sufficient modeling detail for detailed construction work, handles a variety of complex component geometries, and offers improved robustness to partial object occlusion and incomplete sensor data. The GRCSM component modeling technique appears to be a promising tool for the geometric estimation of construction components, especially for situations involving full automation, detailed construction work, incomplete sensor data, and complex object geometry.

8 Conclusion and Outlook

The objective of this research was to explore the extent to which a construction robot can perceive and model construction work components, which is a critical step in making adaptive manipulation decisions to accomplish work. This paper began by briefly describing the sources of uncertainty confronting the construction robot and driving the need for component modeling. The Generalized Resolution Correlative Scan Matching (GRCSM) construction component model fitting technique was then introduced to address such a need. An experiment involving the geometric estimation of a virtual construction joint was presented to evaluate the ability of the GRCSM construction component model fitting technique to model construction joints.

It was confirmed that the GRCSM construction component model fitting technique is capable of estimating the pose and geometry of a virtual construction joint. It was also found that the GRCSM search algorithm is significantly faster than MRCSM in executing the model fitting searches described in this paper. However, it was found that GRCSM is susceptible to modeling failure under certain conditions.

Future work is needed to compare the performance of the GRCSM construction component model fitting technique with other model fitting techniques, such as polygonal approximation and syntactic analysis, for construction feature modeling. It may also prove beneficial to explore the use of segmentation in the GRCSM construction component model fitting technique for such purposes as improving robustness to nearby objects. Additional work is also needed to evaluate how the construction component model fitting technique handles cases with multiple similar objects or unexpected objects in the scene. Lastly, additional work is needed to convert a component model into a robot plan and physically execute the plan on a real construction feature.

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A conceptual framework for tracking design completeness of Track Line discipline in MRT projects

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Abstract –

Tracking design completeness during the early phases of complex construction projects is a vital need for project participants to measure their progress. It is also a challenge, because design completeness depends on both geometric details and engineering information related to the model. Tracking level of development (LOD) of the designed objects is a partial solution that focuses on level of geometric detail of the design elements. However, engineering analysis, documents and process records behind the design are thereby neither assured in terms of completeness nor related to the elements. To address this aspect of the problem, the Construction Industry Institute (CII) published Model Maturity Index (MMI) definitions and the Model Maturity Risk Index (MMRI) Toolkit which aim to help management and engineering teams to provide accurate and timely information about design progress and productivity in building and industrial type construction projects. In this research, new MMI definitions and a related MMRI table is developed for the Track Line discipline in MRT projects by conducting a literature review on track line design and by seeking related experts opinions. Semi-automated assistance for populating the MMRI table using an interface management system integrated with a BIM is also described but is not the main focus of the paper. More accurate engineering progress measurements should be facilitated by the research results.

Keywords –

Instructions; Design Completeness, Mass Rapid Transit Projects, Track Line

1 Introduction

Measurement of the design progress is an evolving challenge in today's 3D modeling dominated design environment [1]. Improvements in the software engineering and computer science fields extended traditional 2D and 3D technical design drawings into more intelligent visual modeling processes in construction industry. Today, Building Information Modeling (BIM) philosophy which can be defined as crating a virtual prototype of the system, is getting more and more important in the construction industry [2]. The main idea behind BIM is creating an intelligent model of the project which includes not only graphical details, but also engineering information of the system such as material data, wind force, cost, schedule, and facility management information, etc. [3].

Today, there are several 3D modeling software options on the market that engineering design can be done on the shared design files among the project stakeholders. Although these improvements bring huge flexibility and power to the construction industry such as automatically superimposing different design files and being able to detect clashes, creating walk-through views of the design models, and estimating projects' quantity takeoff automatically, etc., it is hard to measure engineering design progress during the design phase of the projects.

Traditional design progress measurement technique was counting the completed engineering drawings and completed issued-for-construction files. However, it is hard to perform this technique on 3D models, since 3D design is an evolving process on the same design files. Measurement of design process becomes even harder on complex construction projects, since many project participants are involved in the design of the project.

There are different approaches and tools for measuring design progress in both the literature and industry today. One of these approaches is tracking Level of Development (LOD) of design elements in the model. Mainly LOD definitions are focusing on graphical details on the design elements. However design progress is not only related with the graphical details and representation, it is also related with engineering information added to the model, and documents and process records behind the design. Another approach to measuring design progress, which focuses on engineering information added to the model, is tracking Model Maturity Index (MMI) levels of the project disciplines. Both LOD and MMI level approaches are explained in the literature review section of this paper in detail.

Also, there are several Building Information Modeling (BIM) maturity assessment tools available today that help users to measure their project performance on BIM implementation. Arup, which is a global engineering and design firm, developed one of these BIM maturity assessment tools in 2014 [4]. The main purpose behind Arup's BIM Maturity Measurement (BIM MM) tool is to assess the BIM implementation maturity in projects and compare it between different projects. Although BIM MM tool provides a measurement on "maturity", the usage area of this tool is different than measuring design maturity of the project itself. Therefore BIM maturity tools will not be further explained in this paper.

This paper is part of an ongoing research project related with measuring design progress on complex capital projects. The main focus in this conference paper is on explaining currently used methods for tracking design progress, and introducing a conceptual semi-automated framework for tracking design completeness of Track line discipline in Mass Rapid Transit (MRT) projects. The novelty of this research is developing methods to fill the knowledge gap on design progress measurement for a class of projects that doesn't have specific design maturity definitions. Briefly, the validation approaches of this research are: creating functional demonstrations, getting experts' reviews, and compare developed measurement framework quantitatively with existing systems. Presenting quantitative results from the proposed framework at this time is beyond the scope of this conference paper.

2 Literature Review

2.1 Level of Development (LOD)

Generally, 3D models of construction projects range between a conceptual drawing to a fully detailed and coordinated construction model. One way of measuring design completeness in construction projects is tracking Level of Development (LOD) level of the elements on the model. In 2008, the American Institute of Architects (AIA) released a contract document, "AIAE202-2008 BIM Protocol Exhibit," which defines Level of Development (LOD) and LOD levels, which are related primarily to amount of design detail in the model. According to the AIA, LOD 100 represents a conceptual drawing, while LOD 500 is the as-built model; LOD gets higher during the design phase of the project and reaches its highest level during the construction phase [5]. In 2017, The Level of Development (LOD) Specification which follows CSI Uniformat 2010 organization and LOD schema developed by AIA, is released by BIMForum. In this specification, general insight and definitions of LOD levels for the design elements specified in Uniformat 2010 is provided [6].

Mainly LOD level definitions are related with the graphical details on the design elements on the model. In other words, as the accuracy of the design of the elements gets higher, the LOD level of that elements also gets higher in the model. However, there is no such LOD level of the complete design model. LOD levels are defined only for elements on the model. It cannot easily or consistently be aggregated to total LOD level for project [7,8].

LOD can be added as a shared parameter to the models created on Autodesk Revit to track design progress of the project. During the design phase, LOD level of the elements can be arranged manually by the design team according to the LOD definitions that they created for their project' design elements. When each element's LOD level is defined on the model, the project team can track changes on these levels to see progress in their projects.

2.2 Model Maturity Index (MMI)

Most of the engineering progress in the early phases of complex capital projects is not graphical-design related, and such progress must be captured as well in order to have a complete idea about the progress in the project. Examples of such engineering processes are diverse and include geotechnical studies, mechanical and control systems design, and structural systems analysis.

Similar to the AIA, the Construction Industry Institute (CII) published metrics to measure progress in model-based engineering projects in 2017. These metrics are called Model Maturity Index (MMI) and they are focusing on engineering information added to the 3D model, and documents and process records behind the design. Similar to LOD, MMI definitions have levels ranging between MMI 100 which mainly refers to a conceptual design, to MMI 600 which indicates that facility management data is included to that discipline.

Until today twelve sets of MMI definitions which are namely: Piping, Structural, Instrumentation, HVAC, Equipment, Civil, Electrical, Fire Protection, Layout, Foundations, Buildings, and P&IDs, have been established by CII. Each of these definitions is providing a clear set of modeling requirements for each MMI level in that discipline to fulfill. The MMI levels are calculated per discipline per location on the 3D model, and calculations are done by the Model Maturity Risk Index (MMRI) tool developed by CII [9].

While LOD levels are mainly related to the design detail on the model, MMI levels are related to the amount of the information in the model. In other words, both graphical and non-graphical information associated with the project is reflected with MMI levels. Another difference between LOD and MMI levels is, LOD is mainly related with details on the design of the model elements, while MMI levels are prepared for design disciplines in the project.

2.3 Model Maturity Risk Index (MMRI)

The Construction Industry Institute (CII) developed Model Maturity Risk Index (MMRI) tool that includes questionnaires for each discipline that they defined MMI definitions. By filling these tables for a specific location in the project, MMI levels per discipline in that specific location can be calculated. It also provides percentage of remaining work to achieve higher MMI level within the discipline in specific location too.

The questionnaires in the MMRI tool have inter-disciplinary relationships between the disciplines too. Mainly the questions on the tool are based on the information added to the model such as site plan, geotechnical investigation, design parameters, equipment data, clash detections, etc. The user of the tool needs to select appropriate answer from drop down menu which includes answers as Yes, No, Not applicable, Design Specified, Loaded, Confirmed, etc. for each question. Each of these answers would have connections with different MMI levels and also weights on MMI level calculation. As an example Foundation is a discipline which CII provided MMI definitions and MMRI table. The questionnaire for Foundation in the MMRI tool has questions about the size and location of the design components. While the answer of “preliminary design” to these questions has connection with MMI 100, the answer of “design specified” has connection with MMI 300.

The main usage area of the tool is expected to be a guide showing current maturity of the model and required modeling effort of specific disciplines in different locations on the project. The project team can have better communication in model reviewing meetings by filling the questionnaires, and obtaining current MMI levels of the specific modeling disciplines in different locations.

3 Tracking design progress of Track Lines in Mass Rapid Projects

Mass Rapid Transit (MRT) systems such as Light Rail Transit (LRT), Bus Rapid Transit (BRT), Subways, etc. are important for solving the traffic congestions and mobility of the people in the crowded cities. These MRT projects are generally considered as complex projects due to their size, engineering design and construction complexity, financial approach, contract type, and delivery method.

Although these projects can be considered as linear projects where there are many identical units that are repeated, the graphical details and engineering information added to the model would change location to location on the design file. According to the expert’s opinion from railway industry, it is hard to track design progress in MRT projects since design details and engineering information added to the models are not always similar all around the project. In other words, there would be locations such as stations or areas between stations, where the design model is close to the as-built version, while others locations are still in conceptual design phase.

In this research paper, new conceptual MMI definitions and an MMRI table is defined for the Track Line discipline on Mass Rapid Transit (MRT) projects. Although type of track lines is different in heavy rail and light rail systems, a generalized definition that can be applied on different type of track line systems will be created. However, in order to provide specific examples related with the MMI definitions and MMRI table, among different type of MRT projects, the main focus will be on Light Rail Transit (LRT) projects.

LRT projects are a subdivision of mass rapid transit systems and according to the American Public Transportation Association (APTA), the definition of LRT system is “an electric railway system characterized by its ability to operate single or multiple car trains along exclusive rights-of-way at ground level, on aerial structures, in subways or in streets, able to board and discharge passengers at station platforms or at street, track, or car-floor level and normally powered by overhead electrical wires”. According to the report published by International Association of Public Transport (UITP) in 2015, LRT and tramway systems are operated in 388 cities all around the world. Europe is the richest region in terms of the number of the LRT projects. A total of 206 cities in Europe had LRT or Tramway system in-service. Eurasia follows Europe with 93 cities having LRTs [10].

Track lines on LRT projects would be different than on other types of MRT projects’ track lines, since the main difference of the LRT projects is that the light rail vehicle (LRV) would have the ability of operation in mixed traffic on the street when it is necessary [11]. Therefore, track line types used in LRT projects are generally thinner and they can be used in mixed traffic conditions. In LRT projects, different type of tracks such as ballasted track, direct fixation track, embedded track, etc. are used [11]. Although there are many differences on design of these various track lines on MRT projects, generalized definitions for measuring design completeness of the track line discipline in different type of projects will be created.

3.1 Proposed MMI definitions for Track Line Discipline

Light Rail Transit (LRT) projects can be divided into many different disciplines. In this research, a model LRT project is divided into 14 disciplines which are namely Administration, Procurement, Quality Management, Earthwork, Track line, Structural, Operations/ Maintenance, Mechanical, HSE, Signaling, Civil, Electrical, Telecommunication, and Multidiscipline. Among these disciplines, Track Line discipline is selected for this research to establish new MMI definitions.

In order to create MMI definitions for Track Line disciple, currently available MII definitions provided by Construction Industry Institute is studied, literature on Track Line design is researched in detail, and main design components that can be used for tracking design is selected. The created conceptual MMI definitions for Track Line discipline can be seen on Table 1. This could be further disaggregated and used for each track line section.

Table 1 Conceptual Model Maturity Index Level Definition for Track Line Discipline

MMI Level	Definition
100	Generic model of the site plan, route, and topographic maps are created. Existing conditions have been quantified and graphically represented.
200	The preliminary geotechnical investigation report has been received. The engineering team decided type of tracks to be utilized. Track line components graphically modelled with preliminary size and configuration, as follows; - Site plan, topographic maps and surveys - Horizontal and Vertical layout design - The route of the project - Track components - Track ballast/bed design Design performance parameters, as defined by the project, are associated with model design components as graphic or non-graphic information.
300	The geotechnical investigation report has been received and confirmed. Project-specific layout specifications and track line specifications are attached to the related components. Track line components graphically modelled with design-specified size and configuration, as follows; - Site plan, topographic maps and surveys - Horizontal and Vertical layout design - The route of the project - Track components - Track ballast/bed design Project plans and permits have been submitted to AHJ (Authority Having Juristiction). The environmental and remediation requirements have been submitted to AHJ.
350	Track line components graphically modelled with confirmed size and configuration, as follows; - Site plan, topographic maps and geotechnical investigation - Horizontal and Vertical layout design - The route of the project - Track components - Track ballast/bed design Project plans and permits have been confirmed by AHJ The environmental and remediation requirements have been confirmed by AHJ.
400	Track line components graphically modelled with approved size and configuration, as follows; - Site plan, topographic maps and geotechnical investigation - Horizontal and Vertical layout design - The route of the project - Track components - Track ballast/bed design The IFC (Issued for Construction) drawing package and specifications have been submitted. Project plans and permits have been approved by AHJ.

	The environmental and remediation requirements have been approved by the AHJ.
500	As built: as build conditions are graphically represented in the model
600	FM-enabled: as-built models are supplied with Facility Management information as outlined by project scope

3.2 Proposed conceptual MMRI table for Track Line Discipline

Although Track Line related MMI definitions are at the conceptual phase, a conceptual MMRI table for the Track Line discipline is created to explain how design progress will be calculated with this method.

To create the MMRI table for the Track Line discipline, first the CII MMRI tool is reviewed in detail and seven main categories that would be used in Track Line design are selected among the existed tables. The selected categories are namely; Project data, Design components, Track supports, Routing, Specifications, Related Studies and Permits, and Submittals. Then, fourteen criteria according to the defined MMI level definitions are created under selected categories. In order to be consistent with existing MMRI tables, some of the defined criteria is selected from CII' MMRI tables, while some of them are defined after conducting a literature review and by seeking related experts' opinions on track line design. Developed conceptual MMRI table for Track Line discipline is presented on Table 2.

Applicability column will be added to the right end of the developed MMRI table with the options of "Not Applicable, Yes, No, Loaded, Confirmed, Design Specified, Approved, etc. In order to obtain MMI level of Track Line discipline for a specific location on the project, the applicability of each criterion on the Table 2 is required to be filled with these options for that specific location on the project.

In the MMRI tool developed by CII, these tables require manual entry, and each criterion in the table is connected to an MMI level definition. By these connections, after filling these tables for the project, it would show the MMI level result of that discipline in the specified location. In this research, created MMRI tables are filled with semi-automated assistance by using Building Information Modeling and Interface Management systems data per location. This paper is part of an ongoing research related with measuring engineering progress in complex capital projects by integrating Building Information Modeling and Interface Management Systems. According to the CII Interface Management Implementation Guide, an interface management system is defined as "the management of communications, relationships, and deliverables among two or more interface stakeholders" [12]. By integrating these two systems, some automated assistance to fill MMRI tables can be created. However, details of BIM and IM system integration and semi-automated assistance by using these systems will not be described in detail in this paper. As a general example; geotechnical investigation reports can be tracked over the IM system by checking interface agreements, and request for information system data between civil works and infrastructure stakeholders of the LRT project, since they would share that information with each other over these systems. Similarly, track line layout design related criterion or Track ballast/bed design related criterion can be answered by using LOD levels of the related elements on the BIM file.

Table 2 Conceptual MMRI table for Track Line Discipline

Categories	Code	Criteria
Project Data	C1	The geotechnical investigation is ______
	C2	The site plan, topographic maps and surveys are ___
	C3	Existing conditions have been quantified and graphically represented
Design Components	C4	Horizontal layout design is_
	C5	Vertical layout design is___
	C6	Model of track line components is created with approximate size, material, and location
	C7	Design performance parameters, as defined by the project, are associated with model design components as graphic or non-graphic information
Track supports	C8	Track ballast/bed design is_
Routing	C9	The routing of the track lines has achieved a status which is: _
Specifications	C10	Project-specific layout specifications are____ _
	C11	Project-specific track line specifications are
Related Studies and Permits	C12	Permitting requirements are
	C13	Environmental and remediation requirements are
Submittals	C14	The IFC (Issued for Construction) drawing package and specifications have been submitted

Similar with the CII MMRI tool, the proposed table for the Track Line discipline would provide a MMI level result for each specific section on the project after filling the applicability column. As an example; when the criterion "Existing conditions have been quantified and graphically represented" is filled with "Confirmed" while all others are only "Loaded", MMI level would be 100, but even though Project Data and Design Component related criteria are in the status of "Confirmed", while Track Support and Routing related criteria are in the status of "Loaded", MMI level would still be 200 for that area. In that case, when Track Support and Routing related criteria obtain the status of "design confirmed", then the result of the MMRI table for that specific area on the project would change to MMI 300.

An example filled MMRI table for the Track Line discipline in a hypothetical LRT project station area is presented on Table 3.

Table 3 An example filled MMRI table

Location: CNS Station		
Categories	Criteria Code	Applicability*
Project Data	C1	Confirmed
	C2	Confirmed
	C3	Confirmed
Design Components	C4	Design Specified
	C5	Design Specified
	C6	Design Specified
	C7	Design Specified
Track supports	C8	Loaded
Routing	C9	Loaded
Specifications	C10	Loaded
	C11	Loaded
Related Studies and Permits	C12	Loaded
	C13	Loaded
Submittals	C14	No
MMI Level		**200**

4 Conclusion and Future Work

In this paper, a conceptual framework for measuring design progress on Track Line discipline in Mass Rapid Projects is proposed. The proposed framework contains new Model Maturity Index definitions for the Track Line discipline and a related MMRI table to measure design progress. New MMI definitions and an MMRI table is developed by conducting a literature review on track line design and by seeking related experts' opinions.

An example filled MMRI table is also presented after explaining the proposed framework. Semi-automated assistance for populating the MMRI table using an interface management system integrated with a BIM is also described but is not the main focus of this paper. As future work, the calculation method behind the CII MMRI table will be investigated and applied to this research.

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Optimisation of mixture properties for 3D printing of geopolymer concrete

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ABSTRACT:

Freedom of design, customisation, automation, waste minimisation, reduced labour and building complex structures with cheaper materials are the main initiatives for developing 3D printed structures. The fresh properties of concrete are the most important aspects of a successful 3D printing. Concrete requires high workability for extrusion, optimum open time and high early strength in order to support the subsequent layers for 3D printing. Therefore, a mixture design that can satisfy these requirements is needed. Geopolymer concrete is a sustainable solution to traditional Portland cement-based concrete that uses waste materials. In addition, the controlled alkali-activation of geopolymer precursors in order to achieve optimum setting and workability compared to Portland cement provides freedom of mixture design for 3D printing. This paper will investigate the fresh properties of geopolymer mixtures in order to find an effective mixture that is compatible with 3D printing technology and can be also strong enough to stand as a structure. Rheology (workability), open time and compressive strength, as well as, printing parameters such as extrusion pressure and printhead speed was studied in order to achieve a successful geopolymer mixture for 3D printing.

Keywords -

3D Printing; Mixture Design; Geopolymer Concrete; Additive Manufacturing;

1 Introduction

Additive manufacturing technology (in particular 3D printing of concrete structures) has been introduced to the construction industry for more than a decade. However, 3D printed structures are still under-developed and there exist only a few successful trials which resulted in full-scale production.

Khoshnevis B. [1] developed the contour crafting (CC) technology for the automated construction of buildings and infrastructure on earth and other planets. CC is a similar technology to inkjet printing. This method uses high pressure in order to extrude the concrete through a large nozzle of the printhead attached to automatic cranes which move in XYZ directions. On the other hand, the D-shape method was developed by Enrico Dini. The D-shape printer consists of a stationary horizontal frame (the base) with four perpendicular beams at each corner. The printhead is attached to the beams and moves upward (vertical direction). The printhead has approximately 300 nozzles (20 mm apart) spanning the entire base and utilises a magnesium-based binder to fuse sand or stone dust particles in a process of additive manufacturing. A limited number of successful full-scale 3D printed structures got publicity worldwide namely, the 3D printed residential house in Amsterdam (2014) by Dus Architects and also the mass production of 3D printed houses in Shanghai by WinSun (2014).

The benefits of additive manufacturing are freedom of design, reduced labour, customisation, automation, waste minimisation, and building complex structures with cheaper materials. Despite these benefits, there exist few drawbacks that would require further research and development in order to adopt this technology to the next generation of the construction industry. Printing of subsequent layers of materials results in void formation between them thereby causing additional porosity during the manufacturing process. The void formation can reduce mechanical performance because of the reduction in adhesion between the printed layers. Anisotropic behaviour is also common in 3D printed structures. As the result, properties of material inside each printed layer is different compared to that of at the boundaries between layers or the mechanical properties in each direction is different (affected by the orientation of the printed layers). The layer-by-layer appearance of the sides of 3D printed concrete (opposite to the flat sides of casted concrete) is another challenge owned by the nature of additive manufacturing. These challenges need to be addressed by new materials and machine design.

The fresh properties of concrete are the most important aspects of successful 3D printing of concrete. The possibility of aforementioned challenges can be reduced by controlling these properties. Not only the printability of the mixture is determined by fresh properties of concrete but it also substantially affects mechanical properties of concrete after setting [2]. Rheology of the mixture determines the workability and extrude-ability of the concrete for smooth printing of layers with good shape-stability, less void formation and reduced chance of blockage of the nozzle. The rheological behaviour of concentrated suspensions (e.g. concrete) changes versus time and is of great importance for a hassle-free printing [3]. Even minor changes in rheological behaviour during the time-span of printing can potentially affect the properties of the 3D printed structure. Another important fresh properties of concrete for 3D printing is open-time. There exist an optimum time for the printed layer to get initial strength in order to hold subsequent layers but still wet so the layers can fuse together before final setting. The open-time is related to the initial setting time of the concrete. A sufficient open time is required to support subsequent layers [4]. A well-designed concrete mixture needs to satisfy the requirement of controlled rheology, optimum open-time and suitable strength for a successful 3D-printed structure.

2 Background

A limited number of studies on the effect of the mixture design on fresh properties of 3D printed concrete has been carried out, which are briefly discussed.

Gosselin C. et al [5] developed a printing process method which controls the rheology of the mortar for a longer time-span without a reduction in early strength. This method pumps the accelerator and the premix mortar from two separate reservoirs via separate tubes and then combines it at the printhead before the extrusion. As the result, rheological behaviour before extrusion slowly changes (because of no accelerating admixtures in the mortar reservoir) but after the addition of the admixture at the tip of the nozzle, the mixture can set quickly and get a higher early strength to hold subsequent layers. The reduced open-time results in faster printing and higher buildability. Paul S.C. et al [2] investigated different concrete mixtures and found that the rheological properties of concrete mixtures, especially thixotropic behaviour (changes in the rheological behaviour versus time), is an influencing factor for pumping and printing.

Zareiyan B. and Khoshnevis B. [6] suggested the smaller maximum aggregate size and higher cement to aggregate content which results in higher strength and better interlayer adhesion. The increased thickness of the layers with more time lapse between subsequent layers increased the adhesion between layers but decreased the compressive strength of the printed structure. A shorter setting time is also shown to increase the possibility of cold joints between layers [6]. Kazemian A. et al [7] showed that the addition of silica fume and nano-clay can remarkably increase the shape-stability (the stability of the printed layers against settlement and deformation caused by printing of the subsequent layers) of 3D printed cement paste.

2.1 3D printing of geopolymer concrete

Geopolymer (or alkali-activated materials) is a concrete-like binder with approximately 80-90% less associated CO_2 emissions and mechanical, durability and thermal properties comparable with or exceeding those of normal concrete made of Portland cement [8, 9]. Geopolymer is made in a process of alkali activation of aluminosilicate-based materials (precursors) such as blast furnace slag, fly ash, silica fume or metakaolin [10]. The fresh properties (as well as mechanical properties) of geopolymer concrete greatly change based on the mixture design selected from a variety of precursors, activators, different ratios between them and water to solids (w/s) ratio [11-13]. The limitless mixture design of geopolymer with vastly different fresh properties compared to that of Portland cement (the common binder of normal concrete) introduces more possibilities to design a suitable mixture for 3D printing.

Xia M. and Sanjayan J. [14] investigated geopolymer 3D printing based on a powder-bed method which consists of ground blast furnace slag, sand and ground anhydrous sodium silicate (alkali activator). The liquid binder in order to fuse the powders based on a 3D pattern was water with a small amount of 2-Pyrrolidone. The printed cubes had a considerably low strength of 0.9 MPa with the dimensional expansion of less than 4%. Post-treatment of the samples at a higher temperature (60^oC) in an alkali solution substantially increased the strength up to 16.5 MPa showing a great extent of unreacted powders after printing and before the heat-treatment.

This study looks into finding a suitable mixture design for 3D printing of geopolymer paste by an inkjet method similar to contour crafting (smaller scale). Fresh properties of the paste i.e. rheology and open-time, as well as strength, are the key experimental factors in order to find an optimum mixture design of the precursors, activators and w/s ratio. Finally, required pumping pressure and printing speed necessary for successful 3D printing was studied.

3 Materials and methods

3.1 Materials and mixture design

A mixture of ground granulated blast furnace slag (hereinafter slag) from Australian Builders, fly ash from Cement Australia and silica fume from Redox was used as geopolymer precursors. The chemical composition of the precursors are displayed in Table 1 (determined by X-ray fluorescence (XRF) analysis and excluding loss on ignition). The ratios of slag: fly ash: silica fume were 3:1:0.5 based on the preliminary results of fresh properties and strength of different mixtures of the geopolymer precursors tested in the laboratory.

Table 1. Chemical composition of the precursors determined by X-ray fluorescence (XRF)

	Fly ash	Slag	Silica fume
Na_2O	0.81	1.51	0.00
MgO	1.27	5.56	0.00
Al_2O_3	25.13	14.01	0.00
SiO_2	42.09	32.83	96.85
P_2O_5	1.10	0.07	0.00
SO_3	0.41	2.28	3.15
K_2O	0.41	0.35	0.00
CaO	13.56	41.90	0.00
TiO_2	1.44	0.53	0.00
MnO	0.18	0.22	0.00
Fe_2O_3	13.16	0.50	0.00
Total	100.00	100.00	100.00

Sodium meta-silicate powder (SiO_2: 50 wt.%, Na_2O: 46 wt.% and water: 4 wt.%) was used as the activator. Sodium silicate is a corrosive material and needs to be used carefully. However, there is no negative impact on the environment by using this activator. Two ratios of 8 and 10 weight % of the activator per total mass of precursors and three water to solids (w/s) ratios i.e. 0.31, 0.33 and 0.35 were used as variables. In total, 6 samples were tested for rheological behaviour, open-time (initial setting time) and compressive strength. The codes of these samples are shown in Table 2. The optimum mixture based on the fresh properties and strength results was used for 3D printing where optimised printing speed and pumping pressure was trialled.

Table 1. Samples codes of the six geopolymer mixtures

Activator per solid wt. %	w/s ratio		
	0.31	0.33	0.35
8%	G8-31	G8-33	G8-35
10%	G10-31	G10-33	G10-35

3.2 Test methods

3.2.1 Rheology

A Haake Rheometer (Viscotester 550) was used to measure the yield stress of the different mixtures. The paste was mixed for 5 minutes using a plenary Hobart mixer and poured into a cylindrical plastic container (d: 50 mm and h: 150 mm). The vane H with four perpendicular blades (width: 5mm and height: 25 mm) was inserted into the paste until the blades were entirely submerged. After 60 seconds resting in order to dissipate any accumulated stress after the insertion of the vane into the paste. The rotation rate of 0.2 rpm was applied until the maximum torque was recorded. The measurement was repeated three times and the paste was hand-mixed (to avoid settlement of particles) and rested before each measurement. The maximum torque was converted to yield stress based on the geometry of the vane H corresponding to the methodology used in previous works [15, 16]. The average of three measurements was reported. Yield stress versus time at an interval of 15 minutes up to 45 minutes was measured for each mixture in order to understand the rheological behaviour of the mixtures as time passes.

3.2.2 Initial setting time

The Vicat needle was used to conduct the initial setting time test of the samples and was related to the open-time. The test was conducted according to ASTM C191-13. The fresh sample was penetrated by the Vicat needle and the penetration depth was recorded versus time. The penetration readings were done at 15 minutes intervals. The approximated initial setting time was recorded when a penetration of less than 25 mm was achieved. The penetration was repeated for each mixture three times (freshly made each time). The average of three measurements was reported.

3.2.3 Compressive Strength

Compressive strength was measured using a Technotest compression testing instrument with a loading rate of 1 N/(mm^2.s). The paste was mixed for 5 minutes using a plenary Hobart mixer and poured into a 50 mm cubic moulds, sealed with a plastic bag, cured at around 25^{o}C for 21 days and then were tested. Two parallel surfaces of the samples were smoothed using a sandpaper before applying the load. The maximum load before failure was divided by the surface area under load in order to calculate the compressive strength. Five samples were tested; the compressive strength results were averaged and reported.

3.2.4 3D printer

A 3D-Bioplotter inkjet printer from envisionTEC was used for printing of the geopolymer paste on a small scale. A nozzle with an internal diameter of 1.65 mm was used. The paste was mixed for 5 minutes using a plenary Hobart mixer and poured into special plastic syringes. A controlled pneumatic pressure at the back of the syringe is used by this printer to extrude the materials from the nozzle. Horizontal speed of the head of the printer is also controllable. A combination of horizontal speed, pressure and nozzle size (in addition to the rheology of the mixture) determine the thickness of the printed layer. A 50×50 mm rectangular hollow column was designed by Solidworks and used as the input CAD file for 3D printing. The thickness of wall was 3.5 mm or approximately twice the diameter of the nozzle (in order to accommodate to layers side-by-side).

Figure 1. The inkjet 3D printer used in this study to print geopolymer

4 Results and discussion

4.1 Rheology of the geopolymer mixtures

Unlike Portland cement, the rheological behaviour of the alkali-activated materials (geopolymer) is less well known. This is due to the complexity of the chemical environment and reactions taking place, in addition to different physical properties of the main precursors. For example, an alkali silicate-activated slag has an extremely complicated solution environment with high ionic strength and alkalinity, which is a very challenging environment in understanding rheological behaviour [11]. On the other hand, rheology modifiers such as common superplasticizers (that improves workability without increasing w/s) in Portland-cement based materials underperform in geopolymers [17]. Despite the recent aims for designing a suitable superplasticizer for geopolymer concrete [18], those superplasticizers having a minor effect on the rheology of geopolymers compared to that of Portland cement-based systems.

Internal forces between particles in a concentrated suspension of geopolymer are, namely, short-range repulsion forces, normal and shear stresses, fluid pressure, electric double layer forces, inertial and hydrodynamic effects and sedimentation [19]. The balance of these forces determines the yield stress (as one of the main rheological parameters of the fluid). The relationship between concrete slump (a common workability test in the construction industry) is complicated but normally higher slump height (higher fluidity) corresponds to lower yield stress [20]. Better pump-ability and easier flow which is essential for extrusion require lower yield stress and viscosity. However, a very low yield stress material does not hold its shape after extrusion which results in collapsing and self-levelling (not desired in 3D printing). Therefore, an optimum yield stress which allows easier flow of geopolymer for extrusion during 3D printing but at the same time avoid self-levelling and collapsing of the printed layer of concrete (which also needs to support successive layers of concrete) is required.

Figure 2 shows yield stress of the six samples of geopolymers for 3D printing. The effects of the w/s ratio and the wt.% of the activator are shown for the mixture of solid precursors used in this study.

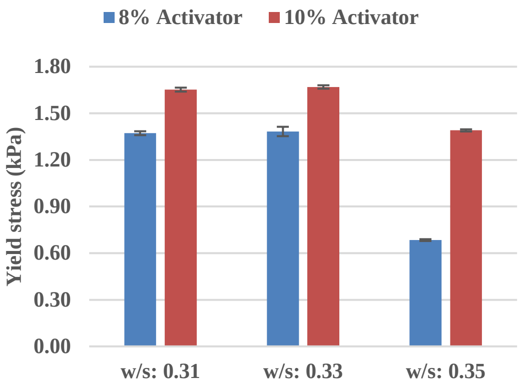

Figure 2. Yield stress of the geopolymer mixtures at different wt.% of activator and w/s ratios

The higher w/s ratio results in an excess water which is no longer used to fill the voids and therefore covers the surface of particles and separates them. The separation of particles by the excess water results in a reduction of bonding forces between particles hence it reduces the yield stress. The substantial reduction as the result of increasing w/s ratio from 0.31 to 0.35 for the sample with 8 wt. % activator is clear in Figure 2. The increase of water from w/s of 0.31 to 0.33 did not change the yield stress. The reason is possibly because of the fact that the amount of excess water for both w/s ratios are negligible in order to facilitate the particle movement and reduce the yield stress. In another word, the sample with w/s of 0.31 is very dry (unsaturated with water) and needs a substantial amount of water before any changes in rheological behaviour takes place.

The addition of alkali activator provides a higher pH and different electrolyte environment in the fresh binder paste (compared to Portland cement-based binders), causing differences in the surface chemistry of particles and their interactions. For instance, the dissolution of slag particles at higher pH (provided by the higher amount of alkali activator) can affect the size of the slag particles and their packing thereby affecting the amount of excess water [11]. Besides the fact that high concentration of ions in the fluid between particles may also cause flocculation of particles thereby increasing the force between particles and yield stress.

In general, an increase in activator dosage results in faster reaction and a higher rate of yield stress increase as previously shown in [11] and also in this study (Table 3). Yield stress can depend on time and shear history which is known as thixotropy. The alkali reaction as time passes affect inter-particle forces via the formation of new chemical or physical bonds between the particles. It also can increase the volume fraction of solids in the fluid as some of the water molecules becomes chemically bound to the solids during the reaction. Therefore, water consumption during the reaction process of geopolymer reduces the amount of excess water which is necessary to disperse slag aggregates. As the results, yield stress increases as time passes.

Table 3. Yield stress (kPa) vs. time of the geopolymer samples (values above 2 kPa shows the sample is semi-hard and yield stress is not measurable)

Sample codes	t=0 min	t=15 min	t=30 min	t=45 min
G8-31	1.37	>2 (hard)	-	-
G8-33	1.38	1.68	1.95	>2 (hard)
G8-35	0.68	1.37	1.76	1.98
G10-31	1.65	>2 (hard)	-	-
G10-33	1.67	2.00	>2 (hard)	-
G10-35	1.39	1.48	1.76	>2 (hard)

The higher amount of water and lower amount activator slows down the yield stress increase by reducing the pH and diluting the system. The only system that can be workable for an extended period of time of 1 hour is the sample with the lowest amount of activator and highest w/s among the samples (G8-35). This sample also has the lowest initial yield stress which was good for extrusion but not suitable for shape-stability after the extrusion. The next options which have prolonged workability (up to 45 minutes) but higher initial yield stress for better shape-stability are G8-33 and G10-35. The required pumping pressure is directly affected by the yield stress of the sample, thereby if the yield stress changes quickly, the pressure also needs to be adapted for homogenous printing. Therefore, minimum changes in yield stress vs. time-span of printing is desired,

4.2 Open-time of the geopolymer mixtures

The suitable time-span to print the subsequent layer of concrete is considered as open-time which is directly affected by the initial setting time of concrete. An optimum open-time is required for the printed layer in order to quickly get a minimum strength to support subsequent layers but long enough so the printed layer is still wet and the subsequent layer can fuse into the previous layer. The printed geopolymer transitions from a fluid material to a semi-solid and then a solid material because of the reaction of the precursors and the activator.

The initial setting time of the geopolymer mixtures with different ratios of water and activator to solid precursors are shown in Figure 3. It can be seen that higher wt.% of the activator (10%) results in considerably lower setting time because of a faster reaction, higher pH and a higher rate of dissolution of particles. Also, a higher w/s ratio causes prolonged setting time by lowering the pH, the rate of dissolution and reaction. The initial setting time can be as low as about 35 minutes for G10-31 up to 230 minutes for G8-35. As mentioned, very short setting time (open-time) although is a sign of getting strength quickly to support the subsequent layers, it can result in less adhesion (fusion) between layers and most importantly the mixture can lose workability for printing very quickly.

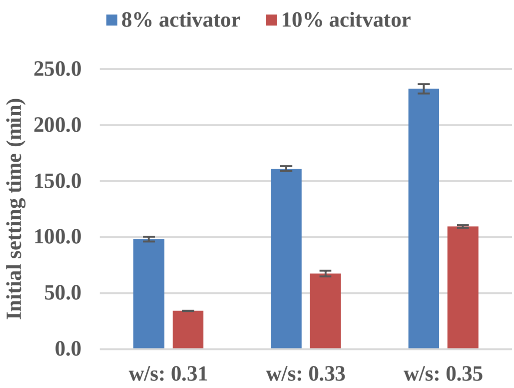

Figure 3. Initial setting time of the mixtures at different wt.% of activator and w/s ratios

The lower setting time can also increase the chance of the blocking the pipes or hardening the sample inside the reservoir. Table 3 shows that G10-31 with an initial setting time of about 35 minutes, is only print-able for less than 15 minutes and after that, yield stress increased and the paste is almost not pump-able (extrude-able). On the other hand, very long setting time (e.g. G8-35) can result in less strength which may not hold the subsequent layers resulting in deformation of bottom layers because of the mass of top layers (inferior shape-stability). It must be noted that sometimes initial yield stress is enough to support a limited number of subsequent layers so then prolonged setting time (slower reaction) would not be problematic (even beneficial for homogeneity of printing) in this case.

It must be noted the reaction also affect the fluidity and extrude-ability of the mixture because the rheological properties are also changing vs. time (Table 3). Reduction in changes of yield stress vs. time is required for homogeneity of printing. However, the samples with lower yield stress changes vs. time showed higher initial setting time (comparing Figure 3 and Table 3). Therefore, a combination of open-time, initial yield stress and changes of rheology vs, time is important to find a suitable geopolymer mixture for 3D printing. And sometimes one property needs to be sacrificed for the other based on prioritising the requirement for printing that can be a better homogeneity, higher number of layers (improved build-ability), easier extortion (better workability) and etc.

4.3 Compressive strength of the geopolymer mixtures

Apart from the fresh properties of the geopolymer mixtures for successful printing, the mechanical properties such as compressive strength must be sufficient enough for a structure. Figure 4 shows the 21-day compressive strength of the geopolymer mixtures with different amount of activator and water to solid ratios.

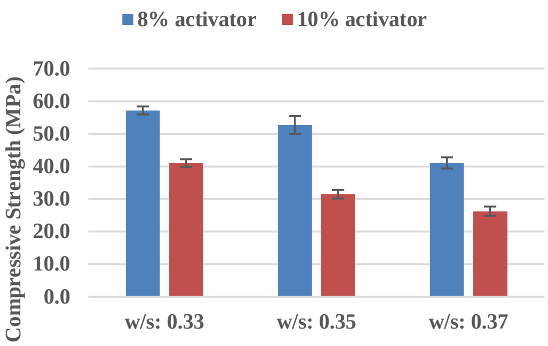

Figure 4. Compressive strength of the geopolymer mixtures at different wt.% of activator and w/s ratios at 21 days

The samples with a lower percentage of the activator (8 wt.%) showed higher strength compared to the samples with 10 wt.% of the activator. Lower alkalinity drive formation of a particular geopolymer gel which increases the mechanical performance [8]. Also, higher w/s normally results in a lower strength of geopolymers as shown in Figure 4.

It must be noted that the samples with 10 wt.% of the activator, despite having faster reaction evidenced by lower initial setting time and faster changes in workability (higher rate of increased yield stress vs. time), showed lower compressive strength. Therefore, 8 wt.% of activator seems a better option for 3D printing considering all these factors.

4.4 3D printing of the geopolymer mixture

Considering, three factors of rheological behaviour, open-time and compressive strength, the samples with 8 wt.% of the activator showed higher strength, increased open-time and reduced change of yield stress vs. time compared to the sample with 10 wt.% of activator. Among the samples with 8wt.% of the activator, G8-3, the yield tress changes increased rapidly (Table 3) and after 15 minutes the workability massively dropped. Therefore, the other two mixtures with higher w/s which are G8-33 and G8-35 are considered for 3D printing.

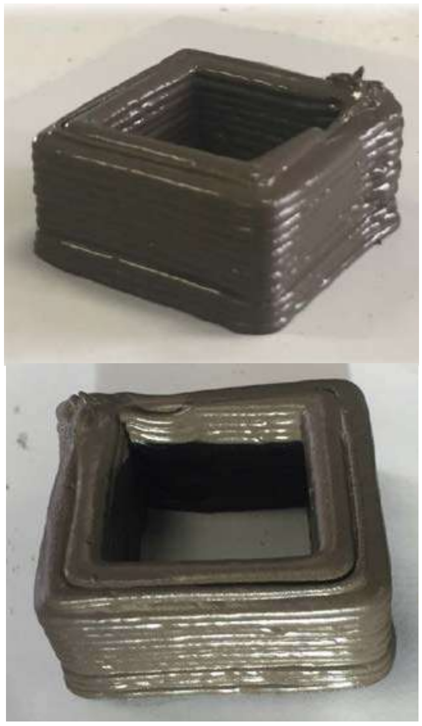

Figure 5. The 3D printed sample of the G8-33 geopolymer mixture (dimensions: 50×50×30 mm)

For G8-35, the printed geopolymer, after extrusion from the nozzle, showed insufficient shape-stability (the printed filaments collapsed and started to spread). This is because of the considerably lower yield stress of this sample as shown in Figure 2. The deformation was significant after printing of the third layer. Therefore, it is concluded that yield stress of around 0.7 kPa for this sample was insufficient for self-supporting of the printed layers. On the other hand, printing of G8-33 was successful as shown in Figure 5 (12 layers and each wall has two filaments printed side-by-side).

Apart from an optimum mixture design, a proper extrusion by the 3D printer is also essential to get the desired quality. Two critical parameters (pumping pressure and printhead speed) considerably affect the printing quality. Pressure is important to ensure an extrusion of a continuous filament from the nozzle. Higher pressure can also push the previously printed layers and affect the shape-stability of the object. The speed of the printhead also determines the time gap between printing of successive layers. Higher speed also may results in discontinuation of the filament (skipping) while printing (which results in air gaps) and it adversely affects shape-stability of concrete (quickly printed layer on top of each other provides a short time span for concrete to set and self-support the structure). Therefore, a combination of speed and pressure in addition of the size of the nozzle determines the thickness of each printed filament; lower speed and higher pressure cause thicker filaments (because the extruded volume of the paste exceeds the volume of material required for a specific length) and vice versa.

The optimum pressure for printing of G8-33 is around 70 to 90 kPa (about 60 times higher than the yield stress of the material) and the optimum speed for this pressure is around 25 mm/s (printing of each layer takes approximately 20 s). The printing of the sample in Figure 5 takes about 4 minutes which is considerably smaller time period compared to the setting time of this mixture. The reservoir capacity of the printer was limited so printing of a larger sample was not possible in one load (reloading takes a considerable amount of time which can affect the quality and homogeneity of the printed object).

The shape-stability of the sample was very good as shown in Figure 6 and except the first layer (because of the uneven substrate), the thickness of other layers are similar with negligible deformation after printing of the successive layers. As the result of the negligible changes in yield stress of the material in the short time period of printing, it can be concluded that the initial yield stress of G8-33 (i.e. ~1.4 kPa) was enough for self-supporting of the number of printed layers. The average thickness of each layer is 2.5±0.2 mm (i.e. approximately 1.5 times larger than the internal nozzle diameter). The thickness of the layer can be controlled by the extrusion pressure and speed of the printhead as well as nozzle diameter. Also, the fusion of the layers seems excellent and no air-gaps between layers is recognizable (Figure 6).

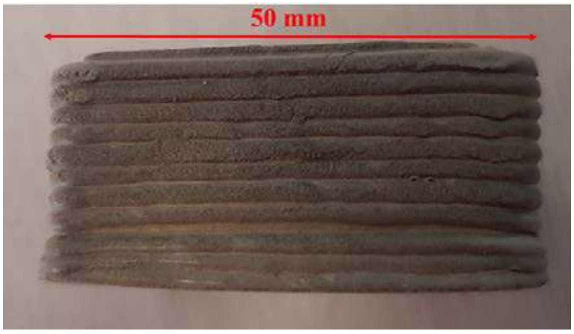

Figure 6. A side view of the 3D printed sample of the G8-33 geopolymer mixture

5 Conclusions

The material properties of a few geopolymer mixtures for 3D printing was studied. Rheology (workability), open-time and compressive strength as well printing parameters such as pumping (extrusion) pressure and printhead speed were studied in order to achieve a successful geopolymer mixture for 3D printing.

In particular, the effect of percentage of the activator and water to solid ratio was studied. The optimised mixture has 8 wt.% of the activator and water to solids ratio of 0.33. Consistent filaments of this mixture were successfully printed through a 1.65 mm diameter nozzle with negligible deformation after printing because of higher initial yield stress and minor changes in yield stress versus time for this mixture. The open-time (setting time) was also high enough to get an excellent fusion (adhesion) between the layers. The compressive strength of the sample was around 50 MPa at 21 days. The optimum extrusion pressure and the printhead speed for the optimised mixture were found to be around 70-90 kPa and 25 mm/s, respectively. However, long-term durability and load-bearing capacity such as the development of internal stresses (which can result in cracking) needs to be investigated in the future studies.

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Preliminary System Design for Teleoperating Construction in Extreme Environments

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Abstract -
Automation of construction is urgent needs for improving efficiency of works, reducing the number of personnel, and working in extreme environments such as other planet or moon or disaster-stricken area. However, the current situation is still insufficient due to reasons of such complexity of work and high risk especially at building sites. In terms of heavy machinery in building construction, it is indispensable to measure its own position and attitude because their precision directly relates to construction accuracy. If lifting and delivering works can be unmanned or teleoperated, it is expected to drastically reduce the number of personnel and improve efficiency. In this research, we have found that a mating connection mechanism can aid teleoperating construction. This mechanism works without any fastener, that is utilized in the construction of the temporary cover of Fukushima Daiichi nuclear power plant unit 1, with RTK/GNSS (Real Time Kinematic, Global Navigation Satellite System) positioning systems is possible to realize the teleoperating construction. By conducting confirmatory experiment of positioning system using a tower crane, we have confirmed the normal operation of all systems. In terms of position and azimuth angle, the accuracy is sufficient to meet requirements for building construction with the mating connection mechanism. Regarding ICP matching by LIDAR (Laser Imaging Detection and Ranging), it was confirmed to be possible to compute the altitude angle with extremely high accuracy utilizing point cloud information from the LIDAR and CAD data using the ICP (Iterative Closest Point) matching library. Detailed preliminary unmanned building construction concept and some results are shown in this paper.

Keywords -
Building Construction; Lunar Base; System Design

1 Introduction

In recent years, automation of construction is urgently required with aims of improving efficiency of works, reducing the number of personnel, and working in extreme environments such as other planet/moon[1, 2] (Fig. 1) or disaster-stricken area. However, the current situation has not progressed rapidly due to reasons of such complexity of work and high risk especially in building sites. Automation of construction works by an unmanned system requires precise positioning method of the self and the target, object recognition and shape recognition system, precise and high speed control, etc. Among them, obtaining detailed position information of the moving object is the most important technique. In terms of heavy machinery such as a crane lifter in particular, it is indispensable to measure its own position and attitude, and their precision directly relates to construction accuracy. If lifting and delivering works can be unmanned or teleoperated, it is expected to dramatically reduce the number of personnel, positioning work of structures, changing work of materials, scheduling lifting plan of cranes, etc. Furthermore, smooth collaboration of information with design, construction control and building management will be achieved. A certain degree of positioning error can be tolerated with our mating connection mechanism (Fig.2).

Figure 1. Concept of Lunar Base Construction (Shimizu Corporation)

Several applications of GNSS/RTK in the field of civil engineering have been reported, however, in the building field, there has been little effort so far due to the high accuracies of the position and attitude are required. In this research, we have investigated whether GNSS/RTK receiver can satisfy the requirement by using single frequency receivers, although "fix"(high-accuracy) solution of a single frequency receiver is difficult to always maintain, a problem in which an attitude angle can not be detected, and two or more frequencies receivers are expensive relatively, and so on. At the same time, redundancy performances of IMU and LIDAR have been investigated as alternate methods.

2 Method

2.1 Unmanned Construction in Extreme Environments

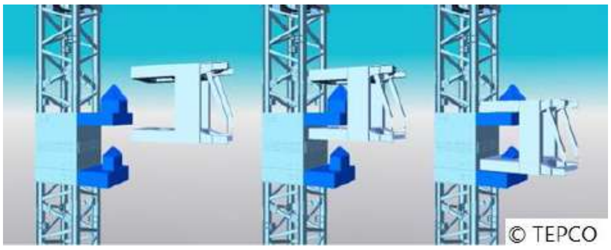

Figure 2. Mating Connection Mechanism

Concerning unmanned construction method, we have experienced and accumulated the engineering techniques in building the temporary cover over the damaged reactor building unit 1 of Fukushima Daiichi nuclear power plant by the teleoperating construction system in high radioactive environment (Fig. 3). All works are conducted with remote control using multiple sensors, cameras, and a crane. It is inevitable that the crane and a lifted object have positional errors, then a tolerate technique is required for safe and reliable jointing. We adopted a mating connection mechanism without any fastener or welding work shown in Fig. 2 that is composed of square holes and quadrangular pyramids. The mechanism is able to tolerate the position and attitude errors of their determination and control by passive adjustment, therefore, fundamentally we adopt the mating connection mechanism positively in this research for building at extreme environments.

Figure 3. Temporary Cover over the Damaged Reactor Building of Unit 1

Concerning the navigation, in these days, low-cost GNSS receiver, single frequency RTK and IMU (Inertial Measurement Unit) are available with ease, and the performance of LIDAR is further improved. Especially global navigation satellites can be seen at least 10 (maximum about 40) in real-time (GPS (United States), GLONASS (Russia), Galileo (Europe), Beidou (China), and QZSS (Japan)). Comparing to other navigation method (single, differential, static, etc.), RTK has advantages of instantaneity and accuracy, although two receivers (base and rover) are required. Thus, lots of GNSS receivers are introduced, distributed, and integrated in our system that can manage highly accurate position and velocity (3-axis) / attitude angle and angular velocity (3-axis) of heavy machinery and lifted objects. Although GNSS is not available on other planets or on the moon, a relative navigation system can be established by another method (e.g. radio navigation, indoor messaging system, pseudolite, total station), and their accuracies are equivalent performances to GNSS. The positioning system is designed as dual-use for uncertain/extreme environments and general building construction site on the earth (Fig. 4) for the reasons stated above, it can also contribute to productivity enhancement.

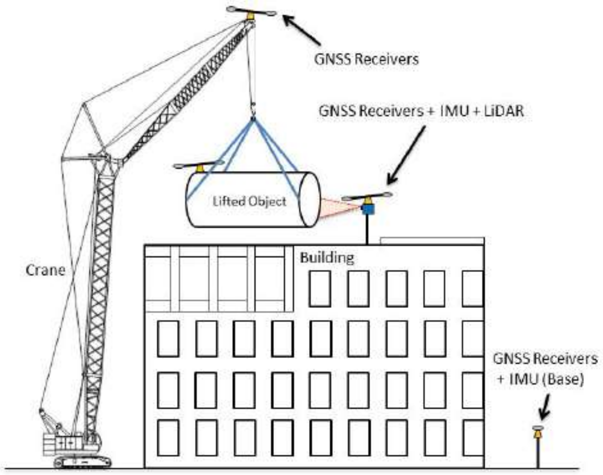

Figure 4. Concept of Unmanned Building Construction

Moreover, we conduct experiments with actual machines with the aim of realizing a production site that can operate construction robots, heavy machinery and general machinery all at once by collaborating with BIM (Building Information Modeling).

2.2 RTK-GNSS Navigation System

2.2.1 Concept

In order to acquire the position and orientation of a crane and a lifted object, the system shown in Fig. 5 was developed. For the purpose of obtaining yaw angle at each position, one pair of GNSS receivers (u-blox NEO-M8T) and antennas (Tallysman TW2710) are located. Since the error of the altitude information is relatively large compared to horizontal position, it also has a barometer (MS5611), which is integrated with a signal from the IMU (AU7554) and transmitted via wired/wireless Ethernet to a microcomputer. Accurate position data is output by analyzing the GNSS signal by the library "RTKLIB" which

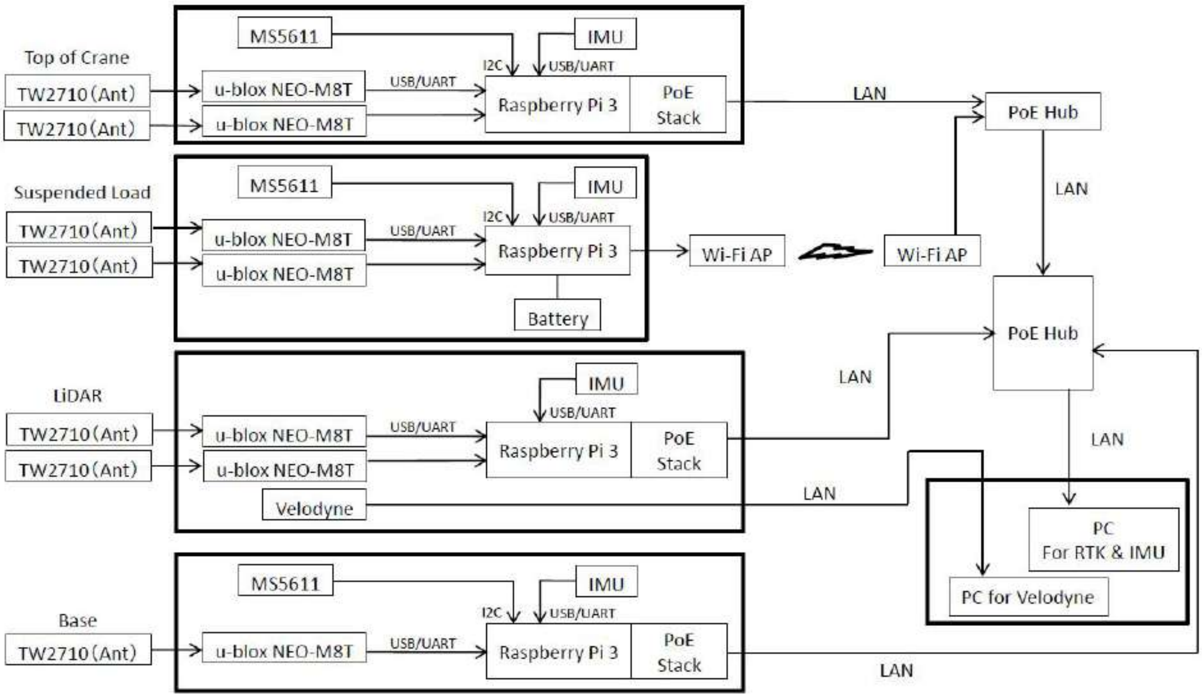

Figure 5. System Diagram

is developed by Takasu[3, 4]. By conducting Loosely-Coupled integration[5, 6, 7] using IMU and barometer signals, appropriate extrapolation is tried to be performed even when RTK solution falls into "float" (low-accuracy solution) using extended Kalman filtering[8, 9, 10] with white noise assumption, or smoothing technique. Internal clocks of microcomputers (Raspberry Pi 3) are synchronized by each time acquired from GNSS, then it can be compensated using the time in integrating multiple sensors.

2.3 System Setup

We developed a measurement system module shown in Fig. 6-7 that is composed of instruments listed up in table 1. PoE (Power on Ethernet) is introduced for power supply of the almost all systems because of the difficulty in accessing the top of the crane for battery charging frequently. However, lifted object is accessible with ease and has the risk of disconnection of wired instrument, batteries and WiFi access point are also attached to it. All electrical systems are in a waterproof-dustproof box, and external antennas are also waterproof. GNSS antennas are attached on wide aluminum plates, and located at 1.5 m height due to prevent the effects of multipath signal on the ground.

In addition, point cloud information from LIDAR is matched by ICP algorithm[11] using the CAD shape data that is stored in the database, thus the attitude angle of the

Table 1. System Instruments

Instrument	Model	Supplier
GNSS Receiver	UBLOX NEO-M8T	CSG Shop
GNSS Antenna	TW2710	Tallysman
IMU	AU7554	Tamagawa Seiki
Barometer	MS5611	TE Connectivity
μC	Raspberry Pi 3	RPF
Storage	MicroSD 16GB	Toshiba
PoE Ejector	PoE-ZR30ATG	Techno Broad
PoE Hub	EHB-UG2B08	Elecom
WiFi Router	WAPS-AG300H	Buffalo
Battery	PowerCore Speed 20000QC	Anker

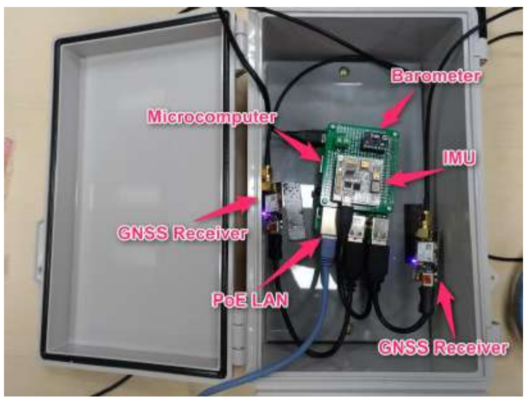

Figure 6. System Box

Figure 7. Integrated System

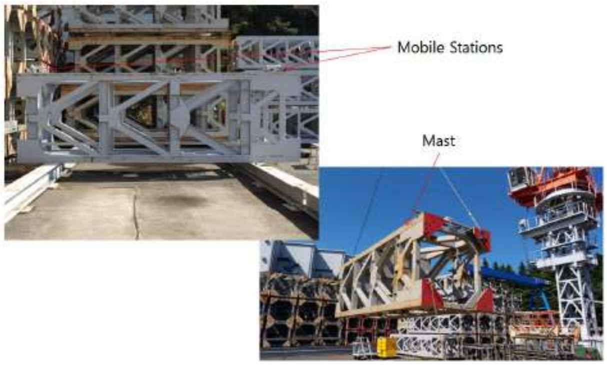

Figure 8. Experimental Site

lifted object is calculated. By adopting the above method, it becomes possible to have redundancy without relying on RTK-only information only.

3 Results

In order to confirm the accuracy of RTK at the building construction site, IMU integration, and the possibility of position and attitude detection by LIDAR, demonstration experiments by lifting was carried out at a facility where a tower crane is permanently installed. The GNSS receiver was installed on several fixed points and lifted object on the ground, and the LIDAR was installed so as to be fixed to the GNSS module and face the direction of the lifted object. Four GNSS antennas are placed at the four corners of lifted object to calculate the azimuth or attitude (Fig. 8). LIDAR is placed in a position where the approach and separation are repeated to see how the difference in point cloud density affects. For the purpose of confirming calculation accuracy of state, a series of operations of lifting the object were repeated 5 round trips by hoisting motion (about 1 m in height), horizontal motion (about 15 m) by slewing, and grounding by hoisting motion. Furthermore, in order to confirm the influence of multipath of RTK/GNSS, it was repeated to move from the place where the stock is accumulated to the open place.

Figure 9 shows the solutions of antenna positions on the lifted object. "1L" or "2R" in the legend means left and right antenna of each measurement system 1 and 2. The average number of satellites used for calculation was about 17. According to preliminary experiments, it is known that the "fix" (high-accuracy solution) rate is highest when 30 deg of masking elevation angle of satellite and 30 dB of masking SN ratio of GNSS signal was applied. In figure 10, the blue line and the green line represent the fix solution and the float solution respectively. Occasionally the position sometimes deviated greatly, then Kalman filter was applied to correct it, however, it did not work well because the slewing speed at the time of the experiment was too slow. Nonetheless, some degree of accuracy is maintained even with a "float" solution, and overall it was within 5.0 cm, which is a general RTK/GNSS error.

Regarding ICP matching by LIDAR, we adopted a method to compare the point cloud obtained by Velocyne LIDAR[12] and the 3D CAD model of the lifted object as shown in figure 11. Although it has symmetry in the rotation in the long axis direction, it seems that there is no problem because the introduced method has high initial value dependency and that the lifted object basically performs only yaw rotation. The CAD model is transformed into point clouds, and the result of executing matching using the ICP library[11] is shown in figure12.

The coordinate system is the LIDAR-referenced, and relative positions and orientations are calculated by fitting a point cloud model in the database to the measured point cloud. Differences of position and attitude estimation by GNSS-RTK were within 0.1 deg and 1.0 cm under optimal condition. However, there were some cases of matching failure, for instance, when the point cloud was not sufficiently obtained. In addition, since one calculation

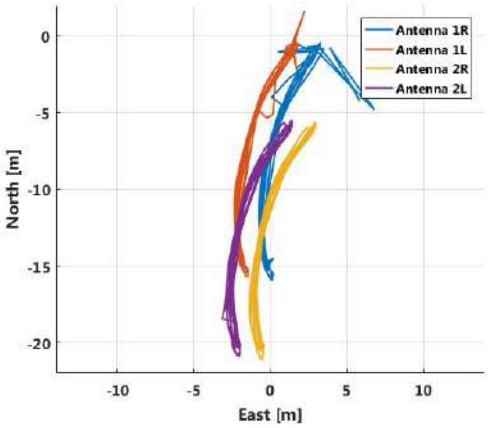

Figure 9. Position Results

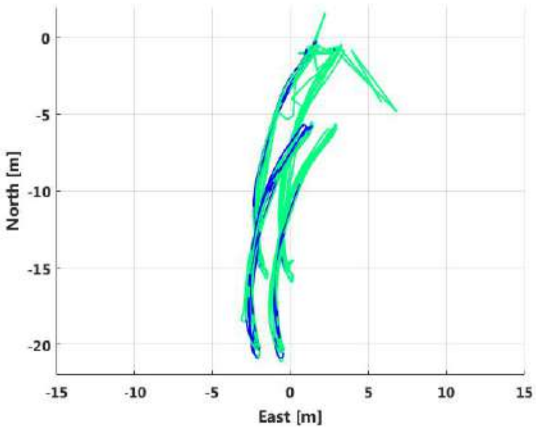

Figure 10. Position Accuracy

time was about 1 second on a typical personal computer, it seems that real-time processing at 1 Hz is also possible. Since there is a problem that LIDAR also detects surrounding objects, recognition and extraction functions will become necessary in the future. Figure 13 shows the distance between the antennas installed on the lifted object calculated from the result of RTK/GNSS position. The correct distance is 1.5 m, and although a slight deviation is observed in "float" solution, the error is kept within 3.0 cm. Based on the above results, we calculated the azimuth angle (Fig. 14). The longer the distance between the antennas, the more stable the azimuth can be calculated. It can be calculated with an accuracy of about 1.0 deg even if the distance is 1.5 m, so it was found that it can be used as an alternative way to a magnetometer.

4 Conclusion

We designed and fabricated a position and attitude determination system for lifted objects for the sake of unmanned construction, and confirmed its usefulness by carrying out the experiments in situations that is similar to

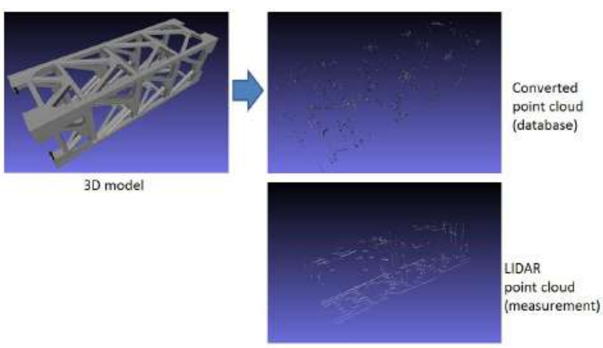

Figure 11. Pointcloud Comparison

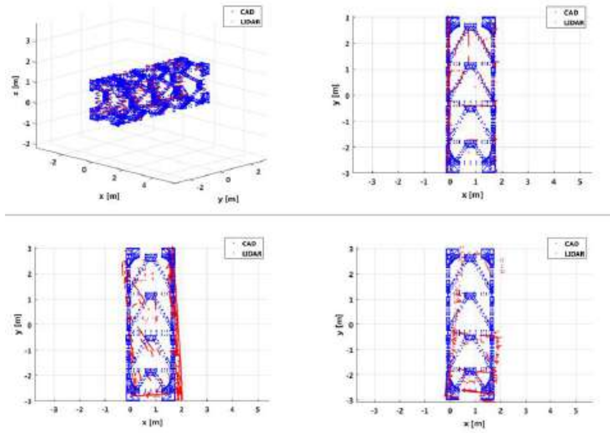

Figure 12. ICP Results

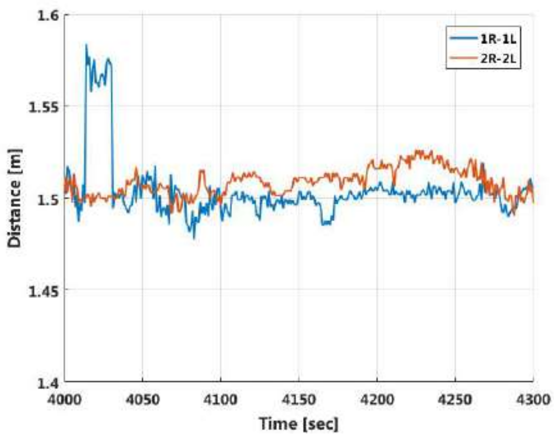

Figure 13. Distance between Antennas

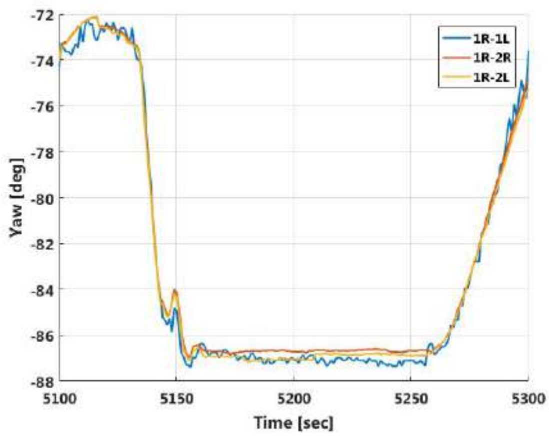

Figure 14. Azimuth Results

actual building construction sites. There was concern that the satellite radio wave environment deteriorated due to surrounding cranes and metal structures, nevertheless the calculation of the position was within the general accuracy of RTK/GNSS without using any optimal filtering. Therefore, it was confirmed that the system would be able to perform remote control using our mating connection mechanism.

ICP matching using point cloud information also succeeded and it was found that there was a possibility that it could be used as a redundant means, however issues such as accurate point cloud extraction of objects remained.

In the future, we plan to develop a system that is able to visualize the position and azimuth of the lifted object in real-time.

Acknowledgment

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Development of BIM-based Design and Inspection Prototype Process for Temporary Works

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Abstract

Temporary work is about 10% of the total construction cost, and affects completeness of a building since it is directly related to the quality of building. However, BIM-based design of temporary work is used as a complement to the 2D design. Furthermore, the inspection and evaluation of temporary facility is carried out only at the self-evaluation of contractor which is so inefficient because the inspectors are spending a lot of time searching for the standards to check and a checklist for the check is also made manually. These are factors that make lower self-evaluation level of the contractor due to missing information or error.

The objective of this research is to develop prototype of temporary work based on BIM for improving the tasks of design and inspection. In this paper, the BIM-based design and inspection work process were defined. Then, the prototype which can design and inspect temporary work was developed based on the BIM library for one of the most typical item. By using the prototype, the BIM library can be used at the design stage to perform the BIM design for the temporary work, so that a high-quality BIM design is possible even if the BIM modeling expert is not present. By automating the generation of checklists, it is possible to prevent human errors that occur due to manual method.

Keywords –

BIM; Temporary work; Design; Inspection

1 Introduction

Installing temporary works in a construction project is about temporarily building and using structures for building the main structure, on the completion of which the temporary works are removed. Even though they are temporary facilities which are used only during the construction period and then removed, installing temporary works takes up about 10% of the total construction cost[1]. And because the task is so important, directly related to construction cost and quality, that its technology decides whether a building project is complete or not, it requires systematic design and inspection. Despite such importance, however, the current BIM-based design of temporary works, which specifically serve to build the main structure, is done exclusively in such a way that after 2D design is completed first, its 3D rendering is used as an accessory tool[2]. Lately, various kinds of research are conducted with a view to applying BIM to the construction industry, but research done on temporary works remains insufficient. For this reason, we are running short of software and professionals specialized in the installation of temporary works, and temporary works design that plays by rule of thumb with 2D drawings causes conflicts among parts, thus leading to the redoing of the work. Therefore, we urgently need to draw up reasonable and scientific temporary work design and management plan[3, 4]. In this light, the ultimate goal of this study is to develop a system that can implement the design and inspection of temporary works and which directly engages in the BIM library-based installation of temporary works. To fulfill the ultimate goal of the study, this paper aims to develop a prototype for the BIM library-based temporary works design and inspection system.

2 Classification of temporary works

Matters related to the technical standard for the temporary works installation in a construction project are specified in the Standard Integrated Construction Codes established by Ministry of Land, Infrastructure & Transport (MOLIT)[5]. The MOLIT Standard Integrated Construction Codes was created in 2016 for efficient management of construction standards. As the past classification standards varied and their details overlapped and clashed for the specifications, the Standard Specification of Building Projects and the Standard Specification of Temporary Works Installation

Table 1. Temporary Works Installation Classification according to Korea Construction Specifications (KCS)

Code Number	Code Name	Code Number	Code Name
21	Temporary works installation	05	Generals on formwork and temporary shoring
10	Generals on Temporary works installation	10	Formwork and temporary shoring for construction of high-rises and high towers
20	Common temporary works installation	15	Formwork and temporary shoring for exposed aggregate concrete
05	On-site temporary works	20	Formwork and temporary shoring for other types of concrete
10	Construction support equipment	60	Scaffold installation
15	Environmental management facilities	05	Generals on scaffold installation
30	Temporary earth retaining work	10	Scaffoldings
40	Cofferdam, construction road, construction access road, temporary stream crossing, bypass	15	Bar grating stair treads and walkway
45	Temporary bridge and road deck panel	70	Safety facilities installation
05	Temporary bridge	05	Generals on safety facilities installation
10	Road deck panel	10	Fall hazard prevention facilities
50	Formwork and temporary shoring	15	Falling objects prevention facilities

were integrated. The Standard Integrated Construction Codes divides into Korean Design Standard (KDS) and Korea Construction Specifications (KCS), each categorizing into Commons, Facilities, and Projects.

The specifications for the temporary works installation are defined in the Facilities of Korea Construction Specifications (KCS) and are managed with Korea Construction Specifications (KCS) as shown in Table 1. KCS is composed of the category of temporary works installation with the code of “21 00 00”, the 8 sub-categories, and 15 sub-sub-categories. The temporary work installation is specified into the different sub-categories of Generals, Materials, and Installation, thus providing installation inspection and measurement information. Therefore, this study taps into the temporary work classification of KCS which quality control construction engineers should use to conduct on-site checks.

3 The BIM-based temporary works design and inspection process

In general, the work system for BIM-based temporary works design is as shown in Figure 1. By acquiring required drawings such as floor plan, elevation drawing, site plan, and section drawing, one figures out what different lines on drawings represent, performs the modeling of parts by eliminating as many unnecessary elements including centerline, dimension line, and text as possible, and arrange on drawings entered attribute data.

The above series of processes can be efficiently handled in a short period of time by BIM design professionals but problematically requires large workforce and much time for SMEs or single-specialty construction companies. By creating and using a BIM library for temporary works and thereby reducing the workforce and time that are put into the BIM modeling, one can lower the barrier to the BIM adoption.

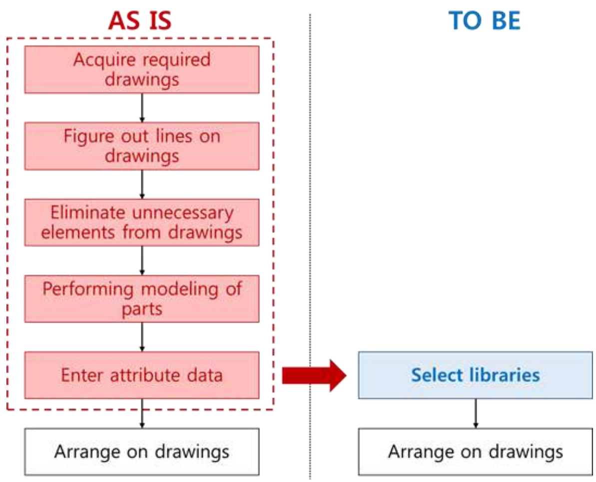

Figure 1. As-Is and To-Be for the work system for BIM-based temporary works design

In general, the builder’s work system for temporary works inspection is divided into the inspection preparation stage and the inspection results processing stage. The work process in the inspection preparation stage involves preparing documents needed for inspection by checking the criteria for the objects of inspection and creating an inspection chart as shown in Figure 2. As it has to extensively search and check various related documents to verify the criteria for the object of inspection, the builder's implementation of the tasks of the inspection preparation stage is inefficient. Furthermore, since the inspection chart for checking its own evaluation is manually prepared, human errors may intervene. This also explains how inefficient work makes the builder work perfunctorily, which downgrades the inspection standards and lowers the quality of facilities. Therefore, to solve the problem, BIM should be used to automatically extract the criteria for temporary works and automatically generate an inspection chart.

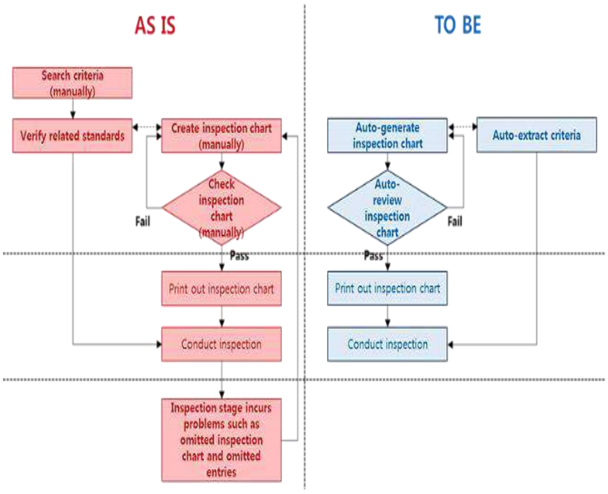

Figure 2. As-Is and To-Be for the Temporary Works Inspection Preparation Stage

Additionally, the work process for the inspection results processing stage involves creating and reviewing the inspection results and therewith creating inspection report, as shown in Figure 3. In processing the inspection results, the builder has to perform all the related tasks manually, which should be automated to minimize data errors and increase work efficiency.

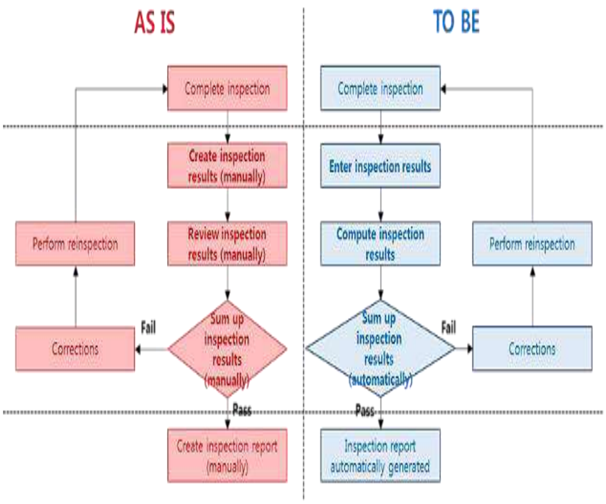

Figure 3. As-Is and To-Be for the Temporary Works Inspection Results Processing Stage

4 A prototype for the BIM-based temporary works design and inspection system

For this paper, I have developed the prototype for the BIM-based temporary works design and inspection system based on Excel by selecting scaffoldings, which are most frequently used and take up the largest cut of the construction budget for the temporary works installation. The algorithm for the BIM library-based temporary work design is as shown in Figure 4.

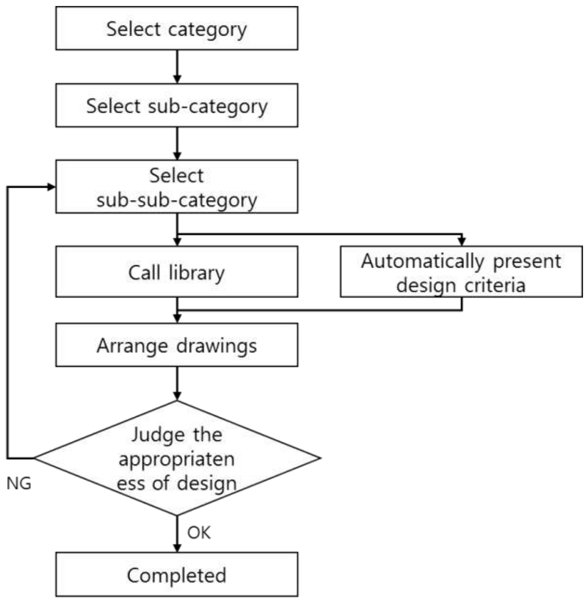

Figure 4. Algorithm for the BIM-Based Temporary Works Design

According to the temporary works classification as described in Table 1, the conditions are selected in categories, sub-categories, and sub-sub-categories to call the library. When the library is called, the criteria that should be applied in designing the current temporary works are automatically presented to minimize design errors and thereby enable the design of the temporary works. Then, the type, structure, and specifications of the designed temporary works are examined to decide if their design is appropriate, and unless something inappropriate is found with them, the design is completed. The prototype for the temporary work design that has been developed based on the algorithm as shown in Figure 4 is as seen in Figure 5.

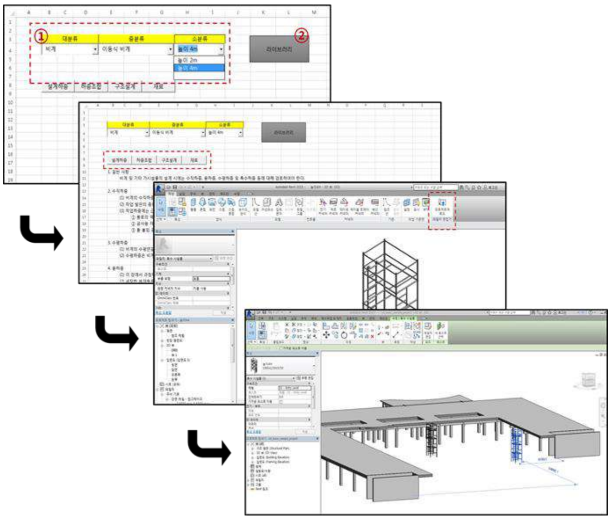

Figure 5. The Prototype for the BIM-Based Temporary Works Design

In this study, the algorithm for the BIM-based temporary works inspection is as shown in Figure 6. The BIM model for the temporary works which is designed based on the BIM library designates and exports attribute data, which is called by the inspection module.

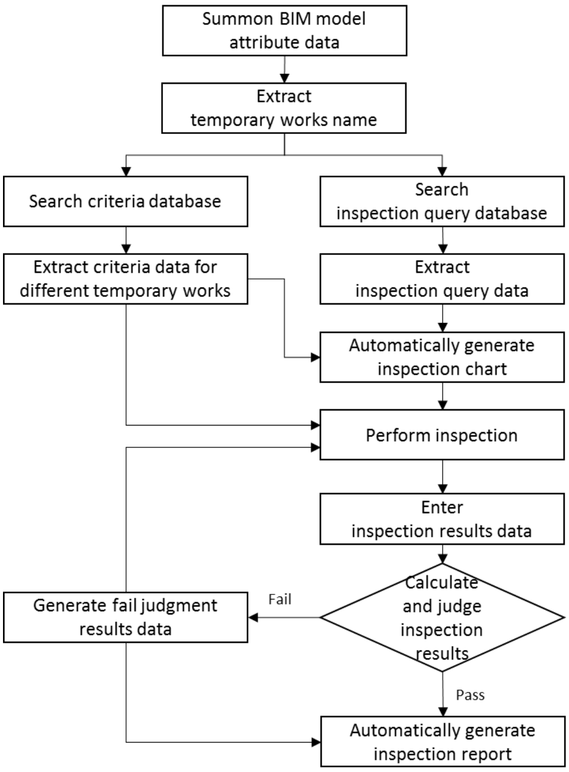

Figure 6. The Algorithm for the BIM-Based Temporary Works Inspection

The criteria database or the inspection query database for generating inspection chart is searched by extracting only the data on the temporary works name from among the summoned attribute data. The criteria shall be extracted for different temporary works through the searched criteria database, while the inspection chart shall be automatically generated by putting into the inspection chart form the temporary work inspection criteria that are extracted from the inspection query database. Also, the results of the inspection for different criteria shall be automatically calculated and judged by putting into the inspection module the inspection results data which are generated after inspection is implemented. By generating the failed criteria with the judgment results, data needed for reinspection is provided, and finally, the inspection report is created.

The prototype for the temporary works inspection system that has been developed based on the algorithm as shown in Figure 6 is as shown in Figure 7.

Figure 7. The Prototype for the BIM-Based Temporary Works Inspection

5 Conclusion

As the tasks of designing and inspecting temporary works are manually implemented in an inefficient manner, there has been concern about human errors and perfunctory operation. Therefore, the study has been conducted for the purpose of increasing the efficiency involved in the construction engineer's design and inspection of the temporary works installation. And looking to improvement, I have presented a prototype for the BIM-based temporary works design and inspection system.

First of all, to accomplish the goal of the study, I have identified the temporary works classification from earlier studies and established the work process for the BIM-based temporary works design and inspection. On this basis, I have developed the algorithm for the BIM-based temporary works design and inspection and the prototype for the system. The BIM-based temporary works design and inspection system as described in this study will greatly reduce the time required for work and automate what is otherwise manual operation, thus preventing human errors and improving the operational convenience.

This study is significant in that as basic research, it has developed a prototype with a view to developing the BIM-based temporary works design and inspection system. However, it has its limitations in that it has failed to complete a system that has perfect functions with regard to its system. Therefore, further research will be carried out to develop a system that can support the design and inspection of the entire temporary works by upgrading and adding functions for a future system

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A BIM-based Conceptual Cost Estimation Model Considering Structural Analysis and Design

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Abstract:

In recent years, considerable concern has arisen over the application of Building Information Modeling (BIM). BIM has been widely utilized for solving the drawbacks of traditional preliminary cost estimation by creating a cost-estimation model. However, since the function of structural analysis and design in BIM is still in its developing stage, the model still lacks precise information of the structural engineering. As a result, the model hypothesizes the structural engineering quantity on the basis of the empirical formula, contributing to a slight inaccuracy in its approximation. Hence, to overcome these shortcomings, this research presents a conceptual cost-estimation model created by linking ETABS (a software used for structural analysis and design of buildings) to the BIM-based model. With the integration of the ETABS and the BIM model, the proposed model can simultaneously consider the two factors (the budget, and the structural analysis) for cost estimation in the early stages of the project: (1) establishing a BIM model on Revit, (2) applying ETABS to conduct structural analysis and design on the BIM model, (3) obtaining quantity takeoffs of the BIM model by Navisworks, (4) retrieving unit price data from PCCES software through results of the quantity takeoffs, and (5) ratifying whether the projected cost meets the owner's budget. The proposed model is tested via a building located on a certain university campus in northern Taiwan. The results show that the proposed conceptual model is significantly superior to the original BIM-based model, and demonstrate that the proposed model can be practically implemented and provide adequate results for the projected cost.

Keywords –

Building Information Model; Cost-Estimation; ETABS; Structural Analysis and Design

1 Introduction

Cost estimation is one of the most critical tasks concerned by all participants in the architecture, engineering, construction, and facilities management (AEC/FM) industry throughout the lifecycle of a building project [1]. In the early stages of conventional construction, there is always enormous and complex information for the cost estimation, causing each cost item can not be calculated and shared accurately in time [2]. Therefore, the management of cost estimation is not only time-consuming but also prone to error. To address the issues, recent years have seen growing importance placed on research in the management of cost estimation.

Building Information Modeling(BIM) as an emerging process and technology has been widely adopted in the building construction industry. BIM is a new approach to design, construction, and facilities management, in which a digital representation of the building process used to facilitate the exchange and interoperability of information in digital format [3]. Through object-oriented concept of BIM, BIM is able to establish the information of each building item and connects it to the cost items to form a BIM-based cost-estimation model. With the increasing usage of BIM, the BIM-based model has been a popular solution for the drawbacks of traditional cost estimation.

However, the BIM-based cost-estimation model still lacks precise information of structural engineering, since functions of structural analysis and design in BIM are still in its developing stage [4]. For example, in the aspect of structural analysis, though it can conduct basic static analysis, and display moment diagrams and structural reactions on the model, advanced analysis is still beyond its ability. As a result, the BIM-based model has trouble with defining the accurate information of structural engineering (beam, column, slab, and wall) crucial to preliminary cost estimation. To overcome the disadvantages, a conceptual model to link ETABS, a professional software used for structural analysis and design of buildings, with BIM is presented in this paper. With the benefits of ETABS, the functions of structural analysis and design of BIM can be enhanced dramatically.

In the paper, we present a conceptual cost-estimation model for linking ETABS and BIM. The paper firstly confers how to integrate the information of ETABS and the BIM software based on the exr. file extension created by Application Programming Interface(API), and discusses the methods of modifying the BIM model when the projected cost doesn't meet the owner's budget. It is hoped that the proposed model will solve the problems about the integration of the accurate information of structural engineering into the BIM-based cost-estimation model, and contribute to a more comprehensive assessment for the civil engineering in the preliminary stages.

2 Review of recent studies

2.1 Structural analysis and design on the basis of BIM

Chang [4] proposed a research that Revit Structure combined ETABS to execute the integration of design. The research firstly established a Revit model subjected to the various external forces. The Revit model with related information was then transferred to ETABS to perform the mechanical analysis and structural design process. Design results were then sent back to BIM platform to renew the members. And since IFC format was not well-developed enough to transfer the structural engineering information between the two software, the research utilized the API as an information transferring interface to renew and create the members. The results found that the data of basic components, such as beams, columns, and plates, could be completely transmitted between the softwares. However, the research was only tested via a simple model, which seems too premature to apply on construction in practical. For example, when the resources in the projects are complicated, whether it will cause other errors related to information delivery between the two softwares, all of which are worthy of being investigated further.

2.2 Applying BIM to estimate construction costs in early stages of projects

Elbeltagi et al. [5] presented a comprehensive cost estimating and monitoring model based on the concept of BIM. With a visualization aid, BIM model could add the color coding help to pinpoint the element clashes, saving considerable time delays and cost wasting. Also, visualization helped construction team to absorb and realize the project information. The results showed that the proposed BIM framework could be considered as an effective tool for the cost estimation in the projects.

Lu et al. [6] thought that traditional method for cost flow analysis were based on the manual integration of time and cost, which was very time-consuming. Therefore, the research presented a BIM-based 5D model of cost estimation on the basis of Navisworks. The research firstly established a BIM model, and took off the properties of items to calculate the quantity of the cost items, which can be stored as a quantity database. The factors of time and cost were subsequently added into the quantity database to create a BIM 5D model. The research utilized this model to analyze the cash flow of the projects. The results found that compared to traditional method, the quantification in Navisworks is simplified and automated, contributing enormous benefits to the cost estimation. What's more, with consideration of time and cost, the whole framework can help contractors analyze the cash flow and make appropriate decisions for different design in construction projects.

Cheung et al. [7] pointed out that current BIM tools were less able to handle concurrency and integration at early design stages, affecting the accuracy of cost estimation; thus, the authors proposed a multi-attribute based tool to address the need to evaluate various aspects of building design, and detailed the cost estimation module that enabled quick and intuitive exploration of early stage design in a 3D environment.

3 Cost estimation of construction practice in the early stages

In the early stages of the projects, a lot of engineering information is still in an uncertain status. Under the condition of limited information, there are, however, some common approaches of preliminary cost estimation in practice, including the cost estimation of Taipei City Government, and the cost estimation of Public Construction Commission of Taiwan. In the end, the chapter will summarize the common parts of these methods to demonstrate the cost-estimation model the research presents is deserving deliberating in depth.

3.1 The cost estimation of Taipei City Government

Taipei City Government divides the cost of the project into direct cost and indirect cost. Direct cost includes structural engineering, decoration engineering, and MEP engineering. The cost of structural engineering (a part of direct cost) is calculated by the total area of the floor multiplied by an empirical value following the rules of Taipei City Government; then, the cost of the other parts of direct cost is calculated by the cost of structural engineering multiplied by an empirical value, and so is indirect cost. In other words, almost all the cost items are presumed by an empirical value (Wang, 2016) [9].

3.2 The cost estimation of Public Construction Commission of Taiwan

Public Construction Commission of Taiwan divides the cost of the project into design cost, indirect cost, price index cost, decoration engineering cost, interest cost, all of which are calculated by direct cost multiplied by an empirical value. And the direct cost is calculated by the area of the floor multiplied by an empirical value. That is to say, like the cost estimation of Taipei City Government, in the preliminary cost estimation, each cost item is involved in a hypothesized calculation (Wang, 2016) [9].

3.3 Summary

From what have been discussed above, we can safely draw a conclusion that due to severe lack of the information of the projects in the early stages, most of cost items' estimation are calculated by an empirical value, especially the cost estimation of Taipei City Government and Public Construction Commission of Taiwan, almost all the cost items are calculated by direct cost multiplied by an empirical value, and the direct cost are calculated on the basis of the cost of the previous projects. Therefore, if the conceptual cost-estimation model the research proposed can be applied into the projects, the problems of scant information in the early stages will be solved by BIM, transmitting the precise information of structural engineering into the preliminary cost estimation.

4 Proposed model

The procedure of the proposed model firstly establishes a BIM model, and then transfers the model to ETABS to conduct structural analysis and design. After analysis and design, the model is then sent back to the BIM software to renew the members, and obtains quantity takeoffs by Navisworks and retrieves unit price data from PCCES software. In the end, the research discusses how to get an alternative cost via the proposed model when the projected cost does not meet the owner's budget. The research selects Revit as the BIM modeling software since it is a commonly-used software in Taiwan. Figure 1 shows the establishment of this proposed model includes five main steps: (1) establishing a BIM model on Revit, (2) applying ETABS to conduct structural analysis and design, (3) obtaining quantity takeoffs by Navisworks, (4) retrieving unit price data from PCCES software, and (5) ratifying whether the projected cost meets the owner's budget.

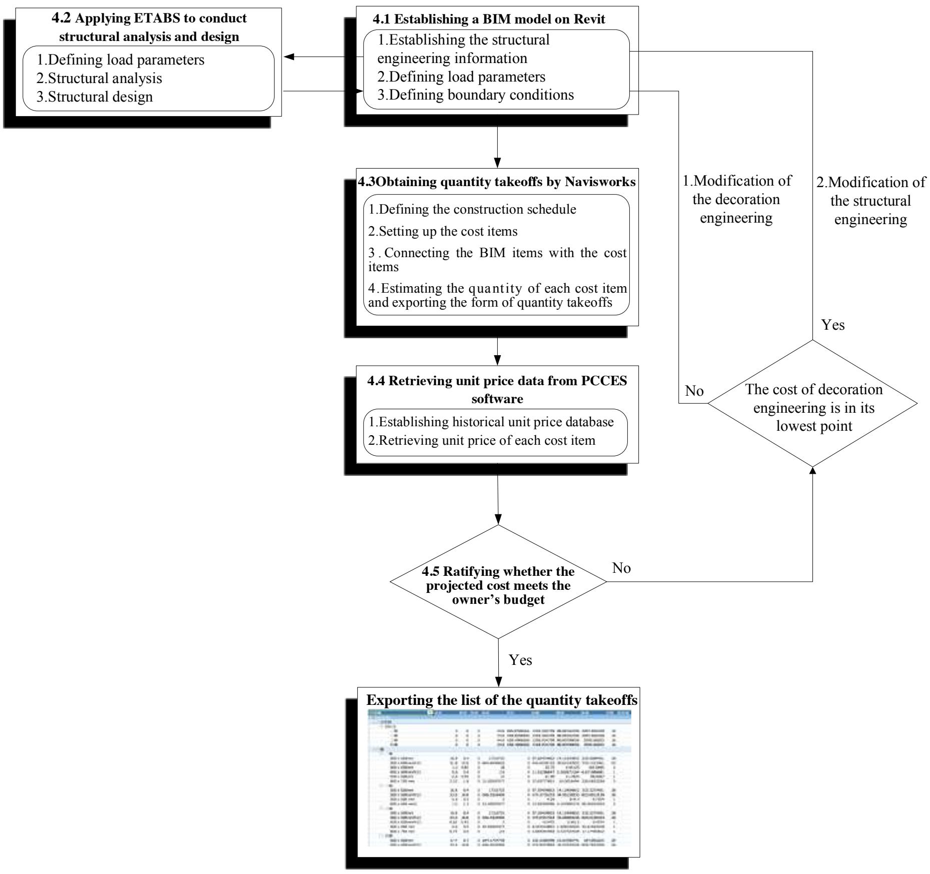

Figure 1. Proposed model

4.1 Establishing a BIM model on Revit

As the BIM handbook [10] noted, when the BIM model needs to conduct structural analysis and design, there are three requirements for the BIM model: 1. establishing the structural engineering information 2. defining load parameters 3. defining boundary conditions.

After establishing the Revit model on the basis of the three requirements, the research utilizes Application Programming Interface (API) as the intermediary of information interoperability between Revit and ETABS instead of Industry Foundation Classes (IFC), since IFC is not functional enough to transfer comprehensive information between ETABS and Revit, causing some elements, such as beams, essential to structural analysis are missed in the transferring process.

On the contrary, the API is capable of exporting the Revit and ETABS model into an exr. file extension to provide a shared format for the two softwares. The API has four functions, "Import to Create New Revit Project from ETABS SAFE or SAP2000 Model", "Import to Update Existing Revit Structure Model from ETABS", "Export to Create New ETABS SAFE or SAP2000 Model", and "Export to Update Existing ETABS Model". Through the functions of the API, the Revit and ETABS models are able to be renewed and established.

The research exports the Revit model into an exr. file extension by the function of the API, "Export to Create New ETABS SAFE or SAP2000 Model", and imports it into ETABS to create a new ETABS model.

There are two categories of the information the exr. file extension is imported into ETABS, the detectable and the undetectable category. The detectable information is the items of structural engineering, including grid, column, beam, wall, slab, boundary condition, and load while the undetectable information is mainly the items of architectural engineering (window, door…etc.) and some structural material properties (density of material and mechanical properties of material), all of which will notify the users in the form of a red signal through the window of the API.

For the undetectable information, the research adds physical properties of the material in the Revit model, or replenishes the structural properties of the undetectable information to transform information from the undetectable into the detectable one.

4.2 Applying ETABS to conduct structural analysis and design

However, to conduct complete structural analysis and design, there is still relatively little information imported from the Revit model; thus, the research needs to define more parameters in ETABS, and requires more professional functions of structural analysis and design from ETABS. The process of structural analysis and design includes three main steps: 1. defining load parameters, 2. structural analysis, 3. structural design.

After structural analysis and design, the information of the ETABS model is imported into the Revit model by the function of API, Import to Update Existing Revit Structure Model from ETABS, renewing the Revit model based on the results of structural analysis and design.

There are two categories of the information the exr. file extension imported into Revit, the detectable and the undetectable category. The detectable information includes grid, column, beam, wall, slab, boundary condition, and load while the undetectable information is nonlinear elements and parts of analysis and design data (rebar area…etc.).

For the undetectable information, the research sorts out the information of the Excel structural analysis and design summary report; then, add it into the Revit model additionally.

After importing ETABS information to Revit, the Revit model is still able to be modified and established, and the information of the Revit model established before being imported to ETABS can be preserved after the structural analysis and design.

4.3 Obtaining quantity takeoffs by Navisworks

To estimate the projected cost after structural analysis and design, the cost estimation is divided into two steps, quantity takeoffs and retrieving unit price data. The research selects Navisworks as the quantity takeoffs BIM software since the system of Navisworks is the same as Revit's, which can reduce the errors of interoperability of information.

To establish a new Navisworks model, the research imports the rvt. file created by Revit into Navisworks by the function of Navisworks, Append, which can record the path of archive and renew the information between the two softwares in time. In doing so, the results of quantity takeoffs can be updated when the Revit model is modified.

After importing the rvt. file into Navisworks, all the information is detectable, such as area and volume. And if the projects need to add additional information into the Navisworks model, the users can utilize the function of Navisworks, "Add New Property".

Through the windows of Navisworks Quantification," Quantification Workbook", "Item Catalog", and "Resource Catalog", the process of quantity takeoffs includes four main steps: 1. defining the construction schedule, 2. setting up the cost items, 3. connecting the BIM items with the cost items, 4. estimating the quantity of each cost item and exporting the form of quantity takeoffs.

After the four steps, Quantification Workbook displays a form of the quantity of each cost item, which can be exported into an Excel form. The Excel form of quantity takeoffs can be divided into different types of forms, including item-pivoted or resource-pivoted forms. For the project, the research selects resource-pivoted forms as the quantity takeoffs form.

4.4 Retrieving unit price data from PCCES software

After sorting out the results of the quantity takeoffs, the quantity takeoffs retrieves unit price from PCCES software to estimate the projected cost. The research selects PCCES as the software of unit price database. And, the process of retrieving unit price from includes two main steps: 1. establishing historical unit price database, 2. retrieving unit price of each cost item.

4.5 Ratifying whether the projected cost meets the owner's budget.

To measure up the requirements of the construction in practical, the research ratifies whether the projected cost meets the owner's budget. In this section, the research hypothesizes the projected cost does not meet the owner's budget, and modifies the model to adjust the cost. The research proposes a scheme to reintegrate the building information for an alternated projected cost on the basis of the proposed model.

Base on the condition of the construction in practice, the modification of the model can be divided into two parts, "decoration engineering" and" structural engineering", and the sequence of the two modifications is first decoration engineering and then structural engineering in the order of complication. Firstly, the modification of decoration engineering includes paint, tile…etc. Since decoration engineering is not in the consideration of structural analysis and design and interior design, the modification of decoration can skip the process of structural analysis and design. When the cost of the decoration engineering has already been decreased to its lowest point, the modification of structural engineering is the next option; the modification of structural engineering includes beam, column, slab, and wall. It requires to not only reanalyze and redesign the structure but also inspect if the interior design corresponds to the laws of the government and the request of the owner. Therefore, the research utilizes the function of API, "Export to Update Existing ETABS Model", to provide an update regarding to the modification of structural engineering to the ETABS model. In doing so, the preprocess of structural analysis and design (defining load parameters) can be skipped.

5 Case study

The proposed model is tested via a building located on a certain university campus in northern Taiwan, as presented in Figure 2 The building was finished in 1982, main building material is reinforced concrete, four floors with no basements, and total area of the floor is 5814.83 ㎡.

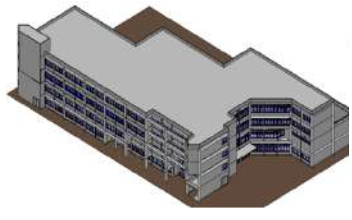

Figure 2. The tested Revit model

5.1 Establishing a BIM model on Revit

The research creates a new project on the construction template in Revit, and builds columns, beams, slabs, and walls respectively; dead load is the weight of the building, which is 0.5KN/m^2, and live load is 2.5KN/m^2, following the rules of the government, and then, assign the loads to the slabs in an uniform distribution; the research sets the boundary conditions as the fixed one at the junctions of columns and ground.

After establishment of the Revit model, the research utilizes the function of API, "Export to Create New ETABS Model", to export grid, column, beam, wall, slab, boundary condition, and load of the Revit model to create a new ETABS model. The results show the items of the Revit model are successfully detected in ETABS, and the ETABS model is able to be modified.

5.2 Applying ETABS to conduct structural analysis and design

The process of ETABS structural analysis and design includes three main steps: 1. defining load parameters, 2. structural analysis, 3. structural design.

After structural analysis and design, the research utilizes the function of API, "Import to Update Existing Revit Structure Model from ETABS", to import information of the ETABS model to update the Revit model, and export the results into an Excel summary report.

To perform the cost estimation, the research establishes the other engineering items, such as ceiling, tile, excavation, skirting, slope protection, and flooring, and then exports the Revit model into a rvt. file.

5.3 Obtaining quantity takeoffs by Navisworks

The research imports the rvt. file into Navisworks by the function of "Append". The items for quantity takeoffs includes geotechnical engineering (excavation and slope protection), structural engineering (concrete, rebar, and formwork), and decoration engineering (ceiling, skirting, flooring, paint, and tile). Furthermore, to retrieve unit price of each cost item, the quantity takeoffs unit of each cost item is the area or volume of the material.

The process of Navisworks quantity takeoffs includes four main steps: 1. defining the construction schedule, 2. setting up the cost items, 3. connecting the BIM items with the cost items, 4. estimating the quantity of each cost item and exporting the form of quantity takeoffs. After the quantity takeoffs, the results are sorted out in Table 2.

5.4 Retrieving unit price data from PCCES software

The quantity takeoffs retrieve unit price from PCCES software to estimate the projected cost. The process of retrieving unit price from includes two main steps: 1. establishing historical unit price database, 2. retrieving unit price of each cost item. Table 2 is the detail of the projected cost; the total projected cost is 38,266,229 NTD.

Table 1 The list of the projected cost

Engineering items	Quantity	Unit	Price (NTD)	Cost (NTD)
reinforced concrete 280kgf/cm^2	3,974	M^3	2,115	8,405,010
rebar SD280	395	T	15,673	6,190,835
rebar SD420	104	T	16,432	1,708,928
formwork	19,817	M^2	332	6,579,244
excavation	4,382	M^3	166	727,412
light-gauge steel frame	5,930	M^2	873	5,176,890
red paint	161	M^3	710	114,310
granitic tile	1,902	M^2	4,000	7,608,000
flooring	5,852	M^2	300	1,755,600
			Total	38,266,229

5.5 Ratifying whether the projected cost meets the owner's budget

The projected cost presented above is about thirty-eight million and three hundred thousand NTD; in contrast, the research hypothesizes the owner's budget is thirty-six million NTD, the difference is about two million and three hundred thousand NTD. Therefore, the research provides an alternated project to meet the owner's budget, which includes two modifications: 1. the modification of the decoration engineering 2. the modification of the structural engineering.

1. The modification of the decoration engineering

To decrease the projected cost, the research changes the granitic tile into cheaper tiles, grey-faced tile, and also modifies the red paint and the light-gauge steel frame of the floors into the cheaper materials.

Since the Navisworks model was established by the function, "Append", the modification can be updated to the Navisworks model by the function, "Refresh". In this way, the cost items do not have to reconnect with the BIM items; then, the results of the quantity takeoffs can be renewed.

On the condition of the lowest cost of the decoration engineering, Table 2 shows that the original projected cost decreases about sixty hundred thousand NTD, which is still a gap of one million seven hundred thousand NTD between the alternated projected cost and the owner's budget. Hence, the research modifies the structural engineering items.

Table 2 The list of the projected cost after the modification of the decoration engineering

Engineering items	Quantity	Unit	Price (NTD)	Cost (NTD)
reinforced concrete 280kgf/cm^2	3,974	M^3	2,115	8,405,010
rebar SD280	395	T	13,412	6,190,835
rebar SD420	104	T	15,000	1,708,928
formwork	19,817	M^2	332	6,579,244
excavation	4,382	M^3	166	727,412
light-gauge steel frame	5,930	M^2	873	5,176,890
red paint	161	M^3	650	104,650

granitic tile	1,902	M^2	3,700	7,037,400
flooring	5,852	M^2	300	1,755,600
			Total	37,685,969

2. The modification of the structural engineering

To decrease another one million seven hundred thousand dollars, the research deletes the partial area of the third and fourth floor, decreasing the number of columns, beams, slabs, walls and rebar, as presented in Figure 3.

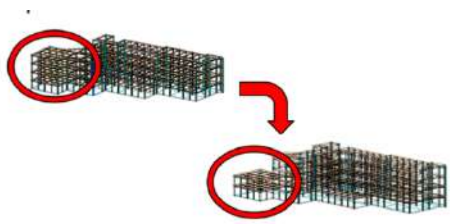

Figure 3. The modification of the structural engineering

The research updates the ETABS model by the function of API, "Export to Update Existing ETABS Model", and then conducts the structural analysis and design again.

After analysis and design, if there are deleted items in the Revit model, the steps of the quantity takeoffs are the same as the modification of the decoration engineering, which do not need to reconnect the cost items and the BIM items; however, if there are added items in the Revit model, it is necessary to reconnect the cost items and the BIM items in Navisworks.

The results show that after the structural engineering modification, the alternated projected cost decreases another two million NTD. In summary, these two modifications decrease two million and six hundred thousand NTD, which meets the budget of the owner, as presented in Table 3.

Table 3 The list of the projected cost after the modification of the decoration engineering and structural engineering

Engineering items	Quantity	Unit	Price (NTD)	Cost (NTD)
reinforced concrete 280kgf/cm^2	3,654	M^3	2,115	7,728,210
rebar SD280	379	T	15,673	5,940,067
rebar SD420	92	T	16,432	1,511,744
formwork	19,017	M^2	332	6,313,644
excavation	4,382	M^3	166	727,412
light-gauge steel frame	5,560	M^2	873	4,853,880
red paint	154	M^3	650	100,100
granitic tile	1,820	M^2	3,700	6,734,000
flooring	5,427	M^2	300	1,641,600
			Total	35,550,657

Through the hypothesis, it's proved that the proposed model is capable of developing an alternated projected cost on the basis of interoperability of information; hence, if the proposed model can be applied on the projects in practice, the projects will have the ability to adjust the cost to meet the owner's cost precisely and smoothly, and also through the comparison between the original projected cost and the alternated projected cost, the owner will have a more comprehensive understanding of the current condition of the projects, achieving the goal of the projected construction cost in the early stages.

6 Discussion of the results

The research compares the proposed model with the model of the preliminary cost estimation Wang et al. [11] proposed. In the two models, the common part is the application of BIM on the quantity takeoffs; in addition, the cost items, the unit price of the cost items, and the tested building are identical while the main difference is the consideration of structural analysis and design, which contributes to different quantity of structural engineering. Therefore, the research discusses the margin of the two projected cost to prove the proposed model has the beneficial effect on the cost estimation in the early stages.

The projected cost of Wang et al. [11] is 42,190,382 NTD, which is a 10% difference between the two projected cost. That is to say, the difference between the projected cost of structural and non-structural analysis and design can be up to 10%, which is unacceptable to the preliminary cost estimation. The difference will not only produce the difficulties on the management of the projects in the late stages, but also influence the progress of the construction. In conclusion, the preliminary cost estimation of the projects should put the structural analysis and design into consideration.

7 Conclusions and suggestions

In civil engineering, a recent surge of research on BIM has given us new opportunities and solutions for the issues of the cost estimation in the early stages. However, since the structural analysis and design of BIM is still in its infancy, there is still a strong assumption of the quantity of the structural engineering. Hence, the purpose of the research is to present a conceptual cost estimation model to better control the details of the projected cost in the early stages.

After the test, through the BIM-based conceptual cost-estimation model considering structural analysis and design, the research successfully estimates a projected preliminary cost, and is also able to alter the cost within the owner's budget. In addition, the research compares the proposed model with the preliminary cost-estimation model Wang et al. [11] proposed. The result of the comparison concludes with certainty the proposed model is feasible. In the end, the research hopes the proposed model should be of importance in the applications of constructions and provide a more comprehensive functions to the lifecycle of the projects.

Three of the suggestions are worth summarizing:(1) The interoperability of information between ETABS and Revit is still defective. For example, the damper cannot be identified in the exr. file extension. Therefore, the research suggests that an area of future research that should be considered is how to enhance the accuracy of the interoperability of information between ETABS and Revit. (2) There are a variety of BIM softwares, and so as the softwares of structural analysis and design. Perhaps future research could examine the interoperability of information between different BIM softwares and structural analysis and design softwares to refine the functions of BIM structural analysis and design. (3) In this research, the model is tested via a RC building and Taiwan architectural laws and guidelines. In the future, the research suggests the other researchers can adopt this conceptual model in different scenarios, such steel building or other countries' laws and guidelines, and accumulate all these implements to form a dynamic database. According to different scenarios, the dynamic database will enhance the ability of the proposed model by providing a wider range of applicability.

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Knowledge Base for a Disaster Management Dialogue System

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Abstract –

This research aims to develop a knowledge base for a disaster management question-answering dialogue system. The rapid growth of the amount of data has led to the variance of data in terms of their formats, sources, and attributes. Hence, the difficulties of decision makers to accomplish their missions accurately and efficiently have increased. To solve this problem, we developed a question-answering dialogue system for disaster management.

In our previous research, we found that the information most likely retrieved in response to a user's request can be determined by calculating the similarity between the keywords and the user's input in a handcrafted keyword–information mapping table. However, we also noticed that managing the mapping table was a tedious task. Moreover, for the inputs that had more than one keyword, the system was unable to provide integrated information. Therefore, we constructed a knowledge base to optimize the performance and maintainability of the system.

To build the knowledge base for disaster management, we designed the domain model by performing an abstraction on the knowledge of professional information providers and the required data on disaster management, while considering their source, certainty, and spatiotemporal features.

The query of requested information from the knowledge base is composed of mentioned entities in the user's input. For the dialogue system to recognize the entities, we applied entity recognition. The subtasks include segmentation, tagging, similarity calculation with the names of the entities in the knowledge base, and intent detection to determine the desired knowledge of the user.

Keywords –

Knowledge base; Disaster management; Entity Recognition

1 Introduction

With the advance of information technology, the capabilities of massive data storage and data productivity have triggered an evolution in the usage of information, especially in the area of disaster management. Decision making in disaster management relies on the gathered information and the knowledge of decision makers. Due to the rapid growth of the amount of data, more data and information are being consumed now than in the past. This has led to the variance of data in terms of their format, source, and attributes, which has in turn increased the difficulties of the decision makers to accomplish their mission accurately and efficiently.

To assist the decision makers in efficiently and accurately utilizing, selecting, and processing information, we developed a dialogue system for disaster management. The dialogue system is based on text input by the decision makers using their devices, such as smartphones or tablets. It provides the data, information, and corpora for the topic of interest by treating the user's inputs as queries.

In our previous research, for providing information and data to the user, we developed a handcrafted keyword–information mapping table and used a fuzzy search algorithm. By searching keywords in the user's input, the system provides the most suitable information from the table to the user. During the implementation, we noticed that it was tedious to manage the keywords and information in the mapping table. In addition, a user experience test revealed that for the inputs that had more than one keyword, instead of providing integrated information, the system could only retrieve the part that mapped to one of the keywords. Therefore, we constructed a knowledge base to optimize the performance and maintainability of the system.

To build the knowledge base for disaster management, we designed a domain model to describe the knowledge base. The domain model is often used in software engineering and ontology engineering. We performed an abstraction on the knowledge of professional information providers and the required data on disaster management, while considering their source, certainty, and spatiotemporal features. A diagram composed of the models, the slots of the models, and the relations between the models was developed. The entities of the knowledge base are later used to recognize entities in the user's inputs. By entity recognition, the intent of the user and the proper response to the user's query can be determined.

2 Previous Research

We developed a dialogue system to provide data to the decision makers of the Water Resources Agency in Taiwan. The language of the dialogue system is Chinese, and the system is implemented as a chatter bot via LINE, a commonly used messaging application in Taiwan.

2.1 Algorithm

To determine the proper responses to a user's request, we developed a handcrafted keyword–information mapping table on the basis of experiments and the needs of the staff and decision makers of the agency. By searching listed keywords in the user's input, the system provides the most suitable information from the table to the user.

The matching of keywords from the user inputs and mapping table are sorted by the similarity of strings. Unlike in English, there is no space in a sentence to segment words in Chinese; therefore, we simply regarded each character as a single token, instead of using a single word as a token.

The similarity is calculated by comparing the number of same characters in the input text and each keyword in the mapping table, using Equation (1).

$$sim(d_j, q) = \frac{\sum_{i=1}^{t} f_{i,j}}{t} \tag{1}$$

- d_j is the j-th text from the corpus of the system.
- q is the user's input.
- t is the number of tokens in the user's input. The tokens are the characters of the text in this case.
- $f_{i,j}$ is the count of appearance of the i-th token in the user's input in the j-th text from the corpus of the system.

For the keyword(s) with a similarity score of 1.0, the system returns the information related to the keyword(s) to the user. If none of the keywords has a similarity score of 1.0, the system returns a list of keywords with a similarity score that is higher than 0.5 to the user so that the user can improve the inputs.

2.2 User Test

The system was tested by the staff of the Water Resources Agency. The users pointed out the following flaws in the system performance:

- Lack of reaction to stickers.
- Requirement of adjusting the views of data presented by tables. Tables are often too small when displayed on smart phones.
- Poor performance in case of long inputs.
- Poor performance in realizing natural language.

In addition, during the user test, in some given tasks for testing that required integrating different types of data, the time taken for accomplishing those tasks was higher than for easier tasks. Instead of retrieving all of the requested information simultaneously, the users had to split the input into fundamental queries to retrieve one part of the information at one time.

2.3 System Management and Maintenance

The keyword–information mapping table was directly handcrafted in the system codes. Hence, it was tedious and difficult to manage the keywords and information in the mapping table. Moreover, it resulted in a lack of flexibility in extending the mapping table, making the task of improving the system performance challenging.

3 Objective

The objective of this research is to develop a knowledge base for improving the ability of the dialogue system to perform the following:

1. Recognize the intent and provide the information requested through user inputs.
2. Respond with proper information depending on the user's request.
3. Provide a better solution for managing data.

To meet these objectives, we developed a knowledge base for disaster management, a system for processing the user input to retrieve the information sought, and a user-friendly console for the system.

4 Methodology

The methodology includes two parts: knowledge base and named entity recognition. The knowledge base stores and provides information, data, and knowledge. Named entity recognition completes the task of recognizing the intent and given information in the user's input.

4.1 Knowledge Base

4.1.1 Overview

A knowledge base is a manually compiled knowledge collection [1]. Knowledge is extracted into entities, relations, and attributes in a knowledge base. A knowledge base can be used to enable intelligent applications such as question answering [2]. The successful integration of a question-answering system prompted us to develop a knowledge base of the required information for management decision making in water-resource-related disasters.

Information extraction techniques are used in the construction and update of knowledge bases. Two types of information extraction methods exist: rule-based and statistical methods. Specifically, rule-based methods are more useful in closed domains where human involvement is both essential and available [3]; hence, we chose a rule-base method for information extraction in our study.

4.1.2 Domain Model

We performed an abstraction on information and data by discussing with the experts from the staff and information providers of the Water Resources Agency. By considering the source, certainty, and spatiotemporal features of the required data on disaster management, we designed a domain model as the model of the knowledge base. The domain model describes the structure of the knowledge base. Models of the domain model are the abstraction of knowledge, data, and information. The entity-relationship model (ER model) diagram is applied as a visualization tool for the system engineer and the disaster management experts to discuss and verify the domain model. The model, slot of attributes, and relation between entities can thus be defined.

The entity in the knowledge base is the instance of the model in the domain model. The attribute of entities is the slot of models filled with values. The relation between entities in the knowledge base is the relation in the domain model. The roles of the from-end and to-end models/entities are defined in association with the relation in the domain model.

4.1.3 Challenges

One of the main challenges in the construction is that the requested information during disaster management may be in the form of streaming data [4]. Therefore, the knowledge base should be capable of updating data in a timely manner. Data can be categorized into two types:

- Static data: data that seldom change, such as the name and location of facilities.
- Streaming data: temporally updating or increasing data, such as observations of precipitation and water levels, logs of transportation resources, meetings, and operations during disaster events.

In the implementation, streaming data are collected from the application programming interface (API) of the information system of the Water Resources Agency. When the data are updated, we archive them into the database of our system in the originally provided format, and extract them using the related model of the domain model into the knowledge base.

The other challenge is that the source of different data and information varies. The requested data of the Water Resources Agency may be provided by other government institutions such as the Central Weather Bureau. In our research, we focus on the data provided by the Water Resources Agency alone.

4.2 Named Entity Recognition

4.2.1 Overview

Named entity recognition (NER) is one of the tasks in information extraction and its purpose is to recognize the entities mentioned in documents. In our research, NER is applied to recognize entities in the user's input in order to query requested information from the knowledge base.

4.2.2 Segmentation and Tagging

The input text is segmented for retrieving a list of words. In addition, position-of-speech (POS) tagging is used to determine the type of each word. Nouns are regarded as candidate entities for later comparisons with the entities in the knowledge base.

In addition, words or phrases tagged as time are extracted and transformed into date/time objects in the system using handcrafted rules. For example, if "yesterday" appears in the input text, it will be transformed into the absolute date of the previous day.

4.2.3 Similarity Calculation

After retrieving a list of nouns, by searching the names of entities and models, the system can recognize the entities or mentioned models in the input and retrieve the requested information from the knowledge base. The type (e.g., location, person, and not-categorized) and content (i.e., the exact text of the word) of the nouns will be compared with the following:

- Names of entities in the knowledge base.
- Names of slots for attributes of the entities.
- Data types of attributes of the entities.
- Values of attributes of the entities.
- Names of models in the domain model.
- Names of slots of the models.
- Data types of slots of the models.
- Names of relations in the knowledge base and the domain model.
- Names of roles of two related entities or models.

The texts mentioned above compose a corpus of the system. The similarity of words in the user's input and the texts from the corpus are calculated using the cosine similarity by treating the texts as vectors in a vector space.

Each character plays the role of a unit vector on different dimensions of the vector space. The vector representing each word is composed of unit vectors, and the weights of unit vectors are determined by text model term frequency–inverse document frequency (tf–idf). The similarity of a word in the user's input and the text from the corpus of the system is calculated using Equations (2), (3), and (4).

$$sim(d_j, q) = \frac{\sum_{i=1}^{t} w_{i,j} \times w_{i,q}}{\sqrt{\sum_{i=1}^{t} w_{i,j}^2} \times \sqrt{\sum_{i=1}^{t} w_{i,q}^2}} \quad (2)$$

$$w_{i,q} = (1 + \log f_{i,q}) \times \log \frac{N}{n_i} \quad (3)$$

$$w_{i,j} = (1 + \log f_{i,j}) \times \log \frac{N}{n_i} \quad (4)$$

- d_j is the j-th text from the corpus of the system.
- q is the user's input.
- t is the number of tokens in the user's input. The tokens are the characters of the text in this case.
- $w_{i,j}$ is the weight of the i-th token in the user's input in the j-th text from the corpus of the system.
- $w_{i,q}$ is the weight of the i-th token in the user's input in the input itself.
- $f_{i,j}$ is the count of appearance of the i-th token in the user's input in the j-th text from the corpus of the system.
- $f_{i,q}$ is the count of appearance of the i-th token in the user's input in the input itself.
- N is the number of the texts in the corpus of the system.
- n_i is the number that contains the i-th token of the user's input.

The nouns from the user's input will be regarded as the entities or models whose related text has a higher similarity score than the given threshold.

4.2.4 Intent Detection

If the name of any model in the domain model is recognized in the user's input, the model(s) will be treated as the intent of the user's request. The desired instances of the intent model(s) will be retrieved from the knowledge base by filtering by other recognized entities and date/time objects extracted from the user's request.

On the other hand, if only entities are recognized, the system will return the entities and links to related entities to the user for further usage.

5 Implementation

5.1 Domain Model

There are, in total, 43 models, 214 attributes, and 126 relations in the domain model. The relations can be categorized into 53 types.

Table 1. Information of models in the domain model. Type 1 refers to static data while type 2 refers to streaming data.

Model name	Type	# of slots
Institution	1	2
WRA Affiliation	1	3
Region	1	2
Village	1	3
Town	1	7
County	1	3
Reservoir	1	13
Storage	1	4
Rain Station	1	4
Water Level Station	1	6
Response Event	1	4
Operation Log	1	2
Operation Standard	1	1
Flood Operation Condition	1	4
Typhoon Operation Condition	1	3
Drought Operation Condition	1	3
River Basin	1	2
River	1	2
Rain Warning	1	4
Water Level Warning	1	4
Reservoir Warning	1	8
Flood Disaster	2	5
Typhoon Disaster	2	12
Drought Disaster	2	4
Provider	1	6
Source	1	2
Equipment Kind	1	2
Equipment Model	1	3
Equipment Log	2	5
Time Interval	1	3
Rain Observation	2	6
Meeting Kind	1	3
Meeting Log	2	3
Meeting Reference	2	3
Pump Model	1	2
Pump	1	2
Pump Log	2	8
Reservoir Observation	2	17
Flood Situation Log	2	14
Facility Situation Log	2	14
Warning Kind	1	2
Warning Log	2	4
Water Level Observation	2	6

Table 2. Information of relations in the domain model.

Relation name	From role	To role	Count
supervised by	supervisee	supervisor	2
as	main	alias	1
follow	institution	standard	2
publish	institution	warning	2
supervise	supervisor	supervisee	2
supervise	institution	district	1
own	owner	object	2
supervise	institution	river basin	2
have	institution	log	2
as	alias	main	1
locate at	district	district	3
warned by	district	warning	3
contain	district	district	3
contain	district	facility	4
warned by	district	facility	1
have	district	log	3
supervised by	district	institution	1
watch	facility	warning	3
observe	facility	observation	3
locate at	facility	district	4
have	facility	log	1
owned by	object	institution	1
locate at	facility	river basin	3
have	instance	log	3
occur at	log	instance	1
originate from	log	standard	1
result in	standard	log	1
consider	standard	condition	3
follow by	standard	institution	1
considered by	condition	standard	3
contain	river basin	facility	3
contain	river basin	rivers	1
supervised by	river basin	institution	2
have	upstream	downstream	1
locate at	river	river basin	1
connect	downstream	upstream	1
watched by	warning	facility	3
warn	warning	district	3
provide	provider	resource	1
publish	source	data	8
provided by	resource	provider	1
categorize	type	instance	7
categorized by	instance	type	7
published by	data	source	9
occur at	log	storage	1
observed at	observation	facility	3
attached with	log	reference	1
occur at	log	event	2
attach to	reference	log	1
owned by	object	owner	1
occur at	log	district	3
of	log	institution	2
published by	kind	institution	1

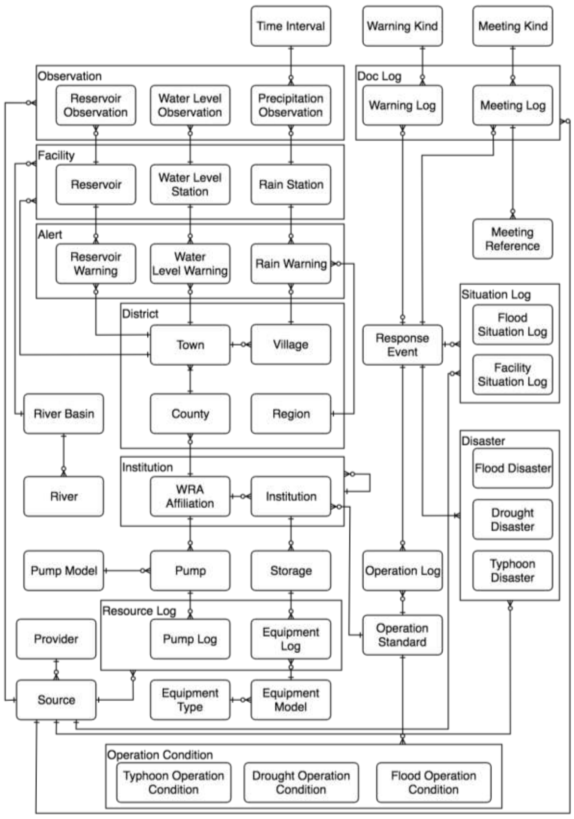

Figure 1. ER model diagram of the domain model.

5.2 System

Python is used in the development. Each part of the system is constructed using the various Python libraries or modules:

1. Jieba [5]: Chinese text segmentation module, used for the segmentation and POS tagging of the user's input. The algorithm of Jieba is based on a prefix dictionary structure to achieve efficient word graph scanning. The dictionary of Jieba can be extended.
2. Django [6]: The web framework consists of an object-relational mapper (ORM), which mediates between models of data and relational databases, used for implementing the domain model and the knowledge base. The domain model is implemented by the ORM, and the data of entities are stored in the database. By mediations using the ORM, the data can be transformed back to entities. It also provides an automatically generated graphical user interface (GUI) console for managing the data in the system.

In development, SQLite3 is chosen as the database for testing and validation.

First, static data and information are added directly to the knowledge base using the domain model. Second, the API listener of the system checks up the APIs of streaming data. If an update is detected, the system archives the newest data in original formats, transforms the data into entities using the models, and adds them to the knowledge base.

After the construction of the knowledge base, the Jieba dictionary is extended by adding texts from the corpus of the system, which is mentioned in 4.2.3. To increase the capability of referring the different names of the same entities, models, slots, and relations, aliases are attached to them, which are also added to the Jieba dictionary.

The transformation of words or phrases tagged as time is done by rules written in regular expressions and compiled in Python. They are transformed into native Python date/time objects and can be used as the attributes of entities or the slot values of models directly.

The data can be managed on the automatically generated console. Adding, modifying, and deleting data on the new system is much easier than on the original one.

The entire system runs as a web application. It receives the messages from LINE, following which the proper information is processed and returned to LINE.

6 Results and Discussion

In the current progress, we focus on recognizing and retrieving requested information by direct relation to other mentioned entities, such as facilities with their locations, in the user's input. By adjusting the threshold of similarity to 0.9 and adding handcrafted rules to improve the accuracy of recognition, the system can currently retrieve requested information from the knowledge base.

For example, when the system receives the text, "Tell me the Rain stations in Taipei City (告訴我臺北市雨量站)," by entity and model recognition, the system determines that the intent is to retrieve rain stations in Taipei City; therefore, it shows the list of rain stations in Taipei City. On the other hand, when the system receives the text, "Rain stations in the Da-an District of Taipei City (臺北市大安區雨量站)," it recognizes Taipei City and Da-an District as a county-level district and a town-level district, respectively, and then determines that the intent is to retrieve rain stations situated in only the Da-an District of Taipei City instead of the other district in Taichung City, which is also called Da-an; therefore, it shows the list of rain stations in the Da-an District of Taipei City.

However, the system can still not retrieve information that is not directly related to other entities provided in the user's input. In addition, setting the threshold of similarity to 0.9 might lead to missing relevant information. Setting the threshold too low, however, may reduce the retrieval speed, lower the accuracy of recognition, and cost more time and computation resources.

7 Conclusions

In this research, to improve the performance of the dialogue system for disaster management, we developed a knowledge base and designed a recognition process; we implemented the system to recognize the intent and provide the information mentioned in the user's input by replying with accurate information depending on the user's query.

By designing a domain model of the knowledge base through discussions with experts, we developed a system to provide and manage the information requested in disaster management. The knowledge base and the domain model increase the capability of the system in recognizing the user's intent and query.

In future work, to improve the accuracy of intent and entity recognition, the similarity between the keywords and the user's input by considering the slot and relation structure of models will be discussed. In addition, the feature of retrieving the requested data and information that do not directly relate to the mentioned entities in the user's input will be developed.

Acknowledgements

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Marking Robot in Cooperation with Three-Dimensional Measuring Instruments

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Abstract –

The marking robot has been developed for the purpose of streamlining marking operations at power plant construction sites and accelerating equipment installation work. This robot can draw line segments with accuracy of 1 mm or less on floors and walls of the construction site in cooperation with a three-dimensional measuring instrument. In addition, it is possible to write arbitrary characters such as position information of drawn line segments.

The marking robot is mainly composed of a marking mechanism and a wall traveling mechanism. The marking mechanism for drawing line segments and characters has been realized by a combination of a XY plotter and an ink jet printer. The small printer head is attached to the XY plotter instead of a pen. And a prism target for a total station is located just above the nozzle of the printer head. By moving the plotter to the four corners of its movable range and measuring its position, the command value of the cooperative operation of two axes of the plotter necessary for drawing an arbitrary line segment and characters is calculated.

On the other hand, by combining a vacuum suction device and a four wheel drive mechanism, the wall traveling mechanism which makes the marking robot of about 50 kg run on a concrete wall has developed.

In this report, we will report on structure of the marking robot, cooperation method of the robot and three-dimensional measuring instrument, and application case of the robot to construction site.

Keywords –

Marking robot; Three-dimensional measuring; Total station; XY plotter; Ink jet printer; Wall traveling mechanism

1 Introduction

In order to achieve requests for shortening construction period from customers and ensure construction quality in construction and remodelling work of thermal power plants and the like we the construction company actively introduces rationalization using the latest technologies such as IoT. This report relates to rationalization of marking work at the time of installation of equipment.

When installing equipment at construction sites we draw many lines on floors or walls of the sites as marks which indicate installation positions of equipment, for example positions of anchor bolts, by using surveying instruments such as automatic levels, transits, and tape measures. Normally, this marking work is carried out prior to the installation of each equipment, but as the construction progresses, the already installed equipment becomes interfering matter, which leads to decrease in efficiency of marking work and increase in the cause of mistake.

Therefore, we are planning to introduce a construction method to draw all the markings before the installation work starts. But in the construction work of a large-scale thermal power plant of 1,000 MW class, the number of the marking is more than thousands. Thus, efficient carry out of the marking work is needed for introducing the method. This is reason why we have developed a support system for marking work using a robot.

Here, some examples of previous studies on the marking devices for construction are shown below. First, Ohmoto et al. developed a marking system which consisted of a self-propelled marking robot that had a cross shape stamp, a laser range finder that guided the robot to the marking position, and a total station for accurately positioning of the stamp. By using this, they semi-automated the work to mark the cross lines with 2 mm accuracy on the floors of building construction sites. On the other hand, Yokoyama et al. developed a marking system to mark the positions of anchor bolts for ventilation jet fans mounted on the tunnel ceiling of highways. Their system consisted of a motor driven total station and a marking device. And the marking device had a cross line stamp on XY positioning mechanism at the tip of a cylinder mechanism extending to the ceiling. By using this, they realized high-place work of marking without scaffolding.

As described above, there are already some kinds of the marking system that use the total station to position the cross stamp at marking points. However, what can be obtained by the stamping method is information of "points". On the other hand, in some cases, information of "lines" indicating the installation orientation of the equipment etc. is also important. Furthermore, if the coordinate values of the marked points and lines, and the name of the equipment to be installed, etc. are not clearly indicated in the vicinity of the markings, there is a possibility of incorrect installation work. Therefore, in this research, we decided to develop marking system which can draw arbitrary line segments and characters on floors and walls of plant construction sites by linking with the motor driven total station.

2 Development of Marking System

2.1 Concept of Marking System

The basic requirement specifications considered in developing this system are shown below.

1. To draw arbitrary line segments and characters on indoor and outdoor concrete floors and walls.
2. To draw line segments with position accuracy of 1 mm or less.
3. Work efficiency equivalent to the conventional one.
4. Easy operation of the system.
5. Marking on walls without scaffolding

The basic concept of the system determined based on the above required specification is shown in Figure 1. The system consists mainly of the following three elements.

1. XY plotter type marking robot
2. Motor driven total station
3. Wireless controller of the system

First, the marking robot needs to draw arbitrary characters besides line segments, so we decided to adopt a relatively simple XY plotter system. In addition, to move on the floor and climb the wall the robot is needed a moving mechanism such as motorized wheels and a wall sticking mechanism using vacuum fan. Using the moving mechanism, we aimed to realize marking work on walls without scaffolding. In addition, we considered that the autonomous movement of the robot to marking points stated in the previous studies mentioned in section 1 was a future development item. Therefore, as our first step of the development, an operator of the system moves the robot to marking points with operation of a remote controller.

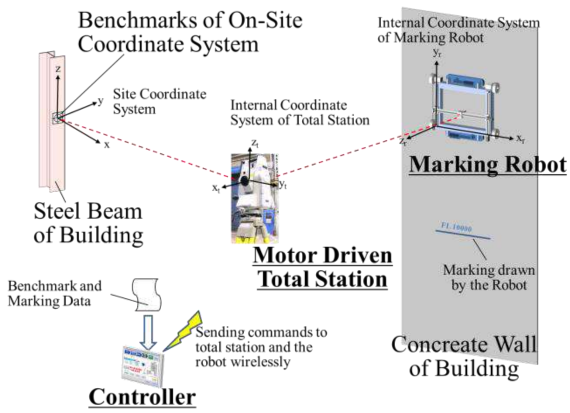


Figure 1. Schematic diagram showing the basic concept of the marking system

The total station is needed as a three-dimensional measuring instrument for grasping positions and orientations of the robot in on-site coordinate system. And the instrument is needed to have measurement accuracy higher than the marking target accuracy of 1 mm. Furthermore, a motor driven one is useful because that can collimate and track prism targets automatically. That can be adopted to automatic measurement of positions and orientations of the robot etc.

The wireless controller of the system is a general tablet PC on which software dedicated to this system was installed. From the controller, various commands to total stations and the robot are given wirelessly. The system operator inputs information such as coordinate values of benchmarks and line segments to be drawn to the controller in advance of the marking work. Based on the inputted information and measurement results of the benchmarks and the robot, the system gives the robot the motion command of the XY plotter necessary for marking.

2.2 Development of Marking Robot

The appearance of the marking robot developed based on the concept mentioned above is shown in Figure 2. And representative specifications such as external dimensions are shown in Table 1. On the other hand, the appearance of the total station adopted to the system is shown in Figure 3. And representative specifications such as measurement accuracy are shown in Table 2.

The robot consists mainly of a marking mechanism, a wall traveling mechanism, and a control unit of those two mechanisms. The following sections explain the concrete contents of each mechanism.

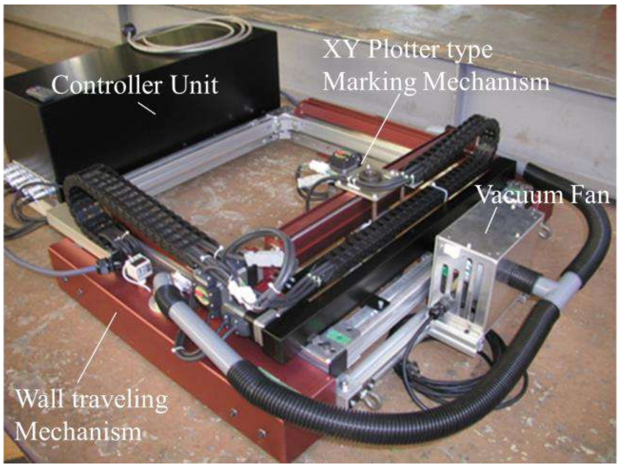


Figure 2. Appearance of the marking robot

Table 1. Specification of the marking robot

Item	Specification
Dimension (mm)	L:1,500 x D:1,000 x H:400
Weight (kg)	56
Main material	Aluminum
Power supply	A/C 100V

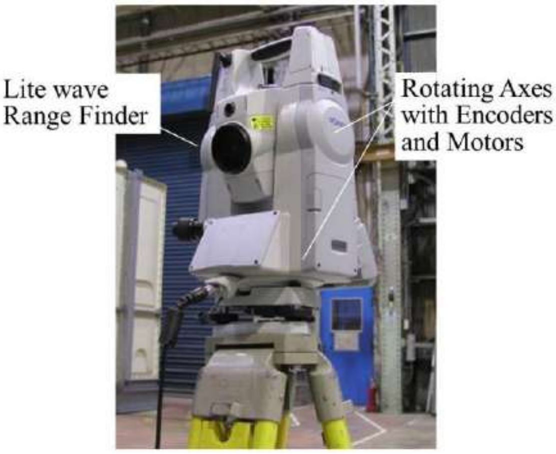


Figure 3. Motor driven total station used for the marking system

Table 2. Specification of the total station

Item	Specification
Manufacture / Model	SOKKIA / NET05
Accuracy of angle measurement	0.5”
Accuracy of distance measurement with using a prism	0.8mm+10^{-3}mm/m

2.2.1 Marking Mechanism

The appearance picture of the marking mechanism separated from the robot is shown in Figure 4. As shown (a), the overview of the mechanism is a two-axis linear motion device imitating an XY plotter of about 700 mm square. Here, the linear motion device is driven by stepping motors. However, as shown in (b), an inkjet printer was adopted instead of a drawing pen of XY plotter.

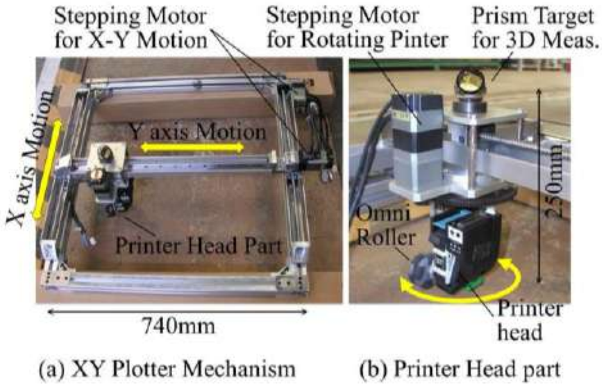


Figure 4. XY plotter type marking mechanism using the inkjet printer

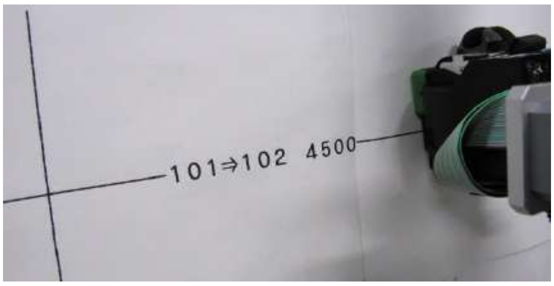


Figure 5. Example of line segments and characters printed by the inkjet printer

This special printer was developed for applications such as printing bar codes and letters on a cardboard box flowing through a production line. Using this, by simply running the XY plotter linearly, it is possible to print an arbitrary character string on the trajectory of the plotter. Incidentally, the height of the drawn characters is about 13 mm at maximum. Therefore, the efficiency of drawing characters is better than the original XY plotter, which needs to move the pen for the number of stroke counts of all the characters. In addition, control of the linear motion can be done simply by specifying only the coordinates of the start and end points and moving speed.

However, for proper printing without distortion, it is necessary to arrange the nozzles of the printer in parallel with the moving orientation of the XY plotter.

Therefore, as shown in (b), a stepping motor for turning the printer head was provided. Further, the printer head can move up and down so as to be able to absorb irregularities on the printed surface. In addition, a spring force acts on the print head in a orientation to press the head against the print surface. Depending on this spring force and an omni roller, the distance between the printing surface and the nozzle can always be kept at a distance suitable for printing. An example of line segments and characters drawn by the printer is shown in Figure 5.

On the other hand, a prism target for measuring the position and orientation of the robot by the total station was provided just above the nozzle of the printer head. This will be described in detail in the next section.

2.2.2 Marking Procedure in Cooperation with Total Station

The flow of the marking operation by the system is shown in Figure 6.

First, it is necessary to measure the benchmark which is the known point of coordinates in the on-site coordinate system by the total station and to obtain the transformation matrix between the internal coordinate system of the total station and the on-site coordinate system.

When after obtained this matrix, the controller of the system can command the motor driven total station to illuminate the work place where marking is drawn next with a built-in laser pointer. After that, a system operator moves the robot to the work place with the pointer as a guide.

Next, in order to draw line segments, it is necessary to obtain the transformation matrix of the internal coordinate system of the robot and the on-site coordinate system. Therefore, the system sequentially moves the XY plotter of the robot to the four corners of its operating range, and in each corner, makes the total station to measure the prism target described in the previous section. As a result, the position and orientation of the robot in the on-site coordinate system can be grasped, and a desired transformation matrix can be obtained.

By following the above procedure, the marking work can be executed by converting the start and end points of the line segments inputted as the coordinates of the on-site coordinate system into the local coordinate system of the robot as shown Equation (1).

$$(\boldsymbol{p}_{start} \quad \boldsymbol{p}_{End}) = f \cdot g \cdot (\boldsymbol{P}_{start} \quad \boldsymbol{P}_{End}) \qquad (1)$$

Here, $\boldsymbol{P}$ represents the coordinate values of the start and end points of the line segments described in the on-site coordinate system. And $\boldsymbol{p}$ represents those of the line segments expressed in the internal coordinate system of the robot. Also, f represents a coordinate transformation matrix between the total station and the robot, and g represents a coordinate transformation matrix between the on-site coordinate system and the total station.

Meanwhile, when marking on slopes, it is necessary to correct the start and end point coordinates of the line segments due to the influence of the height from the print surface to the prism target of the robot. The reason why the correction of the printing position on the slopes is necessary and the idea of the correction amount are shown as schematic diagram in Figure 7.

(1) Operator measures the benchmarks by using total station according to demand from the system

(2) Operator choses the marking data to execute

(3) The system indicates the point selected in (2) by using the laser pointer of the total station

(4) Operator moves the robot to the marking point according to the laser pointer

(5) Operator gives execution command of marking to the system

(6) The System measures position and direction of the robot by the total station

(7) The system executes marking work

Figure 6. Marking work flow by the system

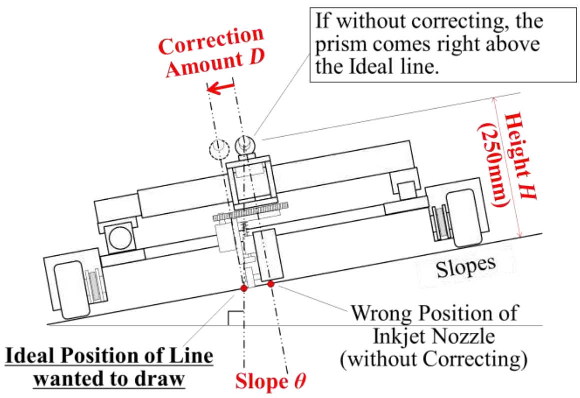


Figure 7. Schematic diagram showing the correction amount of the printing position required when marking on slopes

The prism target of the robot is located at the height H from the printed surface. Therefore, when drawing line segments on slopes, if the XY plotter is controlled so that the prism target passes right above target coordinates of the start and end points of the line segments, as shown in the figure, the lines wanted to draw and ones actually drawn have deviation.

Therefore, when measuring the robot position and orientation, the gradient θ of the slop is obtained, and the print position correction amount D shown in the expression (2) is calculated.

$$D = H \tan\theta \tag{2}$$

The results of the accuracy verification test of the marking mechanism are shown in Section 3.

2.2.3 Wall Traveling Mechanism

A picture of the bottom of the marking robot is shown in Figure 8. Both sides of the marking mechanism is the wall traveling mechanism. The inside of the left and right aluminum boxes is evacuated by a vacuum fan and the boxes are sticked to wall surface. And the mechanism travel the wall by motor driven wheels provided inside the boxes. By adopting four-wheel drive system that connects front and rear wheels with roller chain, not only going up and down but also turning by in-situ is possible.

Storing the wheels in the boxes makes it simple in structure, and since the reaction force from the wall surface by the suction is transmitted to all the wheels, a high payload can be obtained.

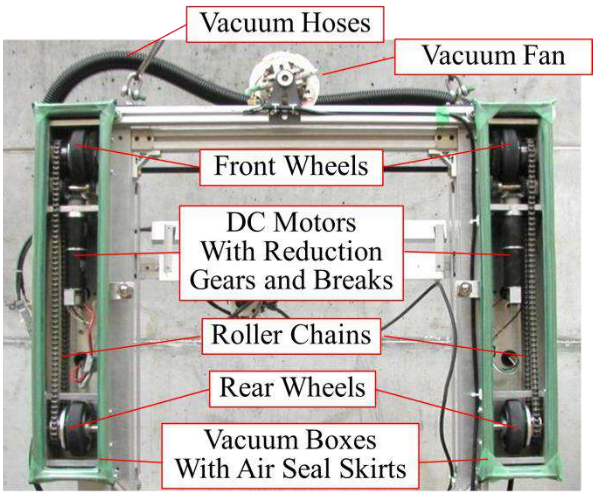


Figure 8. Bottom view of the marking robot

As shown in Figure 9, "skirt" which is the part that makes contact with the wall is made of rubber and sponge material and closely sticked to the wall without gaps. Furthermore, in order to reduce the friction between the skirt and the wall surface during running, a tape is affixed on the skirt.

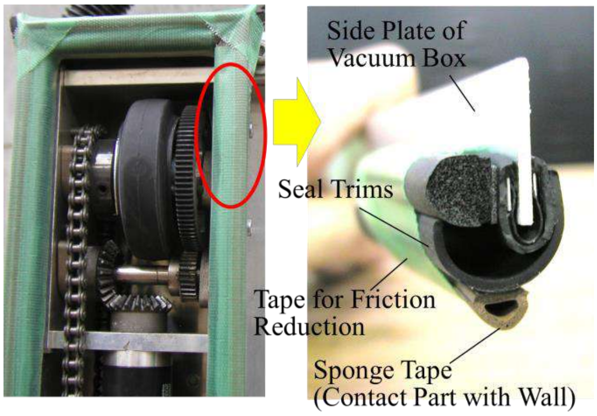


Figure 9. Cross-section shape of the air seal skirt

Table 3. Specification of the wall traveling mechanism

Item	Specification
Dimension of vacuum box (mm)	L:645 x D:100 x H:100 (Sticking Area: 0.065m^2)
Maximum pressure of Vacuum Fan (kPa)	-18
Output of motor for driving wheels (W)	150

Here, as shown in Figure 10, the force F required for the wall traveling mechanism to climb the wall at a constant speed while carrying the payload M (the mass of the robot) is obtained by equation (3).

$$\begin{aligned} F &= (m + M) + f_1 + f_2 = m + M + f \\ &= m + M + N\mu \end{aligned} \tag{3}$$

F: Driving force required to climb wall (N)
m: Mass of the wall traveling mechanism (N)
M: Payload (N)
f_1: Rolling resistance of the wheels (N)
f_2: Friction resistance between skirts and wall (N)
f: Wall climbing resistance (Summation of f_1 and f_2)
N: Wall sticking force (N)
u: Total coefficient value of rolling friction of wheel and static friction of skirt (-)

In addition, at this time, since the wheels must not slip, the driving force F must be equal to or less than the product of the static friction coefficient u_0 of the wheels at the time of rotation is restrained and the sticking force N, as shown in equation (4).

$$F \leq N\mu_0 \tag{4}$$

Here,
u_0: static friction coefficient of the wheels at the time of rotation is restrained (-)

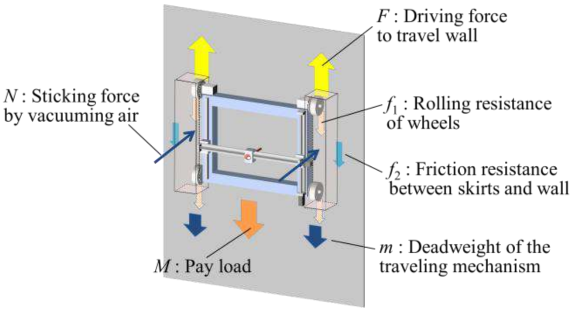


Figure 10. Schematic diagram showing the forces acting on the robot when climbing the wall with constant speed

Based on the relationship shown above, the maximum value of the payload that can be loaded on the wall traveling mechanism is represented by a linear function of the wall sticking force N as shown in Expression (5).

$$M_{mac} = N(\mu_0 - \mu) - m \tag{5}$$

3 Performance Verification of Marking System

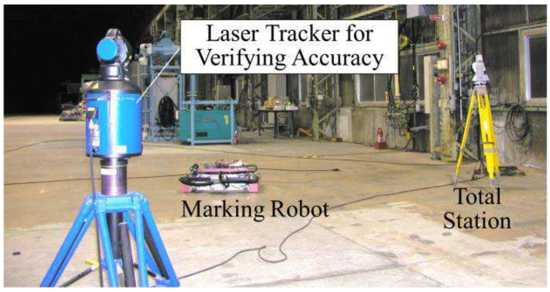
3.1 Verification Method

3.1.1 Verification Method of Marking Mechanism

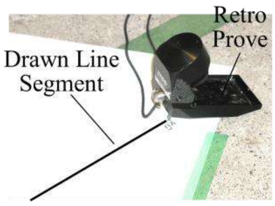
Items to be verified for accuracy of the marking mechanism are shown below.

1. Repeatability of drawing: To confirm whether there is any deviation between line segments drawn when the orientation of the robot are changed.
2. Correction of drawing position at sloops: To confirm whether accurate line segments are drawn on sloops according to equation (2).
3. Position accuracy of line segments drawn: To confirm whether accuracy of drawing position of line segments satisfies development objective.

In order to confirm the three items mentioned above, we did marking work on the floor of an area assumed a construction site, and measured the position of line segments drawn by using a high-precision three-dimensional measuring instrument "laser tracker". Figure 11 shows pictures of the verification test. Here, the main specifications of the laser tracker are shown in Table 4.



(a)Overall view of the test



(b)Drawing of line segments by the robot on white paper put on floor

(c)3D measurement of end point of drawn line by using "Retro prove" which is one of tools for laser tracker

Figure 11. View of verification test on marking accuracy

Table 4. Specification of a laser tracker using the test

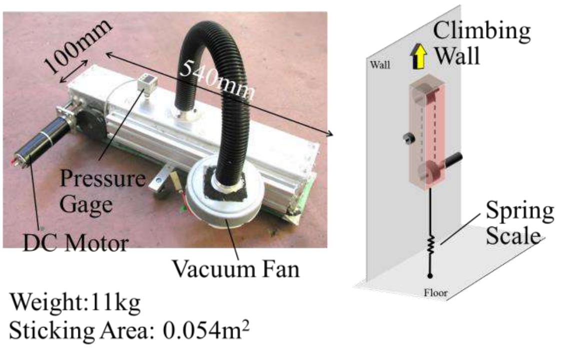
Item	Specification
Manufacture / Model	FARO / Xi
Accuracy of angle measurement	18um+3um/m
Accuracy of distance measurement by ADM	20um+1.1um/m

3.1.2 Verification Method of Pay Load of Wall Traveling Mechanism

In order to establish the design guidelines of the wall traveling mechanism to be mounted on the marking robot, we verified the payload of the mechanism by using a small test model.

(a) of Figure 12 shows the test model used the test. Area of the vacuum box and mounting position of the DC motor of the test model are different from ones of the marking robot shown in Figure 8. But the performance of the motor and the vacuum fan and the structure of the skirt are same of the robot.

As shown in (b) of Figure 12, we measured the reading of a spring scale which was connected between floor and rearward of the test model when the test model stopped to climb the wall because the driving force of the test model and the force of the spring scale was balanced. The test was repeated with changing the sticking force to wall by controlling output of the vacuum fan.



(a) View of the Test Model (b) Measurement Way of Payload

Figure 12. View of a test model of wall traveling mechanism and schematic diagram showing the way of measuring pay load

3.2 Result of Verification Test

3.2.1 Verification Result of Marking Mechanism

- Repeatability of drawing

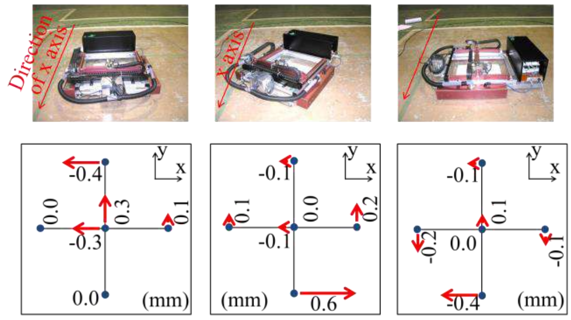
Figure 13 shows the result of the verification test. A cross shape line was drawn three times changing the orientation of the robot by about 45 degrees as shown in the upper photographs of Figure 13. After the drawing operation, positions of five points including the end points of each line segment and the intersections of the cross line were measured by the laser tracker. Here, length of each line segment is about 400mm.

Horizontal and vertical lines in the lower diagrams of Figure 13 show cross lines drawn. And numerals in the diagrams show the deviations between the target values and the measured values. In a similar way, arrows in the diagrams show the orientation of the deviations.

Among the three cross lines, 0.6 mm shown in (b) was the largest deviation. From this result, it can be said that the three cross lines were drawn in exactly the same place.

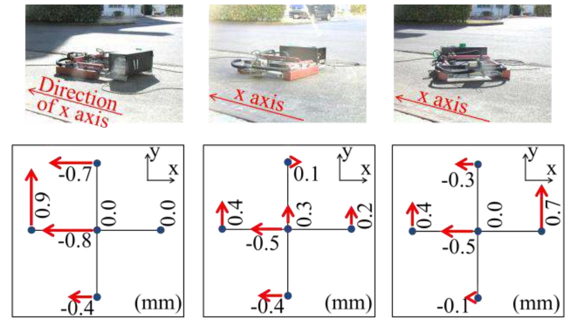
- Correction of drawing position at sloops

Figure 14 shows the result of the verification. As in the test mentioned above, a cross shape line was drawn three times on a sloop changing the orientation of the robot. Here, the angle of the sloop we used for the test was about 3 degrees. Thus, if correction is not done, 13mm of deviation between target values and measured values occurs according to equation (2). On the other hand, the deviation was 0.9 mm at the maximum as shown in (a). Thus, it was confirmed that the correction was performed correctly.



(a)Parallel with x axis (b)-45deg. rotation (c)-90deg. rotation

Figure 13. Confirmation results of repetitive positioning accuracy



(a)Parallel with x axis (b)90deg. rotation (c)135deg. rotation

Figure 14. Confirmation results of repetitive positioning accuracy on a slope

- Position accuracy of line segments drawn

Table 5 shows the evaluation results of the deviations between target values and measured values of coordinates of the intersection point of nine cross lines drawn on the horizontal floor. The maximum deviation from the target value was 0.7 mm, the average was 0.4 mm, and the standard deviation was 0.15 mm. Based on the above results, we judged that the development objective of the drawing accuracy 1 mm or less was achieved.

Table 5. Distance between the intersection of the nine crosshairs drawn by the robot and the true value

Maximum (㎜)	Average (㎜)	Standard Deviation (㎜)
0.7	0.4	0.15

3.2.2 Verification Results of Pay Load of Wall Traveling Mechanism

Figure 15 shows the result of pay load verification of the test model. This figure is a scatter diagram showing the relationship between wall sticking force and payload of the test model. The abscissa of the graph is wall sticking force, which is calculated by the product of the design value of sticking area of the test model and the measured value of the vacuum pressure, and the ordinate axis is the reading of the spring scale. In this case, the reading of the spring scale can be paraphrased as a payload of the test model.

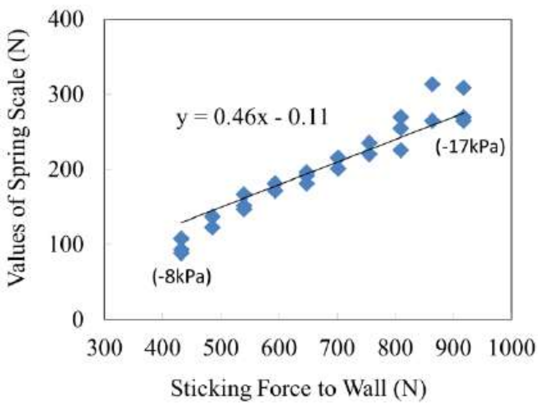
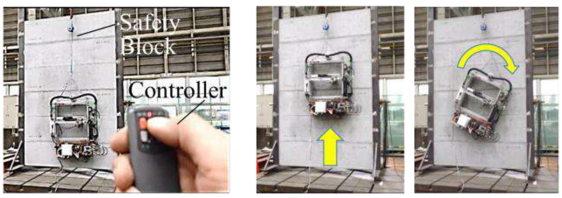


Figure 15. Verification result of pay load of the test-model wall traveling mechanism

As shown in the graph, the sticking force and the payload are almost linear relations. At vacuum pressure of -17 kPa, which is almost the maximum capacity of a vacuum fan, the sticking force was about 900 N and the payload was about 300 N. Since this result is the data of one traveling mechanism, about 600 N of payload will be obtain when two traveling mechanism are used.

A line segment in the figure is linear approximation result of the data. Here, with reference to Equation (5), the intercept of the linear equation was assumed to be 0.11 N of the weight of the test model. As a result, the term (u_0 - u) of the friction coefficient shown in the formula (5) was experimentally found to be 0.46.

With reference to the above results, in the design of the final version, the sticking area of the vacuum box was set to 1.2 times of the test model, taking into consideration the safety factor and the dimension of the marking mechanism. Pictures the marking robot climbing the wall is shown in Figure 16.



(a)The Robot Travels Wall by Wireless Control (b) Climbing Motion (c) Turning Motion

Figure 16. Traveling and marking on concrete wall with using the developed marking robot

4 Conclusion

In order to rationalize the marking work for equipment installation at plant construction sites, we have developed the marking system and got the following conclusions.

1. We developed the XY plotter type marking mechanism using an inkjet printer and made it possible to draw arbitrary line segments and characters by linearly moving the XY plotter.
2. As a result of the verification test of the marking accuracy, it was confirmed that the robot can draw line segments with an accuracy of 1 mm or less. Therefore, the development objective accuracy was achieved.
3. We confirmed that the wall traveling mechanism which sticks to walls by using vacuum fan and moves on wall with a four wheel drive mechanism realized the wall traveling of the marking robot with its own weight of 56 kg.

5 Future Prospects

We have already applied this system at two of our plant construction sites and drawing accuracy have been achieved. However, there are issues such as counter measures to cool the control unit of the robot in outdoor work and weight saving of the robot.

From now on, we are planning to apply the robot to construction sites in earnest and calculate concrete effect, while working on countermeasures for the above problem. Furthermore, we will also work on improving performance such as addition of autonomous running function of robot to marking position.

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Improving supply chain communications for off-site construction using Process Specification Language

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Abstract –
Off-site construction has undergone a rapid development driven by their favorable characteristics, such as fast construction, waste reduction and clean on-site environment. Nevertheless, frequent engineering changes often create unpredictable challenges for precast production planning, resulting in production delay or additional storage costs. In order to achieve the target of just-in-time production and lean construction, it is vital to harmonize the supply chain communication amongst different phases of component production, transportation and on-site assembly. The automatic exchanges and conveyance of the process information amongst different phases are nearly impossible due to the mismatching definitions of semantics and syntax used in different planning software that are adopted in different construction phases, e.g. assembly design, component production, and on-site assembly. To address this problem, the Process Specification Language (PSL) is explored in this paper to unify the process information from multiple planning software applications. A translation framework of process information communications in the off-site construction supply chain has been developed based on the functional analysis. Semantic mapping and extensions of PSL are proposed, given the specific requirements of off-site construction scheduling management. Finally, the superiority of this method is demonstrated using two case studies to confirm the scheduling and sequencing information interaction amongst the phases of assembly design, component production, and on-site construction can be enhanced by the present method.

Keywords –
Process Specification Language; PSL; Supply Chain; Off-Site Construction; Process Ontology

1 Introduction

Compared to the traditional cast-in-situ construction methods, the successful management for off-site construction relies much more on the efficient precast supply chain management [1]. However, the supply chain management of off-site construction still faces many challenges, and the failure of just-in-time delivery of precast components is one of the most vital reasons for the delay on the construction site [2]. If the precast components arrive too early on the construction site, it will result in an increase in cost and on-site storage[3]. The off-site construction supply chain phases consist of planning, design, fabrication, delivery and on-site assembly. Frequent engineering alternations in the fabrication and construction phases, and the lack of or less effective coordination and communication, have made such problems more prominent. Improving the coordination and interoperability for various phases and parties, is considered to be the key to solve such issues in the off-site construction supply chain management [4].

The lack of ICT interoperability is primarily owing to the incompatibility amongst the syntaxes of the languages and the semantics of the terms [5] adopted in different phrases. To overcome this issue, one approach is to develop and update the different direct translators or core database adopted in different phases for each application, which lacks the required accuracy. The alternative approach is to develop a common data standard, e.g. IFC and EXPRESS. The NBIMS (National Building Information Modeling Standard) released the 'Information Delivery Manual for Precast Concrete' to further improve its support for data exchange during the life cycle of off-site construction projects [6]. At present, IFC standards can be used to communicate the product data and primary process data, but the necessary concepts and definitions to support more complex processes, e.g. the complicated scheduling and sequencing information are missing [7].

Construction supply chain management includes a set of process-driven activities. Precast fabricators usually apply ERP (Enterprise Resources Planning) system with MES (Manufacturing Execution System) and APS (Advanced Planning and Scheduling), to deal with the tasks of production scheduling, delivery planning and factory site storage. Contractors use the project management software to develop and control the assembly schedule on the project sites. The communication and coordination between the precast fabricators and contractors is based on delivery order, which is closely related to the progress of fabrication and construction. Thus, it brings up the question on how to achieve the information compatibility and interchangeability amongst the different software packages is of great practical relevance.

PSL ontology is considered as the process information interaction tool applied to the construction and supply chain management [8]. This paper incorporate the process information from different construction planning software and then apply the PSL ontology to strengthen the supply chain communications for off-site construction.

2 Literature Review

2.1 PSL Ontology

The concept of Ontology originated from the field of philosophy. Gruber defined it as 'an explicit specification of a conceptualization' [9]. To date, the research on ontology mostly focused on exploring how to describe a wide range of knowledge-sharing behaviors [10]. Ontology has a unified standard in the interpretation of knowledge items, suitable for data interoperability, information search and retrieval, automated inference and natural language processing in computer. Edward et al.[11] described a system to support multidisciplinary analyses of complex engineering problems by using pre-project planning ontology. Sheryl et al.[12] developed a feature ontology to support construction cost estimation by transforming the designer-focused product models into the estimator-focused product models.

Process Specification Language (PSL) is a set of logic terms to describe process which is applicable to manufacturing, engineering and business processes including production scheduling, process planning and management, business processes reengineering, simulation, realization, modeling and project management. ISO 18629provides the theoretical framework and application guides fpr PSL [13]. PSL contains 38 modules with more than 300 concepts in total. The core theory of the PSL ontology is illustrated in Figure 1 [14].

Cutting-Decelle et al. [15] illustrated the basic theorem of PSL and pointed out that PSL could be used for the representation and exchange of process information in Architectural Engineering and Construction (AEC) industry. PSL was proven to offer the interoperability improvement in the multiple process-related applications due to the function of formal semantic definitions and complete automization [16]. An ontology-based framework based on PSL was established, and the semantic presentation of design using PSL as well as the application in two case studies using CAD/CAM software were illustrated [17]. PSL was used to support the process information communication between multiple software including AutoCAD, Construction Computer Software and Microsoft project [18]. The main-stream methods and techniques to building supply chain communications were presented, including a new semantic-based approach [19]. PSL was used for information exchanges in a cross-disciplinary supply chain environment to describe the business process network and the information exchange of supply chain nodes amongst fabricators, suppliers and contractors [20].

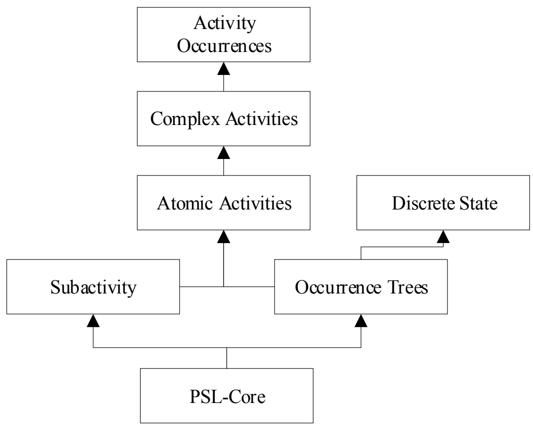

Figure 1. Core theory of the PSL ontology[12]

Cheng at al.[21] developed ontology mapping and information exchange amongst PSL, ifcXML and aecXML which can be applied in the project scheduling in the construction industries as the ontology standards. More studies have shown the ability of PSL in the information exchange of project scheduling among different software applications, e.g. Primavera P3, 4D Viewer Microsoft Project and Microsoft Excel [22]. Another study investigated how the PSL was used to indicate potential conflicts and to perform consistency checking on project scheduling information [23]. On this basis, a prototype framework enabling the remote collaboration of heterogeneous systems was proposed and a standard for data exchange based on PSL ontology was established [24]. A simulation access language (SimAL) based on PSL ontology was described to access and develop software applications for internet purposes[25]. A case study communicated online weather forecasting information with project scheduling and management application was illustrated to describe the use of the SimAL.

In summary, limited research has focused on the application of PSL ontology in AEC industry, which mainly targeted traditional on-site construction management. The instant interaction of process information is essential due to the tight connection of off-site production and on-site construction. Therefore, PSL ontology needs more research focused on its application, as it has the potential to bridge the gaps on the integration of off-site construction.

2.2 Knowledge Interchange Format (KIF)

KIF is a formal language designed to exchange knowledge among disparate computer systems, which is the grammar of PSL [26]. KIF was proposed and developed by the Logic Group of Stanford University and is a proposed draft American National Standard (pdANS).

KIF is based on the first-order logic and its language description includes syntactic and semantic standards. KIF supports declarative semantics, and the language is logically comprehensible [27]. KIF has two variants, i.e. the linear and structured KIFs. All expressions for linear KIF are ASC II strings, and the structured KIF includes characters, language elements, expressions and comments.

3 Process Information Communication in Supply Chain for Off-site Construction

3.1 Information Flow between Engineer, Precast Fabricator and Contractor

The supply chain of off-site construction contains a large array of parties including clients, architects/engineers, contractors, suppliers (precast fabricators) and consultants linked with comprehensive information flows [28]. In general, clients mainly take part in the planning and operation phases, and the consultants may not participate in the actual construction activities. The dynamic and constant communication of information amongst engineers, precast fabricators and contractors is vital for supply chain management during the whole construction processes. The information flowchart is presented in Figure 2.

Architects will pass the design model to engineers in the early stages based on the commencing order instructed by clients. The precast assembly drawings (PAD) made by engineers are then sent to precast fabricators and contractors simultaneously. On this basis, contractors can draw up the construction scheduling (CS), which will be subsequently sent to the precast fabricator. The precast fabricator can work out the production scheduling to meet the requirements of PAD and CS. The precast components will be produced in batches according to their specified delivery dates, and the contractor will use them for the construction assembly at sites.

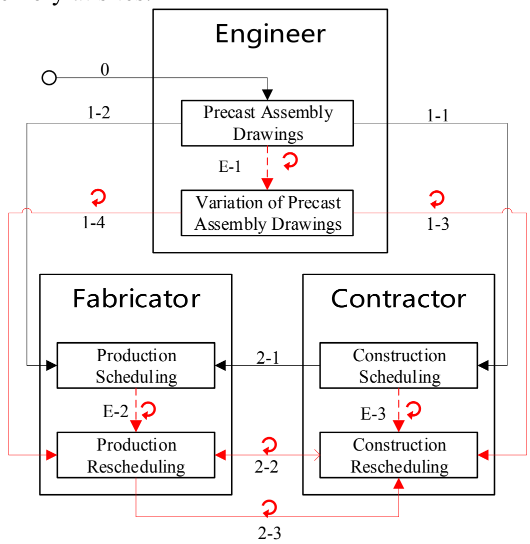

Figure 2. Typical information flow in supply chain

Table 1 Information Exchange and Type

Number	Information Exchange	Type
0	Start Order	Process
1-1	Building Information	Object
	Assembly Sequencing	Process
1-2	Component Design	Object
	Resource Require	O&P
	Assembly Sequencing	Process
2-1	Construction Scheduling	Process
1-3	Building Information Change	Object
	Assembly Sequencing Change	Process
1-4	Component Information Change	Object
	Resource Require Change	O&P
	Assembly Sequencing Change	Process
2-2	Construction Rescheduling	Process
2-3	Production Rescheduling	Process

A large number of engineering changes caused by unexpected situations occur frequently during the construction processes. The variation of PADs is required re-drawn by engineers when the architect modifies the design or the original design error is found and rectified (E-1). After the variation notification of precast design is sent to precast fabricators and contractors, the Production Rescheduling (PR) and Construction Rescheduling (CR) should be formulated accordingly. In addition, the production may also be triggered by the equipment failure or raw material supply delay (E-2). On the contractor side, some uncontrolled factors, such as weather conditions, construction machinery failure, may also lead to the necessity of PR (E-3). As a result, the precast fabricator may also develop PR based on the updated CR. Although these engineering changes occur on a random basis, it tends to occur frequently throughout the entire construction duration owing to the complexity of the construction environment. In summary, the type of the complicated information communication is listed in Table 1.

3.2 Applications by Software

The process information of supply chain can be divided into two types, i.e. business and construction information. Many different software packages can facilitate the construction management. For example, BIM-based software, such as Autodesk Revit, Tekla Structures, Nemetschek Allplan, Structure Works and IDAT CCAD, can support engineers to prepare precast assembly drawings. Precast fabricators use ERP (Enterprise Resource Planning) packages to manage the planning and scheduling of production, e.g. SAP ERP, IDAT ERP, Asprova APS and Nemetschek TIM. MES (Manufacturing Execution System) applications such as RIB SAA may also be adopted by precast fabricators to control machines for automatic production. Contractors often use Project management tools for on-site construction management, and the Microsoft Project, Oracle P6 and Autodesk Navisworks are widely adopted for such purpose. The typical software types used in different phases are shown in Figure 3.

Figure 3. Typical software used in different phases

3.3 Process Information Communication Using PSL Ontology

The process information communicate amongst different applications through syntactic and semantic translation. Figure 4 illustrates an example of data transferring between precast fabricator and contractor. The original files from IDAT ERP or MS Project can be transformed into their KIF syntax. And then they can be transformed into PSL ontology (KIF syntax and PSL terminology), where they can have some exchange. This process is reversible, through which the new data can be send back to their original applications in an opposite direction.

Although the ontology of the original application is usually hidden, users can create their own ontology based on the output from the application. The semantic translator unifies the terminology of each application with PSL definitions.

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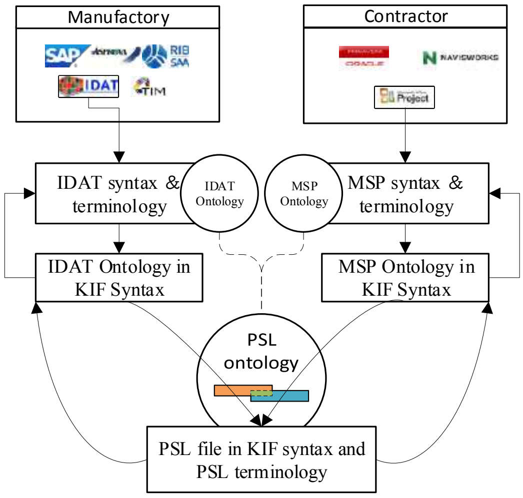

Figure 4. Process information exchange via PSL

4 Process Information Communication for Scheduling

The production scheduling of components needs to be synchronized with the on-site construction scheduling. However, the production and construction planning may be easily affected by the unpredictable factors on each side. In the current practice, the precast fabricator monitors the production anomalies and communicates with contractors on a weekly basis. The negative consequence as a result of this type of communication practice includes the sub-optimal decision-making, inadequate utilization of production capacity, and lagged feedback of information, which will lead to the failure of just-in-time delivery and lean construction. This will cause the delay in the overall project progress and the cost increase for both fabrication and construction. PSL ontology can be utilized to tackle this problem, namely, unify the production and construction scheduling via instant data transfer and synchronized communication. In doing so, the entire process information can be integrated into a single system and the scheduling can be automatically updated should any change in one of the process take place.

4.1 PSL Ontology Mapping for Construction Scheduling

MS Project and Oracle P6 are frequently used to perform construction scheduling in Construction management. Other software with the 4D management capabilities such as Naviswork also share the same principles and basic concepts as MS Project for scheduling management. Multiple concepts including tasks, duration, constraints, ordering relationship, order and resource requirement can be described with these applications. The logic of duration and ordering relationships can be expressed with Gantt chart, using different dependences relationships. The dependence elements include predecessors, successors, basic types and absolute/relative leading or lagging times, as shown in Figure 5, in which the relation between multiple process is also illustrated both in their full and abbreviated terms, e.g. Finish-to-Start and FS.

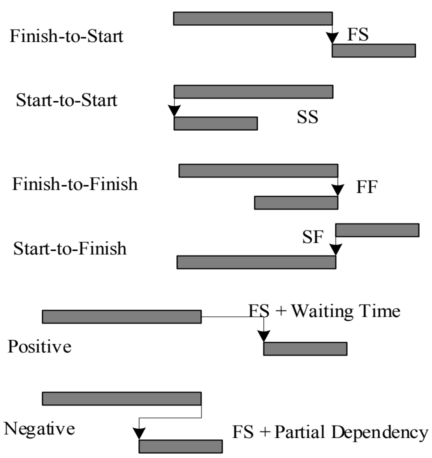

Figure 5. Construction Dependencies in Gantt Chart

Table 2 Semantic mapping of dependences relationship

Concepts in Project Management Apps	PSL terms
Predecessor/Successor	before-start, before-end, after-start, after-end
Finish-to-Start	meets, end-equal-start
Start-to-Start	starts, start-equal-start
Finish-to-Finish	finishes, end-equal-end
Start-to-Finish	start-equal-end
Positive Lag	before-start-delay, before-end-delay
Negative Lag	after-start-delay, after-end-delay

PSL ontology provides enough terms to represent the dependence relationship with the ordering relation extension and temporal ordering relations extension . A semantic mapping between dependences relationship and PSL ontology is listed in Table 2.

4.2 PSL Ontology Mapping For Production Scheduling

Two kinds of casting beds and casting flows exist in precast concrete plants, e.g. the mobile and fixed casting. The mobile casting method is more widely adopted owing to the higher level of mechanical automation and the efficiency in the space use. Hence, the mobile production mode is analyzed in this case study. The production scheduling can be shown by Production Gantt Chart as Figure 6 [29].

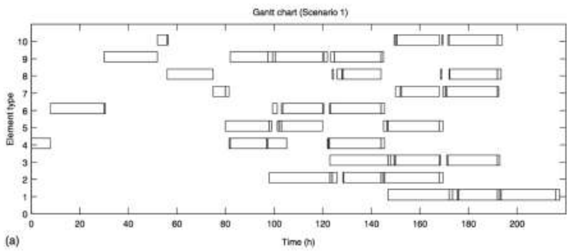

Figure 6. Production scheduling for Mobile Precast Concrete Casting [29]

In the streamline production mode, the semi-finished products may directly be sent into the back-end production line. The ordering relationships are more complicated than these in construction scheduling. Additional dependences relationships of SSFF, FSF and FFS are shown in Figure 7. For instance, SSFF means the start of the first production triggers, the start of the second and both lines will finish at the same time; FFS means that the second line will commence after a period of time following the first line, its predecessor, commences; FSF means that apart from the first round where the finishing of the first line triggers the starting of the second one, the remaining start of the first line will all depend on the finishing of the second line.

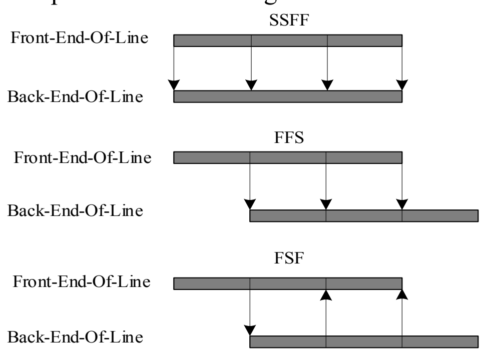

Figure 7. Production Dependencies in Gantt Chart

The relationship of SSFF, FSF and FFS can be described by PSL ontology as in Table 3.

Table 3 PSL term extensions for complex concepts

Concepts	PSL terms extensions
SSFF	*(defrelation SSFF (?a ?b) := (exists (?a1 ?a2 ?a3 ?a ?b1 ?b2 ?b3 ?b) (and (subactivity ?a1 ?a2 ?a3 ?a) (subactivity ?b1 ?b2 ?b3 ?b) (mutually-occurring ?a1 ?a2 ?a3 ?a) (starts ?a1 ?b1) (starts ?a2 ?b2) (starts ?a3 ?b3) (finishes ?a3 ?b3))))*
FFS	*(defrelation FFS (?a ?b) := (exists (?a1 ?a2 ?a3 ?a ?b1 ?b2 ?b3 ?b) (and (subactivity ?a1 ?a2 ?a3 ?a) (subactivity ?b1 ?b2 ?b3 ?b) (mutually-occurring ?a1 ?a2 ?a3 ?a) (meets ?a1 ?b1) (meets ?a2 ?b2) (meets ?a3 ?b3))))*
FSF	*(defrelation FSF (?a ?b) := (exists (?a1 ?a2 ?a3 ?a ?b1 ?b2 ?b3 ?b) (and (subactivity ?a1 ?a2 ?a3 ?a) (subactivity ?b1 ?b2 ?b3 ?b) (mutually-occurring ?b1 ?b2 ?b3 ?b) (meets ?a1 ?b1) (meets ?b1 ?a2) (meets ?b2 ?a3))))*

4.3 Example of Scheduling Communication using PSL Ontology

The information communication contains syntactic and semantic translation into the PSL ontology. The semantic translation is separately presented by PSL ontology mapping for construction scheduling and production scheduling. An example of information communication between MS Project and IDAT ERP software is introduced below.

It is a four-step work. Firstly, the MS Project data file is represented with PSL syntax and MS Project terminology, and then further written as a complete PSL representation. Next, these PSL representations are further transformed into PSL syntax and IDAT ERP terminology. Finally, the PSL syntax and IDAT ERP terminology is written as input file for IDAT ERP. The first two steps are shown below as an example， and the next two steps are the mirror work to the first two. This study takes an example to describe scheduling with multi dependences relationship in Figure 8.

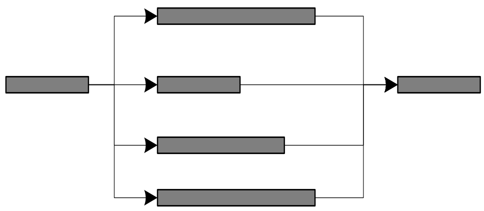

Figure 8. The example of multiple predecessors

The scheduling data written in MS Project using the VBA (Visual Basic for Applications) language, and the coding format and terminologies defined in VBA. The scheduling data file in MS project's representations is as below.

```
{Project        multiple Predecessors –opening (x)}
{Task           predecessor activity,
                intermediate activity group,
                successor activity}
{Dependence     order relationship as scheduling (x)}
{Period         duration as scheduling (x)}
```

For the translation process, a syntactic translator needs to be developed to read the scheduling file from MS Project. The syntactic translator then translates the original data to a presentation with PSL syntax and MS Project terminology as below.

```
(forall (?x)
(=>(multiple_predecessors-opening ?x)
    (task ?a ?b ?c)))
(forall (?b)
    (=>(and(activity_group ?b1 ?b2 ?b3 ?b)
    (StartToStart ?b1 ?b2 ?b3)
    (Period ?t1 ?t2 ?t3 ?b1 ?b2 ?b3))))
(forall (?occ)
(=>(and (ActualStartDriver ?a ?b ?c)
    (FinishToStart ?a ?b ?c)
    (Period ?t4 ?t5 ?t6 ?a ?b ?c)))
```

The PSL syntax can be mapped to PSL definitions. The presentation of the scheduling file adopts PSL ontology, which contains PSL terminology and PSL syntax as below.

```
(forall (?x)
(=>(multiple_predecessors-opening ?x)
    (activity ?a ?b ?c)
(forall(?b)
    (=>(and (subactivity ?b1 ?b2 ?b3 ?b)
        (starts ?b1 ?b2 ?b3)
        (=>(duration ?b1 ?t1))
        (=>(duration ?b2 ?t2))
        (=>(duration ?b3 ?t3)))))
(forall (?occ)
    (=>(and (occurrence_of ?a ?b ?c)
        (meets ?a ?b ?c)
        (=>(duration ?a ?t4))
        (=>(duration ?b ?t5))
        (=>(duration ?c ?t6)))))
```

5 Process Information Communication for Assembly Sequencing

BIM is usually adopted for virtual assembly analysis in addition to the complicated Precast Assembly Drawings. The assembly sequencing from virtual assembly analysis will be sent to precast fabricators and contractors. Process information of assembly sequencing is paramount between the communication of contractor and precast fabrication. The wrong assembly sequencing will result in project delays and additional costs for contractors. To the precast fabricators, the assembly sequencing will determine the stacking sequencing in transport vehicle and on-site yard. The correct stacking sequencing enables the crane to hoist the components directly one by one in order to save construction time and the storage space.

5.1 Example for Assembly Sequencing Process

The example project is a residential based on shear wall structure. The main structure consists of the precast shear walls, precast columns, laminated slabs and laminated beams. The BIM model build by Allplan is shown in Figure 9.

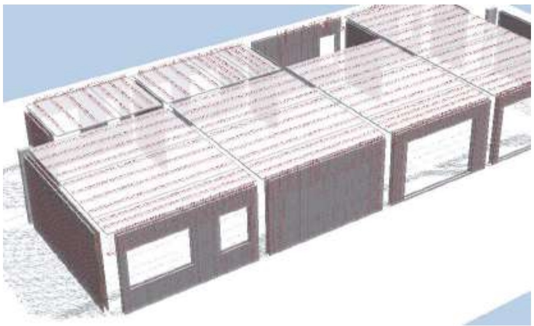

Figure 9. BIM model of the example project

Figure 10 illustrates the positions of precast components in the room at the corner, and the numbers have been assigned for each component. The entire assembly sequencing process of this room is described by IDEF3, as shown in Figure 11 and Figure 12. Figure 11 shows the main activities of the whole assembly process. The precast shear wall and the precast column must first be assembled before the laminated beam is assembled. Figure 12 illustrates the sub-activities of shear wall assembly. The inner wall (S3) and the wall on the other side from crane (S1&S2) will be first assembled. The outer wall and the wall near the crane will be finally assembled to insure the hoisting space.

5.2 Assembly Sequencing Process by PSL Ontology

In order to describe the assembly sequencing process, the PSL ontology is used to translate the activities as indicated in Figure 11.

```
(subactivity assemble-shear-wall)
(subactivity assemble-column)
(subactivity assemble-beam)
(forall (?occ))
    (<=>(occurrence_of ?occ assemble-room1)
    (exsits (?occ1 ?occ2 ?occ3)
    (and (occurrence_of ?occ1 assemble-shear-wall)
    (occurrence_of ?occ2 aseemble-column)
    (occurrence_of occ3 assemble-beam)
    (subactivity_occurrence ?occ1 ?occ)
    (subactivity_occurrence ?occ2 ?occ)
    (subactivity_occurrence ?occ3 ?occ)
    (soo-precedes (soomap ?occ1)(soomap ?occ 3) assemble-room1)
    (soo-precedes (soomap ?occ2)(soomap ?occ3) assemble-room1)
    (strong_parallel ?occ1 ?occ2 assemble-room1))))))
```

6 Conclusion and Future Work

This paper presented the novel method of PSL ontology to improve the supply chain communications for off-site construction. PSL ontology has rich definitions to describe process activities in scheduling and sequencing. It can be used to provide a common framework to exchange data originated from different application packages used in various construction phases. While IFC provides the fundamental data structure of BIM applications, PSL has the potential to be incorporated with IFC so that the supply chain communication for off-site construction can be integrated into both domains of the building information and construction activities.

7 Acknowledgement

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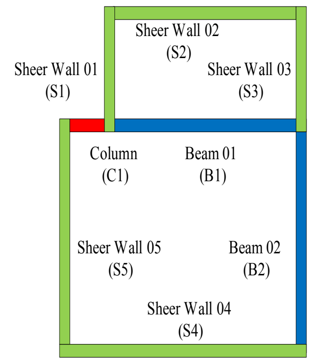

Figure 10. The components position in the room at corner

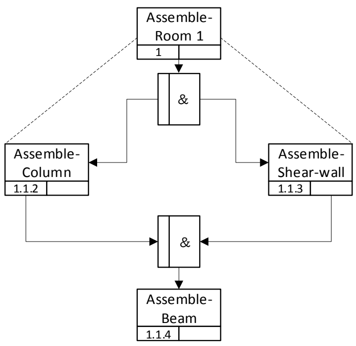

Figure 11. Main activities of the whole assembly process in IDEF3

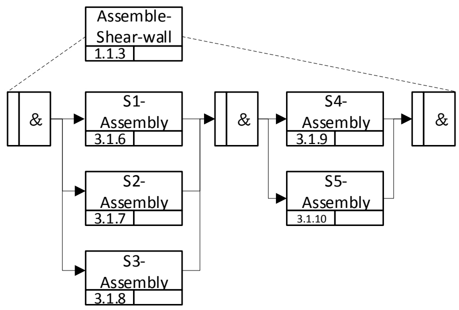

Figure 12. Sub-activities of the shear wall assembly process in IDEF3

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Application of Automation and Robotics Technology in High-Rise Building Construction: An Overview

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Abstract –

More and more high-rise buildings are being erected in extensively populated countries such as China nowadays with the requirement of higher living standards. However, on the one hand, with the development of aging society, the labor shortage has become a remarkable problem; on the other hand, the danger and difficulties in construction increase significantly with the height of the buildings. Thus, the application of automation and robotics technology is expected to ease such problems and concerns. Up to now, various methods and systems using automation and robotics technology have been proposed to be used in high-rise building construction. This paper summarizes the major advance on the application of automation and robotics technology in high-rise building construction through a literature survey and suggests directions of further research in this field. First of all, the research scope, the method and the results of the literature survey are presented. Then, based on the survey results, the relevant applications are summarized regarding the three parts of high-rise buildings, i.e., earth and foundation work, superstructure erection and façade installation. Finally, the future directions and opportunities mentioned in existing research are summarized and discussed. This paper provides a valuable aid in future research and application of automation and robotics technology for high-rise buildings.

Keywords –

Automation and robotics; High-rise building; Earth and foundation work; Superstructure erection; Façade installation

1 Introduction

Due to the demographic and economic developments, the number of the world's high-rise buildings is growing rapidly. The emergence of high-rise buildings mitigates the pressure of the growing population, but also requires a large quantity of labor force during the construction. Meanwhile, the number of young workers is decreasing at the construction site, due to the aging population in many countries in the world. What is more, the safety problems and the workers' psychological fear of the height are also remarkable challenges at the construction site of high-rise buildings. Obviously, both the predictable labor shortage and the life safety of the workers call for leveraging machines and robots to replace human labor in high-rise building construction.

The application of automation and robotics technology in the construction industry have been reviewed in several papers. Bock [1] suggested that conventional construction methodology had reached its limits, and outlined five aspects of future opportunities for construction automation: robot-oriented design, robotic industrialization, construction robots, site automation, and ambient robotics. Son et al. [2] analyzed the topics and contents of 1671 papers in International Symposium on Automation and Robotics in Construction (ISARC) proceedings from 1990 to 2008, to identify trends and future directions of automation and robotics technology in construction. Vähä et al. [3] surveyed on sensor technology and its potential use for construction automation and reviewed robotic applications in the main construction procedures. Taylor et al. [4] summarized the existing automated machinery and construction robots in Japan, and suggested that construction environments should be more structured and controlled to apply construction robots. Maas and van Gassel [5] discussed the development of automation and robotics technology and its influence on performance management, construction engineering, and construction management.

These papers have presented the application of automation and robotics technology in the construction industry as a whole, pointed out the key research areas and analyzed the current and ongoing research and development trends. However, there is a lack of a systematic review of the application of automation and robotics technology in high-rise building construction.

This paper summarizes the major advance on the application of automation and robotics technology in high-rise building construction through a literature survey and suggests directions of further research in this field. To this end, considering the characteristics, the paper focuses on three sub-phases of high-rise building construction: earth and foundation work, superstructure erection and façade construction. In Section 2, the research scope, the method and the results of the literature survey are presented. Then, by analyzing the survey results, Sections 3, 4 and 5 respectively present the application of automation and robotics technology in the construction of foundation, superstructure and façade, and Section 6 summarizes the future directions of automation and robotics technology for high-rise buildings. Finally, the paper is concluded in Section 7.

2 Research Scope and Literature Retrieval

The definition of the term "high-rise building" varies in different countries. For example, according to Chinese standards, a high-rise building refers to a residential buildings over ten stories or 28 m, or a nonresidential buildings over 24 m; in Japan, a high-rise building is over eight stories or 31 m; and in the U.S., it is over 24.6 m or seven stories. Besides, the high-rise buildings taller than 100 m are called "skyscrapers". In this paper, the high-rise building is not strictly defined, and it covers the definitions in different countries and includes the skyscrapers.

To implement a systematic literature review, a comprehensive search was conducted in the major databases, including Engineering Village, Scopus, ASCE, and Web of Science. The search keywords included "high-rise", "robot", "automation", "construction", "assembly", "installation", "machine", "equipment", etc. However, the publications in the form of editorials, books, discussions, or published before 2000 were excluded because they are considered to be of little value for the review. By reading the titles, abstracts and conclusions, we filtered out unrelated papers and finally obtained 50 papers. Particularly, we found the review on application of automation and robotics technology in the sub-phase of earth and foundation work is already comprehensive (which is further explained in Section 3), so we only included three latest review papers of earth and foundation work in this study. The distribution of the retrieved papers related to superstructure and façade (47 papers) is shown in Figure 1.

3 Application in Earth and Foundation Work

The earth and foundation work is an essential sub-phase for the construction of each type of buildings. It contains many repetitive operations and is also among the most dangerous work in building construction. Therefore, the research on the application of automation and robotics technology in earth and foundation work is one of the pioneers in the construction industry, and numerous papers have been published on this topic. Several reviews have been conducted in recent years to summarize the major studies comprehensively. To avoid repetitive work, this study only presents three latest reviews published in 2016 and 2017.

Naskoudakis et al. [6] reviewed 73 papers published from 2006 to 2015 about earthmoving equipment and divided them into seven main research themes, one of which is robotics and automation. Two sub-themes were then identified, i.e., unmanned construction, and real-time monitoring and detection. Azar and Kamat [7] provided a comprehensive review of the technical advances in earthmoving automation in both industry and academic community and discussed the limitations and future directions. They classified the studies of earthmoving equipment automation into four categories: equipment tracking and fleet management, safety management, equipment pose estimation and machine control, remote control and autonomous operation, among which the last one was identified as the most immature fields. Dadhich et al. [8] provided the background of the autonomous earthmoving, and presented a survey covering the key research topics and identified the knowledge gaps of automation of earthmoving machines, especially the operation of wheel loaders in a short loading cycle. In this review paper, the main knowledge gaps were identified as fragmented rock excavation, communication for remote operation, and operator experience during remote operation.

The major specific technologies included in automation and robotics technology and their applications mentioned in the above studies are identified and summarized in Table 1.

4 Application in Superstructure Erection

For the sub-phase of superstructure erection of high-rise buildings, the construction difficulty increases significantly as the building height grows, which mainly appears in three aspects, the low productivity and safety concerns due to the manual work in hazardous working environment, the vertical transportation of workers, materials and equipment, and assembly of heavy objects, especially for steel structures. Thus, the related studies are classified into three sub-themes corresponding to the three aspects: automated construction systems, automated lifting systems, and robot-based steel assembly systems. The following sub-sections will describe them respectively.

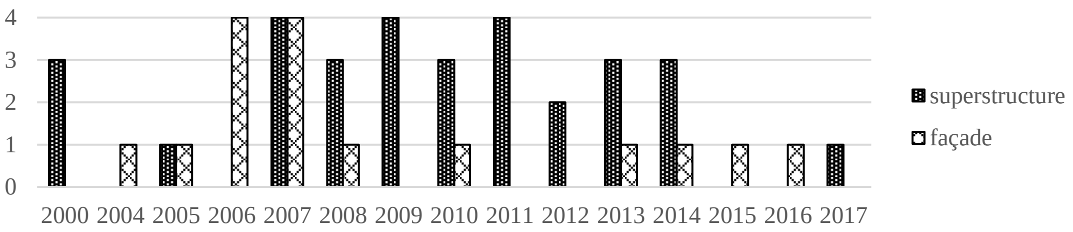

Figure 1. Distribution of the related papers of superstructure and façade

Table 1. Summary of the major specific technologies and their applications in the above studies

Application area		Function	Specific technology	Reference
Automated management	equipment management & progress monitoring	Localization	Radio-based technologies, such as GPS, RFID, and UWB; Vision-based technologies.	[6-8]
		Operation action recognition	Vision-based technologies.	[7]
	safety management	Accident warning	Vision-based technologies and 3D point cloud reconstruction.	[7]
Automated earthmoving operation	Remote operation	Human-machine interaction to improve the spatial and situational awareness of the operator	3D point cloud reconstruction; Augmented reality (AR); Haptic feedback joystick.	[6-8]
		Real-time information transfer	Wireless communication.	[8]
	Autonomous operation	Pose estimation of the end-effector	Radio-based technologies, such as GPS and UWB.	[7]
		Pile characterization for suitable excavation location and pose	Vision-based technologies; Laser-based technologies.	[8]
		Automatic control	AI & reinforcement learning.	[8]

4.1 Automated Construction Systems

Automated construction systems are designed to stabilize the construction process and improve the productivity of high-rise building construction by establishing a comfortable working environment which is suitable to employ the automated equipment and robots. In this study, seven related papers were identified.

Miyakawa et al. [9] proposed an automated building construction system (ABCS) for high-rise steel structures, which integrates three parts: 1) a synchronously climbing structure that encloses an all-weather working space, called "Super Construction Factory (SCF)"; 2) a parallel delivery system for material lifting; and 3) centralized management systems, for production management, equipment operation management and machine control. Based on ABCS, another system called "Big Canopy" was developed for prefabricated high-rise reinforced concrete buildings [10, 11], which adapts to the characteristics of reinforced concrete construction.

Compared with the conventional method, ABCS and Big Canopy successfully improved the working conditions and construction productivity. However, the equipment configuration of the SCF limits the versatility of automated construction systems. Moreover, the costs and weights are extremely high because of the combination of the robots, massive cranes and lifting systems [12, 13]. Therefore, Kang et al. [12] developed a robotic-crane based automatic construction system (RCA system) for steel structures of high-rise buildings, which comprises a construction factory (CF), a steel assembly system and a monitoring and control system. In RCA system, the tower crane was installed at the core of building so that the heavy lifting and robot systems are independent of the CF, which decreased the weight of the system and reduced the construction cost as well as provided a convenient working space. Kim et al. [13] developed several conceptual CF alternatives to improve the working environment, and evaluated them with the Computational Fluid Dynamics method. The evaluation procedure and results provided an economical approach to select the CF in high-rise building construction.

With the development of the automated construction system, assessment methods were proposed to measure the economic and construction efficiency. Kim et al. [14] developed a benefit/cost analysis process for the application of robot-based construction automation systems, which can measure the economic viability of the automated systems. Van Gassel [15] conducted a simulation of the construction process of a Dutch high-rise building, involving the use of an automated construction system. By comparing the simulation results and the real construction data, the paper verified the economic benefits of automated construction systems, and promoted the application of automated construction systems in the Netherlands.

4.2 Automated Lifting Systems

For high-rise buildings, the vertical transportation of workers, materials and equipment significantly influences the construction efficiency. Therefore, several studies have been conducted to improve the automation level of the vertical transportation equipment. Eight related papers are identified.

Kim et al. [16] proposed a table formwork lifting system integrated with construction hoists, which improves the productivity, cuts down the high initial cost and overcomes extra work for assembly and operation. Cho et al. [17] developed a hoist-mountable intelligent toolkit for the lift car. With this toolkit installed, an existing lift car can be converted to an intelligent one, which can utilize remote sensing and communication technologies to capture the information of material movement and manage it intelligently. Based on this toolkit, a concept of a smart robotic lift [18] is proposed, with functionalities of automatic loading/unloading operation and wireless communication.

Operation planning and optimization are major factors to determine the productivity of the automated lifting process. Sin et al. [19, 20] proposed an unmanned smart lifting system and devised an optimized operation algorithm for twin or multi-cage lifts, which can reduce work hours and traffic queues. Cho et al. [21] provided a simulation method of construction hoists to calculate the lifting cycle time according to lifting heights and loads, and to generate an optimal hoist operating plan. They also developed an optimal algorithm [22] for path planning of the multi-lifting operation in super-tall buildings. These algorithms and methods optimized the automatic control of the lifting system, and thus enhances the work efficiency of vertical delivery.

Operation monitoring is another important aspect, especially for the smart tower cranes. Lee et al. [23] proposed an automated lifting-path tracking system for a robotic tower crane, which used laser devices to measure the linear distance, and an encoder and an accelerometer to measure the horizontal and vertical angles. The system monitors the operation actions of the tower crane and is helpful in safety management and lifting path planning.

4.3 Robot-based Steel Assembly Systems

The robot-based steel assembly task in high-rise buildings can be divided into three aspects: alignment of the steel components and the bolting holes, transportation of the bolting robot, and bolting operation. Fourteen related papers are identified.

A research team from Korea University continuously studied on robot-based steel construction and proposed a robotic beam assembly system (RBA system) [24-26], which comprises three sub-systems: a robotic bolting device, a control system, and a robotic transport mechanism. The bolting device [27] consists of an end-effector for bolting operation, a robotic manipulator that places the end-effector in the bolting position, and a cabin as the control station. The robotic transport system [28] consists of a cross-wired lift and a rail sliding mechanism, respectively in charge of the vertical and horizontal transfer of the RBA system. Lee et al. [29] also proposed a robot-based steel beam assembly system with sub-systems of transportation and positioning. The transportation system combines a rail with a boom, and the positioning system comprises four wires-suspended motion control devices which can be teleoperated.

The steel components to be assembled are usually suspended from the tower cranes and have the problem of swinging, which affects the alignment operation. For easier and more precise alignment of the pendulum-like heavy objects, Jung et al. [30, 31] developed a robotic manipulator control algorithm to grip the steel components stably and efficiently. Bae et al. [32] designed an end-effector to fix the relative motion of the steel components and the end-effector itself. Mo et al. [33] developed a bolt-hole detection system with a 3D camera, which can estimate the location of a bolt-hole precisely and is robust in different illumination conditions.

To provide a safer and more convenient working environment for the human operators, Jung et al. [34] proposed a teleoperation system based on the RBA system. A control station is built outside the cabin, which comprises two joysticks, monitoring systems, and a controller for teleoperation. Liang et al. [35] developed a robotic assembly system for steel beam erection and assembly, which consists of four methods: rotation, alignment, bolting, and unloading. The system works autonomously without an operator in high places.

5 Application in Façade Installation

Façade installation is a common operation in high-rise building construction, which deals with heavy glass ceiling panels and exterior wall panels made of various materials. The operation locations are hazardous for workers to access and there is a high risk of injury and damaging the expensive panels in manual operations. In addition, the requirements of high-precision panel positioning and suitable weather condition further increase the difficulty. With these problems, façade installation robots and systems have been a hot research topic. A total of 16 related papers are identified.

The macro/micro motion-based robot is widely adopted in the proposed systems for both wall panel and glass ceiling installation. As shown in Figure 2, these robotic systems are usually combined with two relatively independent systems, respectively for macro and micro motion. The macro motion manipulator is usually a commercially available mini-excavator [36-40] or an aerial lift [36, 41, 42] to lift and move the panels, and the micro motion manipulator is usually a multi DOF robotic end-effector for precise handling of the panels. The installation is based on human-robot cooperative manipulation, which requires an intelligent manual robot controller to feedback the reaction forces from the environment. Compared with the manual operation, the robotic systems can improve the productivity and lower the safety risks at the construction site. Particularly, Cinkelj et al. [37] developed a closed-loop control system for the semi-automated façade assembly system by upgrading a commercial hydraulic telescopic handler. The closed-loop computer control significantly improves motion performance to meet the precision of façade installation and assures straight line motion of the end-effector.

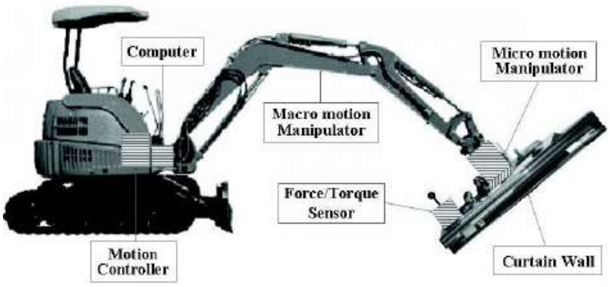

Figure 2. A typical macro/micro motion-based façade installation system [36]

Pan et al. [43] improved the conventional tower crane-based installation method and proposed a concept of a precast concrete panel installation system for high-rise buildings, which provides an integrated approach for panel loading, transportation, assembly and management. Van Gassel et al. [44] proposed a concept of a self-supporting robotic curtain wall system that integrates the assembly, disassembly and user functions of the curtain wall. Furtherly, they designed the mechanics and workflow of a self-assembling curtain wall system [45]. The stand of the system remains as part of the façade after installation, with the potential to serve in the following robot applications for disassembly or other user functions.

6 Discussion and Future Directions

As shown in Table 2 to Table 4, we summarized the major future directions and opportunities mentioned in the above-reviewed papers.

In the sub-phase of earth and foundation work, the current research is at the stage of semi-autonomous and tele-remote operation while the future work is towards fully autonomous operation. Therefore, the real-time communication, the situation awareness of the operator, the characterization of the geometry, and autonomous operation algorithms appear to be major problems. In addition, the technologies of Artificial Intelligence (AI) and machine learning are prospective to be adopted to deal with the various machines and materials and improve the automation level.

The automation and robotics technology application in the sub-phase of superstructure erection is divided into three sub-themes. First, the automated construction system was a versatile construction system when firstly proposed, while it has converted to several light-weight and independent systems, and the previous concept has evolved into "construction factory", which develops at the aim of providing a more desirable working environment for both workers and robots. Second, the automated lifting system should be combined with a ground-delivery system and a smart central control system to optimise the communication and operation planning. The radio-based technologies such as RFID are helpful in the lifting management. Finally, the robot-based steel assembly system is developing in the direction of teleoperation and autonomous operation, and the method of precise alignment of the wire-suspended swinging objects remains to be improved.

Table 2. Summary of the future directions (Sub-phase of earth and foundation work)

Future directions	Reference
Implementation of unmanned construction equipment and aircraft	[6-8]
Adoption of vision-based technology for monitoring	[7, 8]
Improvement of the situation awareness and reaction of the operator	[7]
Improvement of the real-time communication for remote operations and among the machines	[7, 8]
Adoption of AI and machine learning technology to support variations in machine and material	[7, 8]
Improvement of automatic pile shape and geometry classification with the technology of Simultaneous Localization and Mapping (SLAM)	[7, 8]
Development of autonomous loading algorithms and the method of fragmented rock loading	[7, 8]

Table 3. Summary of the future directions (Sub-phase of superstructure erection)

Future directions	Reference
1. Sub-theme: Automated construction system	
Simplification of the construction and dismantling of the temporary structure	[10, 11]
Improvement of the delivery efficiency	[10, 11]
Extension of the functions to be applicable for special-shaped building construction beside rectangular ones	[12]
Development of a light-weight system	[13]
Improvement of the simulation method	[13]
2. Sub-theme: Automated lifting system	
Implementation of RFID and USN technologies to improve the management	[17]
Optimization of the communication among the lifts, workers and the control system	[19, 20]
Improvement of the operation planning to adapt to various condition changes and lift unit changes	[22]
3. Sub-theme: Robot-based steel assembly system	
Extension of the functions to be applicable for special-shaped building construction beside rectangular ones	[24]
Development of complete robotic automation steel assembly system	[26]
Estimation and minimization of the shock of wire-suspended objects and development of robots that can absorb tremendous shock from heavy swinging objects	[30]
Improvement of the actuator for the alignment end-effector	[32]
Development of intuitionally joystick to improve operational performance	[34]
Adoption of AR and haptic technology to improve the working environment	[34]

The research on the sub-phase of automated façade installation is also on the way to teleoperation and autonomous operation to avoid human operators working in high places. Besides the remote operation techniques for human-robot cooperative manipulation, the development of algorithms and control strategies, and the implementation of related sensors will also improve the motion precision and installation performance. In addition, the façade installation robot can be adapted to other tasks involving lifting and carrying.

Although various technologies have been adopted in the application of automation and robotics technology in each construction sub-phase to deal with different problems, there are some basic equipment and operations.

Table 4. Summary of the future directions (Sub-phase of façade installation)

Future directions	Reference
Improvement of human-robot cooperative manipulation	[36]
Teleoperation based on force feedback	[36]
Development of software for integration of the handler into semi-automated façade assembly system	[37]
Implementation of inclinometers and ultrasonic sensors for automated leveling and distance measurement	[37]
Development for more application in other tasks involving lifting and carrying	[37]
Development of a mobile platform to replace the excavator for macro motion	[38]
Development of the control strategy and algorithms for human-robot cooperation	[36, 41]

Moreover, the steps of the automation process are also similar. For example, the five steps towards the autonomous operation of earthmoving machines [12], i.e., manual, in-sight teleoperation, tele-remote operation, assisted tele-remote operation, and fully autonomous, are also suitable in the development process of automation and robotics technology in other construction sub-phases. Therefore, the specific-task robots and automated systems are expected to learn from each other and may develop to handle more versatile tasks.

7 Conclusions

This paper summarized the application of automation and robotics technology in high-rise building construction from 50 papers published from 2000 to 2017 to provide a systematic review of the recent research and developments in this field from the perspective of three major construction sub-phases: earth and foundation work, superstructure erection, and façade installation. The paper also discussed future directions in each sub-phase in construction based on the literature.

This paper is expected to contribute to the knowledge body in that provides a valuable aid in future research and application of automation and robotics technology for high-rise buildings.

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A Framework for Constructing Semantic As-is Building Energy Models (BEMs) for Existing Buildings Using Digital Images

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Abstract –

Retrofits of existing buildings have great potential to reduce global energy consumption and greenhouse gas emissions. Energy modeling of existing buildings, which is commonly conducted to prioritize retrofit strategies, relies on as-is building energy models (BEMs) that represent actual conditions of buildings. Recent efforts have focused on leveraging sensing technologies such as laser scanning and photogrammetry to capture as-is conditions of buildings and developing automatic methods for creating BEMs using the captured data. However, the majority of these efforts are limited to reconstructing 3D facade geometries with poor semantic information for rough BEM use. To this end, this paper presents a framework for an image-based approach to construct complete and semantic as-is BEM geometry models for existing buildings. The framework consists of four modules: 1) the data capture module that collects digital images of building facades and interior spaces and relevant "placement" information for geometry definition; 2) the building surface geometry reconstruction module that recognizes main building components required by BEM and reconstructs their 3D surface geometries from captured images; 3) the semantic enrichment module that adds the required geometry-related semantic relationships among the reconstructed building elements and interior spaces; and 4) the BEM creation module that stores the semantic geometry model in IDF data model. This framework is expected to extend existing research by creating complete (i.e. include not only building facades but also interior spaces) and semantic-rich as-is BEM geometry models.

Keywords –
Building energy model (BEM); building surface geometry; image-based 3D reconstruction; semantic enrichment; existing buildings; IDF

1 Introduction

The building sector accounts for almost 35%-40% of the total energy end-use worldwide [1, 2]. In this sector, most energy consumption is contributed by the operation of existing buildings [3]. Retrofits of existing buildings towards energy efficiency improvement have been well recognized as an important role in reducing global energy consumption and greenhouse gas emissions. Building energy simulation is a powerful and computerized approach for assessing building energy performance [4]. In building retrofit decision-making processes, this approach is commonly used to prioritize various retrofit strategies by quantifying their potential energy performance improvements and associated cost savings. To implement such simulations reliably, as-is building energy models (BEMs), which represent the actual conditions of existing buildings, need to be created first.

The creation of a BEM for an existing building requires large amounts of inputs, which typically include building geometry, constructions, HVAC systems, space loads, local weather data, operating schedules and other relevant parameters [5]. In the current practice, these inputs are primarily manually prepared by energy modelers using design documents (e.g., 2D CAD drawings and specifications) and/or actual photos [4]. This manual process is usually labor-intensive, costly, and error-prone, and inevitably arbitrary due to the human interpretation of the design documents [6]. Furthermore, the resulting BEMs may only exhibit the as-design rather than the as-is conditions of buildings [7]. This is because buildings tend to be deteriorated in performance and usually undergo various renovations over their service lives. In addition, design documents for many old buildings are even not available.

To address these issues, some recent efforts have focused on leveraging sensing technologies such as laser scanning and photogrammetry to capture as-is conditions of buildings and developing approaches that can use the captured data to automatically create as-is BEMs or as-is

BIMs for energy analysis purposes [8, 9, 10, 11]. According to the type of input data, these approaches can be roughly categorized into two groups: point cloud-based approaches and image-based approaches.

Point cloud-based approaches extract 3D semantic models from the point clouds of buildings that are usually collected from a laser scanner. Wang et al. [9] developed a methodology for automatically reconstructing 3D surface geometries of building envelopes using point cloud data. In their method, five types of building components required by BEM (i.e., walls, doors, windows, floors and roofs) can be recognized and reconstructed. Dı´az-Vilarin˜o et al. [8] developed a 3D as-built modelling methodology for solar shading analysis of existing buildings. In this method, three types of building envelop components (i.e., external walls, floors and roofs) and surrounding shades are considered. As both works only focus on the reconstruction of building facades, their outputs only support some rough and preliminary energy analysis (e.g., envelope choices, building orientation and shading analysis). They cannot be used for more complex energy analysis like whole-building energy simulation which requires the geometric description of entire buildings including building interiors (i.e. internal thermal spaces).

Semantic as-is modelling of building interiors using point cloud data has also been explored by some researchers, but they do not have a specific consideration for BEM use. In other words, the resulting models usually do not carry all semantic information (see details in Section 2) required by BEM. For example, Xiong et al. [12] proposed a context-based approach to semantically reconstruct building interiors. However, in the resulting models, the semantic information included mainly refers to the component type (i.e., walls, floors, ceilings windows, and doorways) that each 3D surface belongs to. Other required semantic information for a surface are not included, such as the geometric/topologic relationships between this surface and other surfaces and outside conditions (facing to outdoor environment, an indoor space or another surface).

Image-based approaches in 3D as-is condition modelling have received increasing attention in recent years. On one hand, as-is condition capture using digital cameras is more convenient and economic than using a laser scanner [13]. On the other hand, the accuracy loss of point cloud-based approaches due to noisy and missing data could be effectively addressed by image-based approaches [13,14,15]. In the context of as-is BEM creation, a recent work was conducted by Cao et al. [11] who developed an approach to reconstruct building facades from low-resolution aerial images. Building facade components including walls, doors and windows can be recognized. Again, this approach does not handle building interiors so that it cannot produce detailed geometry models required by complex building energy simulation. Another significant limitation of this approach is that it cannot automatically merge building facades reconstructed from different images into a single model. This approach requires additionally manual efforts to combine surface models generated from different images.

To address the limitations in existing efforts, this paper aims to develop a framework for an image-based approach to automatically construct complete and semantic as-is BEM models for existing buildings. This paper specifically focuses on detailed building geometry model creation for accurate whole building energy simulation purpose. The particularities of the proposed framework are threefold: (1) it enables the recognition of building components and the extraction of their surface geometries from images of both building facades and interiors; (2) it provides the mechanism to automatically merge the surface models generated from individual images into one single and uniform model; and (3) it computes all geometry related semantic information required by BEM.

The rest of the paper is structured as follows: Section 2 explains the features of BEM geometry models and the relevant semantic information requirement; Section 3 details the main modules of the proposed framework; and Section 4 concludes this paper and outlines future work.

2 BEM Geometry Model Description

A BEM geometry model mainly consists of three types of information: building geometry, coordinate systems, and geometry related semantic information. Building geometry is composed of basic building elements (e.g., walls, floors, windows, doors, and roofs, etc.) and shading devices, which are usually defined as a collection of planar surfaces [16]. Geometrically, the surfaces of building elements are 3D polygons with a normal pointing to the outside of the zones that they bound [16]. The geometry of each surface is depicted in a given coordinate system, which can be global or local. These coordinate systems enable the integration of these surfaces to form a complete building model. The geometry related semantic information mainly include the building object type that each surface represents and the geometric/topological relationships between those surfaces (i.e. building elements). These kinds of semantic information are detailed later in a specific case.

The organization of these information varies in different BEM tools as they usually have their own internal data models. In this paper, EnergyPlus is selected as the target tool due to its prevalence and wide utilization. Input Data File (IDF) is the native input format of EnergyPlus. In IDF, the building geometry can be described by six classes in an up-bottom approach [17], as shown in Figure 1. The roles of these classes are described as follows [17]:

- *Site:Location*: to define the location of a building.
- *Building and Zone*: to define the hierarchical coordinate systems for the building geometry description.
- *BuildingSurface:Detailed*: to define building components including walls, floors, ceilings and roofs.
- *FenestrationSurface:Detailed*: to define opening elements including windows and doors.
- *Shading:Zone:Detailed*: to define attached shading elements of a building.

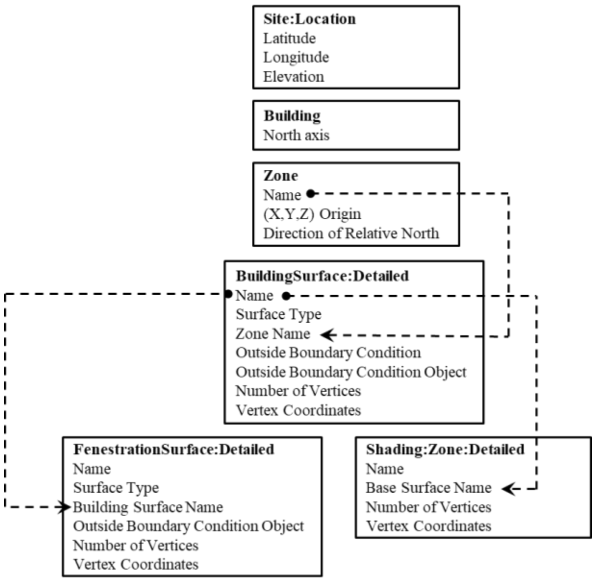

Figure 1. IDF classes for building geometry description. Note: classes providing general surface definition methods are selected; for each class, only geometry definition related attributes are listed; and only attached shading devices are considered.

Essentially, the latter three classes with various attributes provide means of defining building geometry with semantic information. In these classes, common attributes including *"Number of Vertices"* and *"Vertex Coordinates"* are used to define the exact surface geometries of building elements. Other attributes specify the required semantic information, which are summarized as follows [17]:

(1) *"Surface Type"*: to specify the building element type that the surface represents.

(2) *"Zone Name"*: to specify the zone that the surface bounds. This attribute builds the geometrical/topological relationship between building elements and relevant zones.

(3) *"Building Surface Name"*: to specify the parent surface (i.e. a building component) that this surface (i.e. an opening element) is attached to. This attribute builds the geometrical/topological relationship between openings and the building components that host them.

(4) *"Base Surface Name"*: to specify the surface (usually a wall) that this surface (i.e. a shading element) is attached to. This attribute builds the geometrical/topological relationship between shading elements and their influenced walls.

(5) *"Outside Boundary Condition"*: to specify the condition of the other side of this surface. The condition can be outdoors, ground, a surface that bounds another zone, or adiabatic.

(6) *"Outside Boundary Condition Object"*: to specify the surface that is located on the other side of this surface. This attribute together with attribute (5) build the geometrical/topological relationship among non-shading element.

Most efforts on automatic as-is modelling of existing buildings for energy analysis are limited to reconstructing surface geometries of specific building elements (e.g. facades and shading elements) with poor semantic information (usually only includes (1) and (3)). The framework proposed in this paper aims to achieve an automatic creation of complete building geometry with all semantic information required by whole building energy simulation.

3 Framework for Constructing As-is BEM Geometry Model Using Digital Images

The proposed framework consists of four modules (see Figure 2): image and placement data collection, building surface geometry reconstruction, semantic enrichment, and BEM geometry model creation.

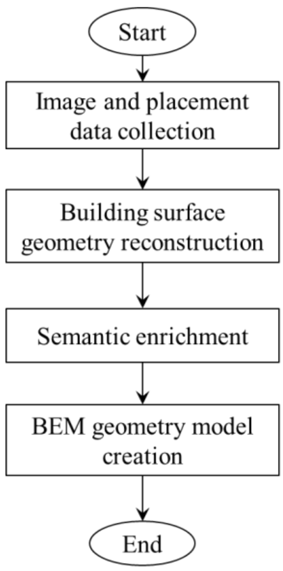

Figure 2. Proposed as-is BEM creation framework

3.1 Module 1: Image and placement data collection

The digital images of building facades and interiors as well as relevant placement data need to be collected for the 3D reconstruction of the entire building. Image data can be conveniently collected by some commonly used and economic devices with the image taking function. In this paper, a drone with an amounted camera is used to capture images of building envelops and a smartphone is used to capture images of building interiors. The placement data refers to a set of measurable parameters that can be used to determine the relative spatial relationships among the building elements in different images. The need of the placement data is because building elements reconstructed from an individual image can only be defined in an assumed coordinate system but the relationships between the assumed coordinates of building elements in different images are unknown. The placement data helps to geometrically link the building elements extracted from different images. Using one-storey building as an example, Figure 3 illustrates the parameters that need to be measured and the principle how these parameters are used to determine the relative spatial relationships between building elements in different images.

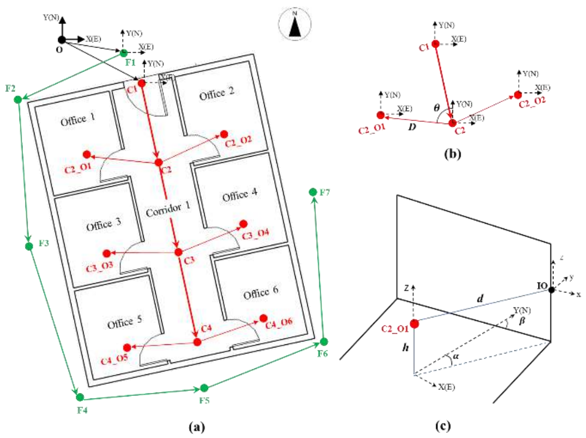

Figure 3. Data collection: (a) reference points setting; (b) parameters required for computing TR_CC; and (3) parameters required for computing TR_IC

In Figure 3(a), two sets of reference points are set up for building facades and building interiors respectively. These reference points work as a medium for geometrically connecting the building elements that can be viewed from these points. The point **O** refers to the root point used for combining the two sets of reference points. Two requirements should be satisfied for setting these points: (1) the range of vision from these points together can cover entire building facades and interiors; and (2) two adjacent points should be able to see each other. The method to obtain the required placement information is detailed as follows.

First, set up two types of 3D coordinate systems:

- Local coordinate system for reference points (see Figure 3(b)): origin (0,0,0) is set at a constant height from a floor (for interior points) or from the ground (for exterior points), axis X refers to East, axis Y refers to North, and axis Z is decided based on X and Y using the right-hand rule.
- Local coordinate system for each image (see Figure 3(c)), more specifically for describing vertical elements in each image: origin (0,0,0) is located on the right edge of the wall surface (when facing the surface at relevant reference point) and at the height same to relevant reference point, axis Z is identical to that of relevant reference point, axis Y is perpendicular to the surface of the vertical element and points to the outside of the space (or outdoors) that the surface bounds, and axis X is decided based on Z and Y using the right-hand rule.

Second, establish the transformation relationships (denoted as TR_IC) between the coordinate system of images and their corresponding reference points. Through TR_IC, a building element surface can be transformed from its own local coordinate system (LCS) to the LCS of the reference point. This means that the geometries of building elements sharing a common reference point can be linked together in the LCS of the reference point. Figure 3(c) illustrates three parameters (i.e., α, β and d) that need to be measured for computing TR_IC.

Third, establish the transformation relationships (denoted as TR_CC) between the coordinate systems of two adjacent reference points. Through TR_CC, a building element surface defined in the LCS of a reference point can be transformed into the LCS of any other reference point. In other words, building elements reconstructed from individual images can be combined as an integrated building model. Figure 3(b) illustrates two parameters (i.e. θ and D) that need to be measured for computing TR_CC.

Among the five parameters, all angular parameters are measured using a smartphone with the embedded compass, and all distance related parameters are measure using a portable and cheap laser rangefinder.

3.2 Module 2: Building surface geometry reconstruction

Based on the images and placement data collected from Module 1, this module reconstructs building surface geometry in two steps: vertical building element reconstruction and horizontal building element reconstruction.

3.2.1 Vertical building element reconstruction

Vertical building elements including walls, windows, doors, and columns are reconstructed from relevant images. First, a neuro-fuzzy system (NFS) based algorithm, as shown in Figure 4, will be established for the automatic recognition of building elements contained in an image. In order to take into account the possibilities of information shortage and inaccuracy in collected images, the fuzzy logic algorithms are investigated, which can reason with imprecise information. Fuzzy logic systems can make decisions even with incomplete or uncertain information. However, individual fuzzy logic algorithms cannot automatically acquire the rules used to make those decisions and have its own limitations. To overcome these limitations, this paper adopts an intelligent hybrid system (i.e., a neuro-fuzzy system), which combines fuzzy algorithms with neuro-computing systems. Interpretability and accuracy, which are main strengths of the neuro-fuzzy method, are the key criteria for choosing algorithms in this module.

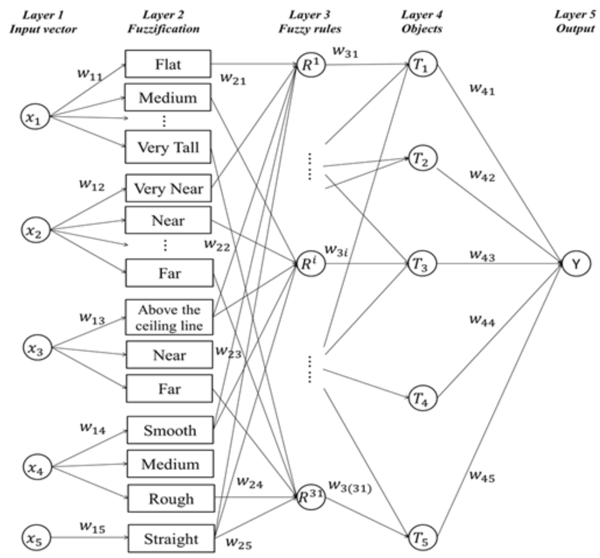

Figure 4. Architecture of proposed NFS for Module 2

Second, an image-driven feature extraction system will be developed to obtain the geometric dimension of these recognized building elements. A ruler will be set in the target scene (i.e. the scene that is to be pictured) for the reference of measuring dimension. Real distances for boundary edges of each recognized element are calculated based on the pixel distance (d_p), which is defined by the Euclidean distance ($d_{Euclidean}$) for a binary image $B[i, j]$:

$$d_p = d_{Euclidean}([i_{1p}, j_{1p}], [i_{2p}, j_{2p}]) = \sqrt{(i_{1p} - i_{2p})^2 + (j_{1p} - j_{2p})^2}, p \in \{l, r\} \quad (1)$$

where $[i_{1p}, j_{1p}]$ and $[i_{2p}, j_{2p}]$ represent the locations of different pixels in the binary image; l is the length of lines (e.g., line 1 and line 2) defined by the pixel distance for each selected component; and r is the length of the reference ruler measured by the pixel distance.

Images of horizontal shading devices like overhangs are processed additionally based on the adjustment on the neuro-fuzzy system and the image-driven feature extraction system.

Finally, each extracted surface is output as a polygon with a list of ordered 3D vertices in its own LCS. The "ordered" for an interior surface means that the resulting polygon is defined with a normal pointing to the outside of the space that the surface bounds, while for an external surface its normal points to the outdoor environment.

3.2.2 Horizontal building element reconstruction

Horizontal building elements including floors, ceilings and roofs are inferred based on the reconstructed vertical building elements. More specifically, the slab and the ceiling of an interior space are extracted from the vertices (with smallest z value and largest z value respectively) of vertical walls and columns that enclose the same space. Specifically, these wall and column surfaces need to be transformed first into LCS of the space (i.e. the LCS of a reference point in the space). Therefore, the resulting slab and ceiling surfaces are defined in the LCS of the space. Similarly, the geometry of a roof is inferred from the vertices (with largest z values) of all external wall surfaces that have been transformed into a same coordinate system.

The expected output of this module is a complete building surface model including building facades and interiors (see the example shown in Figure 5). In the output, all the surfaces are defined in the LCS of corresponding reference points, and the transformation relationships between the LCS of reference points are also stored.

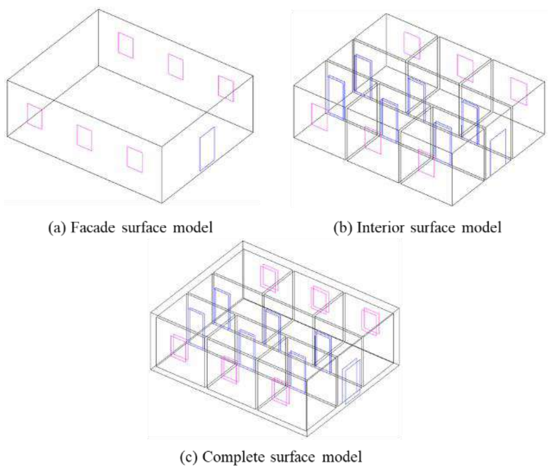

Figure 5. Visualization of the resulting building surface geometry model

3.3 Module 3: Semantic enrichment

So far, for a surface, its geometry defined in the coordinate system of a reference point, and some semantic information (i.e. the space that the surface bounds and the building element type that the surface represents) have been obtained. This module further adds the remaining semantic information required by BEM for each surface. The whole process is implemented in four steps which are detailed as follows.

3.3.1 Building surface geometry transformation

In this step, all surface geometries are transformed from their own coordinate systems to the root coordinate system based on the transformation matrices between control points. In the case of Figure 3(a), the root coordinate system refers to the coordinate system set on the control point **O**. Surfaces defined in the coordinate system on a control point like **C2_O1** can be transformed into **O** by tracing the established image collection route **C2_O1** -> **C2** -> **C1** -> **O**. By this transformation, all surfaces are described in a uniform coordinate system, which enables the geometry operations involved in the following steps.

3.3.2 Semantic enrichment for surfaces of walls, floors, ceilings, columns and roofs

As introduced in Section 2, the IDF class BuildingSurface:Detailed is used for defining surfaces of walls, floors, ceilings and roofs. Columns considered in this paper are treated as walls so that they can be accepted by the IDF data model. For these surfaces, two types of semantic information, i.e. Outside Boundary Condition and Outside Boundary Condition Object, need to be added (see Figure 1). In IDF, the outside condition of a surface can only be one of the situations: Surface (i.e. these is another space on the other side), Adiabatic (i.e. these is a building element on the other side), Outdoors, and Ground, etc. [15]. This means the surfaces reconstructed from Module 2 may need to be spilt by taking the outside conditions into account. A typical example is illustrated in Figure 6(a): the wall surface colored with red has two different outside situations, i.e. space (i.e. Room 2 and Room 3) and building element, while the wall surface colored with green has one outside condition. Therefore, the red wall surface needs to be geometrically spilt into three pieces and the green wall surface does not need (see Figure 6(b)). Only if the outside condition of a surface is Surface, the Outside Boundary Condition Object will be specified (see Figure 6(b)). A specific algorithm to achieve this semantic enrichment process is developed and Figure 7 shows its pseudocode. Figure 8 shows the processing result of the building surface geometry model by this step.

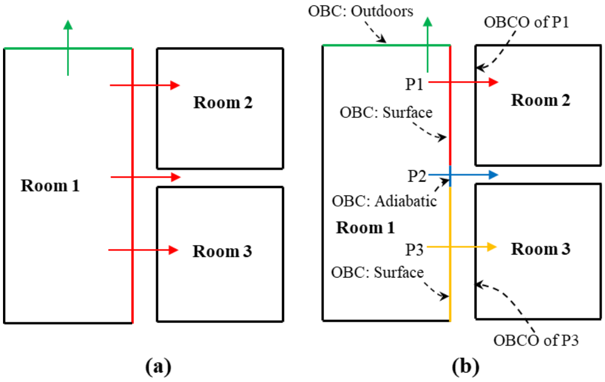

Figure 6. Illustration of the outside conditions of a wall surface. Note: Outside Boundary Condition = OBC; Outside Boundary Condition Object = OBCO.

```
Input: Reconstructed building surfaces S
1:  Extract surfaces of walls, floors, ceilings and roofs from S and
    store as S_walls, S_floors, S_ceilings, S_roofs respectively
2:  foreach  s ∈ S_walls do
3:      find all surfaces s_all that represent the same wall to s
4:      foreach t ∈ s_all  do
5:          project t onto (s_all - t) (all other surfaces in s_all) along the
            normal direction of t
6:          spilt t into two parts: Part 1: t ∩ (s_all − t);
            Part 2: t − (t ∩ (s_all − t))
7:          if  Part 1 are internal and not empty  then
8:              set the outside condition of Part 1 as Surface
9:              set the outside condition object of Part 1 as t ∩ (s_all − t)
10:         else if  Part 1 are empty  then
11:             set the outside condition of Part 1 as Adiabatic
12:         else if  Part 1 are external to outdoor environment  then
13:             set the outside condition of Part 1 as Outdoors
14:         else if Part 1 are external to ground  then
15:             set the outside condition of Part 1 as Ground
16:             set the outside condition object of Part 1 as t ∩(s_all − t )
17:         end if
18:         if  Part 2 are not empty  then
19:             set the outside condition of Part 1 as Adiabatic
20:         end if
21:     end foreach
22:     S_walls ← S_walls - s_all
23: end foreach
24: repeat process from Line 2 to Line 21 for S_floors, S_ceilings,
    S_roofs  respectively
```

Figure 7. Semantic enrichment algorithm for the surfaces of walls, floors, ceilings, and roofs

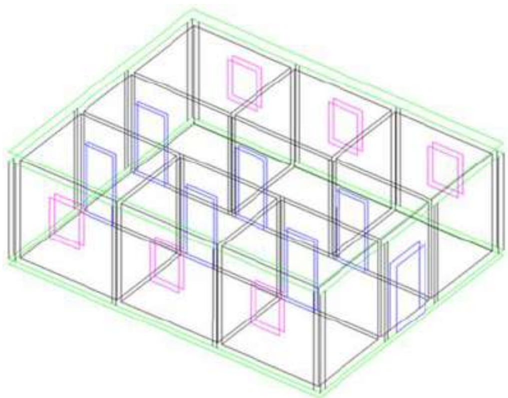

Figure 8. Visualization of the processed building geometry model

3.3.3 Semantic enrichment for surfaces of windows and doors

Surfaces of opening elements (i.e. windows and doors) are defined with *FenestrationSurface:Detailed* in IDF. For these surfaces, two types of semantic information, i.e. "*Building Surface Name"* and "*Outside Boundary Condition Object"*, need to be computed. The first type specifies a parent surface (usually a wall surface) that holds the opening surface. Such parent surface can be computationally detected by finding a surface, the polygon of which geometrically contains all the vertices of the opening polygon.

An opening element (except external openings) is usually defined as a pair of opening surfaces in BEM. For an opening surface, the *"Outside Boundary Condition Object"* specifies another corresponding opening surface, which can be detected by the following procedure: first, identify all other opening surfaces that are parallel to this surface; second, compute the distances between all the identified surfaces and this surface. The surface nearest to the opening surface is thus recognized as the target.

3.3.4 Semantic enrichment for surfaces of attached shading devices

For a shading device surface, the base surface (usually an external wall surface) that it is attached to needs to be specified. The base surface can be easily detected by finding a building facade surface, which geometrically contains one edge of the shading device surface.

3.4 Module 4: BEM geometry model creation

After the semantic enrichment of all building surfaces are finished, an IDF-based BEM geometry model is generated in this module by wrapping these objectified surfaces with corresponding IDF classes following the syntax of IDF schema. Surfaces of walls (columns), floors, ceilings and roofs are defined with the IDF class *BuildingSurface:Detailed* and its attributes; surfaces of windows and doors are defined with *FenestrationSurface:Detailed* and its attributes; and surfaces of shading devices are defined with *Shading:Zone:Detailed* and its attributes. All surface geometries have been transformed into a common coordinate system which takes North as Y axis and East as X axis. This coordinate system is actually identical to the global coordinate system used in IDF [15]. Therefore, a global coordinate system rather than a set of local coordinate systems is used in the resulting IDF geometry model. This means that the values of the attribute *"North Axis"* of *Building* and the attribute *"Direction of Relative North"* of *Zone*, which are used to define hierarchically local coordinate systems for IDF geometry models, can be ignored (i.e. no need to calculate). The geographical location of a building defined by *Site:Location* is usually directly obtained from a weather data file.

Once these geometries, coordinate systems and the semantic information for an existing building are integrated and well organized into IDF format, a corresponding semantic IDF geometry model for this building is achieved. It can be used together with other input data such as local weather data and construction materials to conduct energy performance analysis for the building for various purposes (e.g. assessment of retrofit strategies and optimization of operating schedules).

4 Conclusions and Future Work

In this paper, we present a framework for an image-based approach to automatically construct complete and semantic BEM geometry models for existing buildings. The framework consists of four modules. In the first module, we develop a specific data capture approach which can obtain the "placement" information in the process of collecting images of building facades and interiors. The "placement" information helps to Module 2 to combine surface geometries of building elements extracted from individual images into a uniform building model. Specifically, a neuro-fuzzy system and an image-driven system are presented for recognizing vertical building elements (i.e. walls, windows, doors and columns) from images and reconstructing their surface geometries respectively. The approaches for reconstructing horizontal building elements (i.e. floors, ceilings and roofs) are also introduced. In Module 3, computational approaches for enriching geometry related semantic information required by BEM are proposed. The generation of IDF-based geometry models is explained in Module 4.

This framework is expected to extend existing research by: (1) enabling the reconstruction of building elements from images of building facades and interiors; (2) providing the mechanism to automatically combine the reconstructed elements from individual images into one uniform model; and (3) allowing the addition of all geometry related semantic information required by BEM. The resulting BEM geometry models can be used for accurate and detailed energy simulation purpose.

For future work, all the approaches and algorithms involved in the proposed framework will be compactly implemented and examined. Several multi-storey office buildings with regular shapes and less furniture in building interiors will be selected to verify the proposed framework in terms of the feasibility and the accuracy.

5 Acknowledgements

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A master model approach for design and analysis of roof trusses

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Abstract

Apartment housebuilding takes too long time and optimal solutions are seldom found. In housebuilding projects, there is an increased popularity of using virtual models for analyses of structural integrity and floor layout. However, these analyses are seldom coordinated since the models rarely are linked and the designers are not working close enough. As such, optimal designs are hard to find and time flies since even small changes turn into many iterations between design and structural analysis. General building information modeling and virtual design and construction methodologies suggest the use of interoperability and automation to bridge these gaps. There are examples of design tools that link different models using off-the-shelf tools or programming. However, most of the housebuilding companies seldom have these advanced tools or have the competence to do advanced programming. In this paper, we suggest an approach of using visual programming in a common BIM-software to explore the linking of different models. As an example, we study design of roof trusses since for many different roof shapes the same rules usually apply to the design of the truss. This project connects a BIM-software and a FEM-program with a master model. The model automatically generates a roof with the designed truss, draws the representation in a BIM-software and analyze it in a FEM-program. The early evaluations of this visual programming based approach are promising as there are possibilities to connect other domain models and create an even richer evaluation bases for early apartment housebuilding design.

Keywords –

Roof trusses; Design automation; Finite element model

1 Introduction

The housebuilding industry strives to cut lead times, increase quality and reduce cost. In early design, many important decisions are taken which will impact the rest of the building life cycle, why the use of virtual models are increasing in popularity to predict life cycle effects, e.g. structural integrity, energy consumption, constructability changes due to design changes. Although more and more models are being used during design there is still a challenge to coordinate design and analysis in a way that promotes evaluation of more design alternatives than just a few, why solutions tend to be good enough instead of optimal. Making changes in models tend to take time since not all models are linked with each other and not always have parametric capabilities. Building information modelling (BIM) sets the framework for how to create parametric and information rich models [1], and virtual design and construction (VDC) likewise sets the framework for visualization, interoperability and automation [2]. Thus, BIM and VDC targets this challenge on an overarching level.

Looking in to more specific applications several researchers exemplify applications of how to link models, e.g. [3], or automating design tasks, e.g. [9], using off-the-shelf tools or text-based programming, such as C++ or Python. These types of applications are suitable for larger housebuilding companies or very specialized consultant companies with competences and resources to handle such advanced technology. But, many small and medium sized construction companies do not have these opportunities.

Therefore, the aim of the paper is to suggest an approach that creates a master model using visual programming languages (VPL), since VPL with its graphical interface enables a lower threshold to climb than most text-based programming languages.

There are examples of architects using VPL to automated generation of more shape-based buildings or artefacts [4]. Other examples of VPL use includes leveraging it to enable BIM-based assessment of environmental performance [5]. The use of VPL for model coordination within construction design and analysis is yet to be detailed by the research community. The approach suggested in this paper is exemplified with a design tool for roof trusses.

2 Background

This paper deals with virtual construction and particularly how to use models to enable flexible and efficient design and analysis during early design of buildings. As mentioned above the fields of BIM and VDC are framing the theory for this paper and below we introduce the areas of design automation and master models which are key topics for the presented approach. Research regarding roof truss design tools are also described.

2.1 Design automation

Design automation stems from the area of parametric mechanical CAD (computer aided design) and can, according to Cederfeldt and Elgh [6] within the manufacturing industry, be a way of developing tools that enable re-use of engineering solutions. According to Sandberg et al. [7] design automation in construction relates to several different techniques of which we here briefly introduce knowledge-based engineering, configuration and modularization.

Knowledge-based engineering (KBE) is essentially rule-based CAD where rules are implemented using for example object oriented programming. These rules are used to generate geometry models, finite element models, reports, bill-of-materials etc. [8]. The term knowledge-based comes from the act of acquiring knowledge from engineers to allow for automating some of their routine tasks to free time for more challenging engineering tasks. This act of automating engineering tasks has been used by experienced engineers since the dawn of the computer, as one of the important roles of the computer is to automate tasks.

Configuration is usually enabled by developing a product platform which consists of a limited number of modules that can be combined into many products and can be used during detailed design [9]. So, compared to KBE, configuration usually is connected to modular product architectures while KBE also is used for more integral product architectures. KBE can be used for both early, system and detailed design while configuration is more common to apply in detail design. Of course, there is overlap here and one could say that a KBE tool is used to configure a product. A difference is that KBE tools also can include generation of analysis models. In short configuration can be seen as a subset of KBE.

Some architects do design automation by building up parametric models using VPL such as Grasshopper, Dynamo, GenerativeComponents etc., [4]. This is a more shape-based type of parameterization that uses more advanced mathematical expressions, compared to KBE and configuration, and is suitable for calculating the form of more advanced shaped architectures. In a more similar fashion to KBE, the use of VPL has been seen in the realm of environmental concern. For example, Asl et al. [5] presented a framework for BIM-based performance optimization where VPL was used to generate design options, assess environmental performance, and search for the optimal design solutions. Other applications of VPL include Khaja et al. [10] that investigated using VPL to automatically populate non-geometric data into BIM models for operations.

2.2 Master models

The idea with master models is to reduce the need for manual updates of virtual models and instead create a governing product definition that is linked to other domain models of interest, e.g. finite element models, energy calculations, micro climate estimations. So, when the product definition is changed in the master model, this change automatically propagates to all other linked models. This idea has featured some modelling computer systems since the 1970s, [11].

The main idea of having information stored in one place connects to the idea of the BIM-hub [1] and some off-the-shelf CAD and BIM software also feature master model capabilities. Some examples are the connection between the BIM-tool Revit and Vico Office for model-based cost estimation and planning, or Revit and Robot for structural integrity evaluation, although these links require many manual interventions as well.

Negendahl [4] describe three ways of coupling tool models: 1) *combined model method*, where the design and analysis functionalities essentially are integrated but the user is restricted to the options and features offered by a particular software, 2) *central model method*, which is close to BIM where the data is centralized in a shared data schema usually using IFC (industry foundation classes) or other neutral formats such as gbXML (Green Building Extensible Markup Language) and is argued to be time consuming to use in team based design exploration, and 3) *distributed model method*, is compared to the central model method not hierarchal, instead the connections are more distributed into a more flat model organization.

The field of multidisciplinary design optimization (MDO) also connects to the master model idea by embracing the importance of linking models to each other allowing for automated design and analysis loops. According to Díaz et al. there is still research work to do to overcome parametrical issues and challenges to create interoperability between models, [3].

2.3 Roof truss design tools

Shea et al. [12] present a performance-driven generative design tool for cantilever roof truss design. GenerativeComponents (Microstation) is used together with an optimization process called structural topology and shape annealing within the generative structural design system called eifForm. By applying XML models, it is possible to link these softwares together.

Flager et al. [13] present a method for fully constrained design applying gradient-based optimization that also is exemplified for steel roof trusses for a sports arena. The process integration and design optimization software ModelCenter was used together with the Digital Project CAD software and a finite element analysis software. The implementation was evaluated with conventional design and the results showed that the implementation took 30 man-hours longer but evaluated almost 500 times more solutions.

Villar et al. [14] describe how to use genetic algorithms to optimize the design of heavy timber trusses. This research is centered around an analysis model where the design optimization is done. It was found that genetic algorithms are effective for optimization of glulam roof truss structures.

2.4 Research motivation

Since off-the-shelf MDO tools as well as automating BIM activities usually involves advanced programming in this paper explores how the possibility of using VPL to mitigate the parametrical and interoperability issues by creating a master model. Also, automatic design tools connecting design and analysis models seem to focus steel structures why it is a need to investigate automatic design tools for timber roof trusses.

3 Research process

This research was conducted by studying earlier research to motivate the research gap and serve as input to the development of the proposed approach. Developing the master modelling approach was an iteration between studying literature, generating ideas and developing the example tool.

Discussion were held with designers from a company that was interested in the field of making design and analysis more efficient using virtual models. The company conducts design and production of prefabricated modular multi-family timber buildings. Roof truss design was identified as an interesting topic, since they are featured in all projects, and an implemented design tool has the possibility to be used continuously in future projects. The company supplied drawings from a recent building project as input to the tool development. The drawings showed a surprising number of different configurations and the possibility to standardize the design of roof trusses was identified as an opportunity for saving design costs. As a way of limiting the design space the company articulated that it is most economic to use trusses with same length for the top beam.

The development of the example tool was done mainly by the first author and discussed among the authors. First, a simple version was developed to investigate if Revit, Dynamo and Robot worked as expected. Then the tool was further refined to incorporate more details and parametric capabilities. When the second version was developed the tool was evaluated against relevant literature.

4 Results

4.1 Proposed approach

The proposed master modelling (MM) approach is shown in Figure 1. A design and analysis loop can be conducted and contains 1) giving product definition input to the master model, 2) generating analysis models, 3) evaluating objective function (design goals) and 4) if not satisfied repeat.

The MM contains the logic done in VPL that represents the building geometry and its properties as well as other parameters needed for linking to the other domain models. If the VPL part is not enough in terms of built-in functionality to automate the generation of the domain models, scripts and software-specific macros might be needed. A database with additional information regarding e.g. materials, environmental product declarations can be either part of the MM or provided as a linked resource. If a fully automatic design and analysis loop is reached, then optimization is possible to conduct. This could be done either through the VPL part or by a separate managing unit using e.g. MATLAB or text-based programming.

Using the MM starts with giving input. If it is a fully automated MM then the input concerns the optimization, e.g. objective function, possible parameter values, maximum number of iterations. Then the MM is executed and models are generated and evaluated until the optimization unit is satisfied or maximum number of iterations are done. If the MM is used in a semi-automatic fashion, then the input is values for the design parameters and then the model generation is executed. When the models have produced their results, the user or users within the design team must evaluate the results and decide if another design and analysis loop should be initiated.

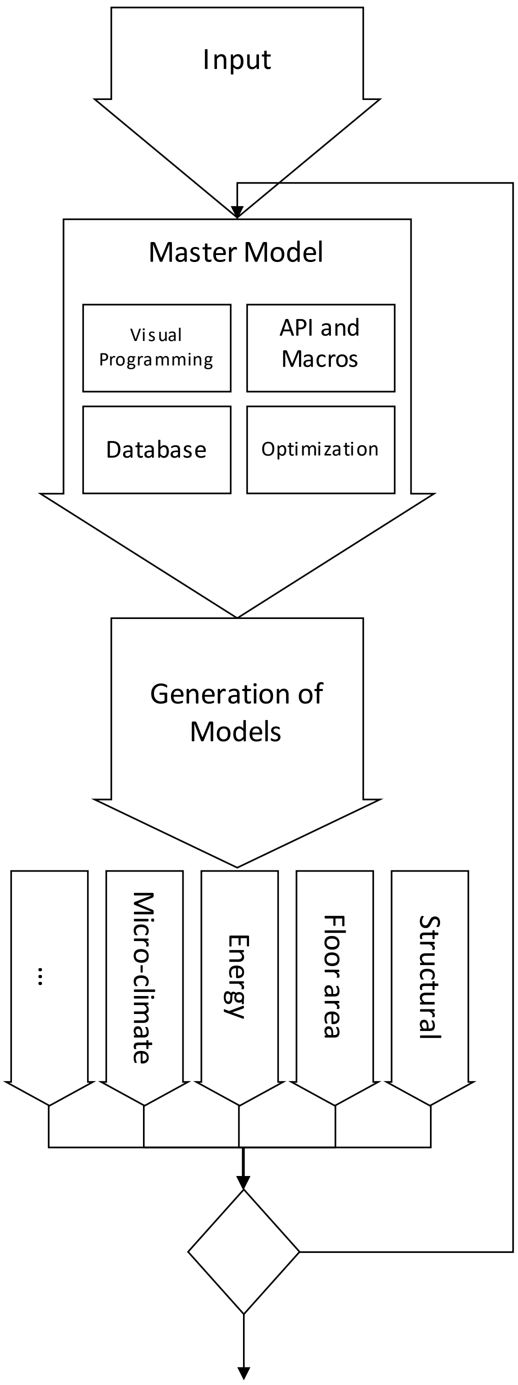

Figure 1. The proposed master modelling approach.

4.2 Example

Here, the inner workings of a MM approach for a framework of a double pitched roof is explained. Dynamo is used as the VPL of choice as it provides links to both a BIM tool, namely Revit, and a tool for structural analysis, Robot. A two-stage approach is adopted. First the whole geometry for the framework is created in Dynamo using points and lines. Then, depending on the situation, the geometry is either used to generate the BIM representation within Revit, or sent for structural analysis in Robot.

4.2.1 Dynamo model

The framework of a roof contains several trusses that are set in given spacing. To generate the framework, Dynamo uses points that in pairs create lines. Only the coordinates of the three corners of each truss are necessary to specify in an Excel sheet, see Figure 2. Each point contains x-, y-, and z-coordinates in the Cartesian coordinate system to describe it and users must type in the coordinates in a specific order. It should be noted, that the x-coordinates must be typed in column A, y-coordinates in column B and z-coordinates in column C.

	A	B	C
1	0	0	0
2	8	0	0
3	4	0	3
4	0	1,2	0
5	8	1,2	0
6	4	1,2	3

Figure 2. Input coordinates in Excel.

Each row describes one point and every three rows describe one triangle. The first point of each triangle is the bottom left corner, the second point the bottom right corner and the last point is the top point. With that method, it is possible to create as many triangles as needed for the framework. The Excel sheet is linked in the Dynamo model so that Dynamo can read the data and generate the specified points. Then, Dynamo generates lines between each of the three points and the lines of these triangles will later be defined as top or bottom chords.

The second input is for the “box”, a room to fit within the framework, which can be used as e.g. a utilities room. These input parameters, for the box, control the length, width, and height and its bottom left position. Dynamo creates a box from the bottom left point to the upper right point of the box. In the next step, lines (diagonals) between the chords are generated to support the triangles. There are two different ways how they are built that depend on if the box intersects a roof truss or if it does not.

1) The box does not intersect a roof truss: All triangles that does not intersect the box are generated like a W-beam. At first an uneven number of sections must be selected. It is possible to choose between 3 up to 9 sections. More than 9 sections are not necessary for a roof truss. The sections are the subdivision of the bottom

chords. The top and bottom chords are subdivided in equal lengths with points. Lines connect the points to build diagonals.

2) The box intersects a roof truss: First the framework for the box is built. Dynamo generates vertical lines on each side of the box. They reach from the bottom chords to the top chords. A horizontal line between the vertical lines is generated to mark the height of the box. Diagonals are created to support the top chords next to the box. Two separate cases of the intersection between the box and roof truss are managed:

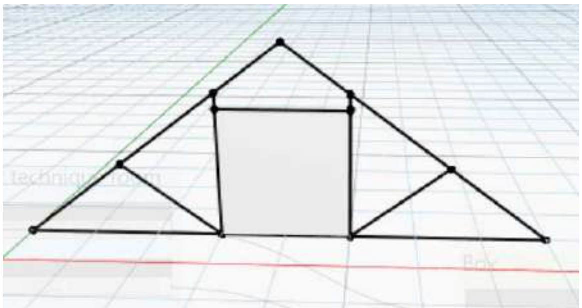

Figure 3. Case a) Box in the middle.

Case a) the box is placed in the middle under the left and the right top chords, see Figure 3. In this case Dynamo generates a diagonal line on the left side and a diagonal line on the right side of the box. Each line starts on the bottom side of the box and ends at a specific point of the top chords. That point is in the middle of the distance between the start of the top chords and the end of the vertical line of each side.

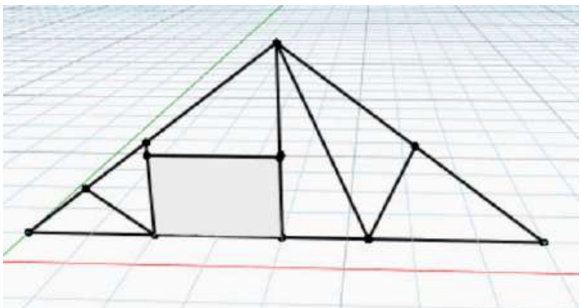

Figure 4. Case b) Box is on one side.

Case b) describes a position of the box, where it is on one side of a truss, see Figure 4. Two diagonal lines will be generated at the side without box. They start at the half distance between the one side of the box and the corner of a truss. The top point of a truss is an endpoint and the middle of the top chords is the other endpoint. The program generates a diagonal line like in case a) at the side with the box. The program generates four lines that are used for wind bracings. They start at each bottom corner of the framework. The endpoint is at the top of the second truss or rather the next before the last truss. All lines are joined in a list at the end of the Dynamo model. The list will be used for the Revit model and the Robot model.

4.2.2 Revit model

The Revit model uses a node within Dynamo that contains a collection of all the lines generated for the trusses. It distinguishes the lines in the different structural elements of the framework, e.g. top chords, and assigns the appropriate structural framing type to them. This information is then relayed to Revit where a representation of the truss is generated. Through the change of parameter values, different aspects of the elements in the trusses can be altered, e.g. rotation and dimensions.

4.2.3 Robot model

The Robot model uses the same collection of lines as the Revit model. However, due to differences in object types, Dynamo does not send the lines automatically to Robot. As such, they must first be changed into analytical bars before they can be transferred. See Figure 5 for an excerpt of how coding in Dynamo looked.

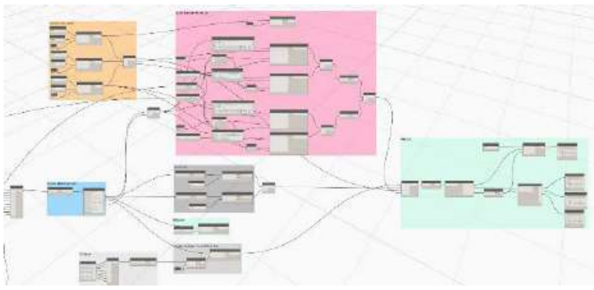

Figure 5. Code in Dynamo for generation of the Robot model.

For the whole and larger programming layout see the Appendix on the last page of this paper.

5 Discussions and conclusion

A master modelling (MM) approach based on visual programming languages (VPL) has been presented and exemplified with a roof truss design tool. MMs could increase the chance of finding optimal solutions instead of just good enough solutions since the design and analysis loop enables multiple solutions to be evaluated. Compared to configuration, [9], MMs could be used for developing building systems since the optimized solution could be reused and therefore could become a member of a company’s product platforms. Compared to the tool model coupling methods that Negendahl [4] presents the

MM, and especially the presented example, is closer to the distributed model since the models are created in a process flow, i.e. first the Dynamo geometry model is created, then the Revit model is created and lastly the Robot model is created. Also, Asl et al. [5], with their case study showed an application of VPL in closer resemblance to configuration where parametric changes are made to existing objects. Although, the authors also acknowledge that their framework could be used in a far broader extent than exemplified.

VPL is more graphical and possibly more intuitive compared to text-based programming languages. VPLs makes it possible to link models and the master model in our example is a Dynamo model that is linked to Revit and Robot. The example show that several roof truss solutions can be found faster than manually generating the different geometrical representations in Revit and Robot.

The design teams that could use a tool like this should preferable have members from each of the included domain models, in our example architect and structural engineer. With the design team having basic programming skills it would be possible for them to develop tools like this and keep them maintained with latest data.

As Negendahl [4] argues, the presence of VPL does not solve all interoperability issues why the inclusion of scripting (potentially using text-based programming) and macros in the MM is important to increase the possibilities for full automation capabilities. For fully automated master models, the early design stages are suitable since then the building design is still overarching and therefore less effort is needed for automation.

Compared to other truss design tools, e.g. [12] and [13], the presented tool was developed within a BIM environment which is important to increase the possibilities for model coupling between architects and structural engineers. Also, the presented tool is for timber truss design and analysis where earlier similar tools have a majority within steel trusses. There are examples of timber truss design tools, e.g. [14], but most of them are design tools for structural engineers and not for both architects and structural engineers.

Future work involves connecting more models and implantation of full automation to enable more efficient optimization. Conducting design studies is also of interest.

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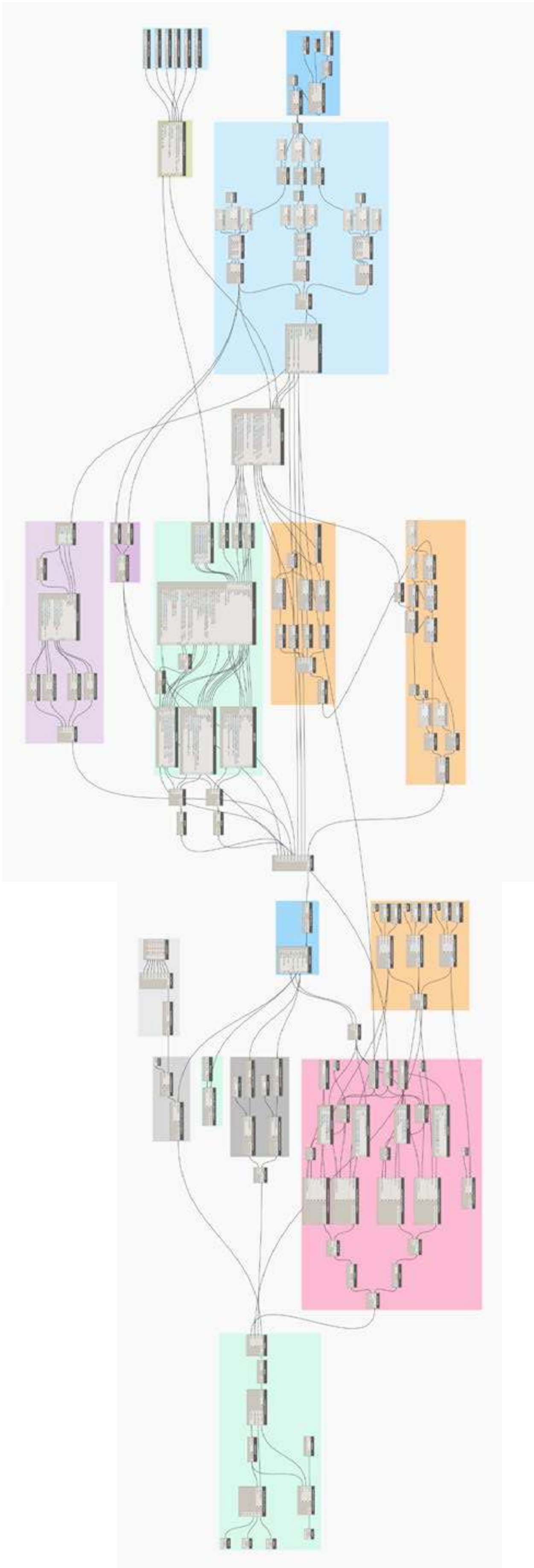
APPENDIX – The full layout of the Dynamo programming blocks used in the example



Inferring Construction Activities from Structural Responses Using Support Vector Machines

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Abstract –

On-site data collection during construction activities help in evaluating productivity rates and preparing more accurate schedules. One of the challenges here is in collecting data automatically such that activity start times and durations can be computed reliably. This paper proposes a methodology to infer construction activities that are being performed on site using the structural responses collected from construction equipments. This methodology is applied to the case of a launching girder, an equipment used in the construction of viaducts in metro rail projects. There are four stages involved in the construction of a viaduct; Auto launching, Segment lifting, Post tensioning and Span lowering. Strain values from the launching girder are used to predict the stages of construction using machine learning techniques. Support Vector Machines are used to classify the strain data into one of the four classes corresponding the stage of construction. Data from a typical construction cycle is used for training. Using the model generated by the training data, subsequent activities can be inferred.

Keywords –

Support Vector Machines, Machine Learning, Automated Data Collection, Construction Progress Monitoring

1 Introduction and Background

Construction activities are inherently complex with the large extend of uncertainties involved in site conditions. Well prepared construction schedule is essential for successful implementation of any construction project. Problems caused by an optimistically biased baseline schedule of a construction project can be rectified by real time accurate construction monitoring. Most of the time, precise monitoring of construction activities are highly challenging. Control of project performance based on manually collected data is a strenuous task. Depending upon the level and accuracy of data required, the cost and effort associated with manual data collection and interpretation of the same for useful information are high [1]. Automated data collection techniques such as barcode [2], Radio Frequency Identification [3], Ultra wide band [4], Global Positioning System [5], imaging [6], LIDAR [7] etc. provide reliable data about on site construction progress. Automated data collection methods generate more accurate and integrated control information less expensively. However, the effectiveness of each mode of automated data collection is highly dependent on the type of construction activities involved. Lack of mobility is one of the major drawbacks of currently existing automated data collection techniques. Major project control decisions are usually delayed due to lack of real time progress monitoring or lag in reporting and interpretation of existing progress data. These problems are addressed by integrating the progress monitoring system with main equipment involved in the construction activity.

Sacks et al. proposed a system which use automatically collected data from a central construction equipment for real time progress monitoring which help in better project performance control [8]. The monitoring system consists of a decision rule processor which uses a knowledge base, as well as data from the Building Project Model and a monitoring 'black box' installed on the equipment. The construction equipment selected by Sacks et al. is a tower crane which is used for lifting majority of materials used in construction. Navon and Shpatnitsky monitored an earth moving equipment for automated progress monitoring of road construction [9]. They developed a monitoring and control model which uses location of the equipment and time of measurement collected, using GPS technology as input data.

Depending upon the type of construction, the central equipment to be selected for automated progress monitoring varies. Soman et al. measured structural responses from a launching girder (LG), an equipment used for construction of viaducts to monitor progress of construction [10,11]. Auto launching, Segment lifting, Post tensioning and Span lowering are the four stages involved in the segmental construction of a metro rail viaduct. Structural response data from the equipment is acquired through a strain based wireless sensing system. Model based system identification methodologies were then used to find out the state of the construction process to monitor the progress [11]. Three different algorithms were evaluated in this work. The first algorithm used a conventional system identification methodology based on a population of models that represents various possible states of the structure. This approach could not accurately identify the stages of construction. A modified system identification methodology which uses domain specific knowledge in the form of possible sequences of construction activities provided the best results. While this approach has been proved to be successful, there is high computational and cognitive complexity involved. Thousands of models need to be created and simulated using finite element analysis software. Model free approaches using machine learning techniques do not have this drawback. These methods do not require models of physical behaviour and are entirely data driven.

Machine learning techniques use data to enhance the performance of software [12]. Some of the major applications of machine learning include device control, recognising biometric parameters, robotics etc. With recent advances, machine learning has entered into almost all industry including construction. Tixier et al used machine learning models Stochastic Gradient Tree Boosting (SGTB) and Random Forest (RF) to predict injuries in construction industry [13]. This study has given dependable probabilistic forecasts of likely outcomes of occurrence of an accident. Akhavian and Amir used machine leaning methodologies to identify and classify activities of construction workers from the data collected using sensors embedded in smart phones [14]. Machine learning techniques are extensively used in structural health monitoring [15] as well as durability and service life assessment of structures [16].

A support vector machine (SVM) is a machine learning technique that has been found to be successful in solving pattern recognition problems [17]. SVM can be used for supervised learning tasks like regression and classification [12]. It has found wide applications in various fields of construction industry. Complex problems such as contractor prequalification can be successfully solved with decision support framework based on SVM [18]. Wauters and Vanhoucke showed that SVM regression model delivers better project control forecasting results than the presently available Earned Value and Earned Schedule methods [19]. Evolutionary Support Vector Machine Inference Model (ESIM) is developed by combining SVM and fast messy genetic algorithm (fmGA). ESIM is capable of determining Estimate at Completion (EAC) of a project [20], identifies the critical parameters that influence the success of a project [21] and acts as a intelligent decision support system for effective construction project management [22]. SVM techniques are extensively used in areas which demand attention to details and patterns, handling of huge amount of data, precise analysis and prediction of future demands. Some of those applications include selection of materials [23], prediction of demand of equipments [24] and working posture analysis of labours [25]. However, inferring construction activities for progress monitoring using predictive analysis by support vector machines classification has not been explored yet.

This paper aims to infer the construction activities of the metro rail viaduct from the structural responses collected from the launching girder using SVM classification.

2 Support Vector Classification

In a simple binary classification problem, the data points are categorised into two classes labelled as positive or negative. The user supplies the training data consisting of values of attributes and label of each of the data point. The learning task is to determine the function that separates the data points into classes. Figure 1 shows a binary classification in which data points consisting of two variables are separated by a straight line. Here, the decision boundary (also known as the classifier or the discriminant) is linear. Decision boundary will be a hyperplane when a linear function divides the classes in multiple dimensions as shown in Figure 2. Equation of a hyperplane is given below [12].

$$f(x) = w_1x_1 + w_2x_2 + w_3x_3 + \cdots + b = 0 \qquad (1)$$

where w_1, w_2, w_3... represent weight factors, x_1, x_2, x_3... stand for input variables and b represents the bias. All the points belonging to one class lie above the hyperplane and those belonging to the other class lie below the hyperplane. The learning algorithm finds the best hyperplane by adjusting the weight factors appropriately. The value of the function f(x) for the first class will be greater than zero and for the second class will be less than or equal to zero.

SVM outputs an optimal hyperplane known as the maximal margin classifier, for a given labelled training data. A good separation is achieved by this hyperplane that has the largest distance to the nearest training data points of any class [12]. Figure 2 shows a maximal margin hyperplane. From the decision boundary, nearest negative data points and positive data points are equally distributed.

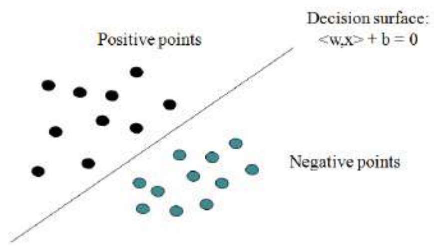

Figure 1. Binary Classification of data points with straight line as decision boundary

When we label the training data as $\{x_i,y_i\}$, i = 1, ... , l, $y_i \in \{-1,1\}$, $x_i \in R^d$, the equation of the hyperplane can be written as given in (2). The solution is obtained by Kuhn - Tucker conditions as given in (3). $\alpha_i, i = 1, \ldots, l$, stand for positive Lagrange multipliers introduced.

$$f(x) = sgn((w.x) + b) \tag{2}$$

$$w = \sum_{i=1}^{l} \alpha_i y_i x_i \tag{3}$$

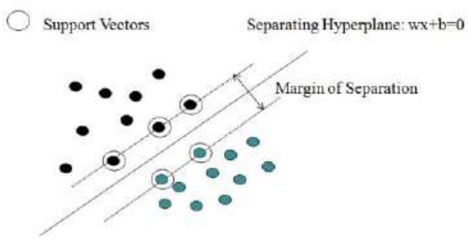

Figure 2. Classification of data points with linear separating hyperplane

We will not get a feasible solution, when we apply the above mathematical model to non-separable data. Therefore, positive slack variables are introduced in the constraints with an additional cost. Larger the value of the newly introduced parameter C in the constraint, higher the penalty to errors [17].

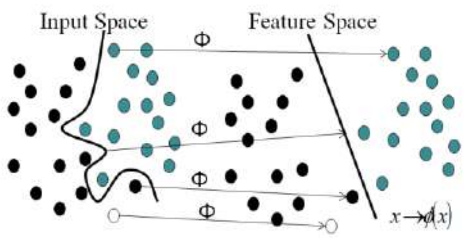

Figure 3. Nonlinear classification of data points with radial basis function

The decision function (2) can also be written as (4). In nonlinear classification, first we embed the data into a high dimensional feature space by a map ϕ and then separate the classes using a maximum margin hyperplane as shown in Figure 3. By suitably introducing a kernel function, K as in (5), the decision function will take the form (6). All concepts of linear classification cases are applicable to nonlinear classification cases. By using kernel function as in (7) the support vector algorithm develops radial basis function (RBF) classifier [26]. Here, σ is the width of the Gaussian kernel.

$$f(x) = sgn\left(\sum_{i=1}^{l} y_i \alpha_i.(x.x_i) + b\right) \tag{4}$$

$$K(x, x_i) = (\phi(x).\phi(x_i)) \tag{5}$$

$$f(x) = sgn\left(\sum_{i=1}^{l} y_i \alpha_i.K(x, x_i) + b\right) \tag{6}$$

$$K(x, x_i) = e^{\left(\frac{-\|x-x_i\|^2}{2\sigma^2}\right)} \tag{7}$$

3 Methodology

Strain readings collected from 14 different locations on the launching girder (LG) in the previous study [11] are used in this research. The objective of this research is to determine whether patterns in strain data could be used to infer construction activities using support vector classification.

11,130 strain gauge readings were used, each from 14 locations of the launching girder during the erection of the viaduct which consisted of 26 cycles. One set of strain data was collected every minute during this measurement sequence. The construction activity corresponding to each data point was obtained from the log book. Strain data for one cycle consists of strain values for the operations, auto launching, segment lifting, post tensioning and span lowering. Data for one cycle is used for training the algorithm and the strain data for other 25 cycles were used for prediction. The aim is to test whether the activities are correctly predicted when compared to the entries in the log book. Prediction is done by linear as well as nonlinear SVM classification. RBF is used for nonlinear classification. The error penalty, C is varied from a range of 10 to 50 and width of the Gaussian kernel, σ is varied from 0.1 to 0.5. It is examined whether these parameters affect the accuracy of prediction as explained below:

In each cycle, data for one operation (such as auto-launching) is taken as the set of positive examples and data for all the remaining operations are taken as negative examples. The SVM is trained using this data for one cycle and remaining data is used for prediction. If the recorded data in the log book matches the identified class, it is considered as correct prediction. The percentage of correct predictions is computed. The results of analysis is discussed in next section.

4 Results and Discussion

Prediction results for each operation involved in a cycle using linear SVM classification and nonlinear SVM classification with RBF are given. Percentage of correct values in prediction (P) is plotted against operations that are treated as the positive class during training (Figures 4-8).

Table 1. Effect of C and σ on Percentage of correct predictions (P) of LG operations

Operations	Linear SVM classification	Nonlinear SVM classification with RBF
Auto launching	P increases as C increases.	P decreases as σ increases; remains same for σ = 0.3 and 0.2, then decreases. Change in C value is not having much impact on result.
Segment lifting	P increases as C increases till C= 20, then decreases.	P increases as σ increases. Change in C value is not having much impact on result.
Post tensioning	P increases as C increases till C= 20, then decreases for C= 30, again increases with C. C= 20 gives better results than other higher values.	P increases as σ increases. Initially P increases with C, then decreases. Value of C corresponding to peak P values, changes with σ value.
Span lowering	P increases as C increases till C= 30, then decreases.	P increases as σ increases. P increases as C increases till 20, then decreases.

Auto launching is having highest percentage of correct predictions. Predictions using RBF gives better results in all the cases, meaning that the decision boundary is non-linear. Prediction of auto launching using RBF gives zero misclassifications in all combinations of C and σ except for C = 20 and σ = 0.2. For that combination of parameters 2 misclassifications were obtained with 98.77% of correct values in prediction. Post tensioning is the operation which shows lowest percentage of accuracy in prediction. Figure 9 shows instantaneous variation of strain at sensor location near middle span of the launching girder during each operation in a cycle. From Figure 9, we can observe that pattern of instantaneous variation of strain during post tensioning is similar to that of span lowering. This makes the prediction process difficult. Initial strain variation pattern of auto launching and segment lifting are similar. This might be the case for all the adjacent operations. But segment lifting operation gives much better results compared to post tensioning. This might be due to large number of training data points involved as well as significant difference in pattern of strain variations.

The percentage of correct predictions (P) varies differently with different combinations of C and σ. Effect of each parameter on each of operations in linear SVM classification and nonlinear SVM classification with RBF are summarised in Table 1.

Soman et al used three system identification methodologies for predicting the construction activities from structural responses [10]. Out of that, a modified system identification methodology using domain specific heuristics is found to be most effective. Table 2 compares the prediction results of linear and nonlinear SVM classification with the modified system identification methodology based on heuristics (MSI). SVM classifications give better predictions compared to MSI in terms of percentage of correct values when you compare the best predictions. As discussed earlier, the best prediction results are from nonlinear SVM classification with RBF and for auto launching operation. In medium level prediction results, only nonlinear SVM classification performs better than MSI. But the identified operation is post tensioning instead of segment lifting as in other methods. As you compare the worst prediction results, MSI gives the most accurate results. Here we can observe the influence of the type of operation identified and values of C and σ. In order for the SVM classifications to give best results we need to carefully choose the tuning parameters.

5 Conclusions

The feasibility of using structural responses from an equipment to infer construction activities is studied in this paper. SVM classification using linear and nonlinear kernels are used to classify the strain data collected from site. Error penalty, C and width of the Gaussian kernel, σ are used as tuning parameters for the study.

It is observed that certain operations such as auto launching and segment lifting can be identified accurately with both classification methods. Computer based pattern recognition is found to be essential in clearly identifying these operations which involve minute changes in strain data, which cannot be accurately detected by humans. Certain other operations such as post tensioning cannot be identified with either of the methods.

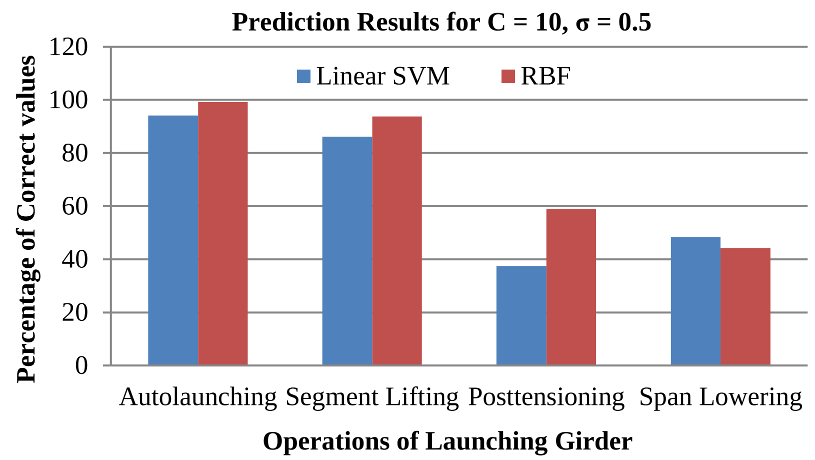

Figure 4. Percentage of correct values in linear and nonlinear SVM classifications. X-axis contains the operations those are treated as the positive class during training. Y-Axis consists of the percentage of correct predictions for this operation.

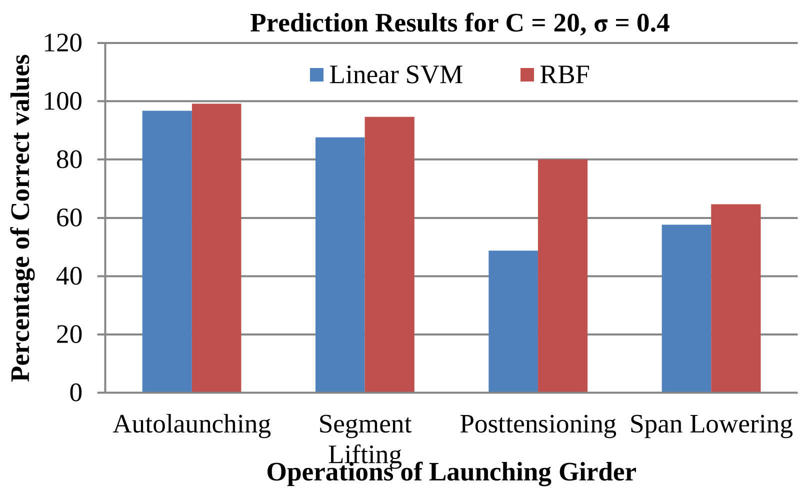

Figure 5. Percentage of correct values in linear and nonlinear SVM classifications.

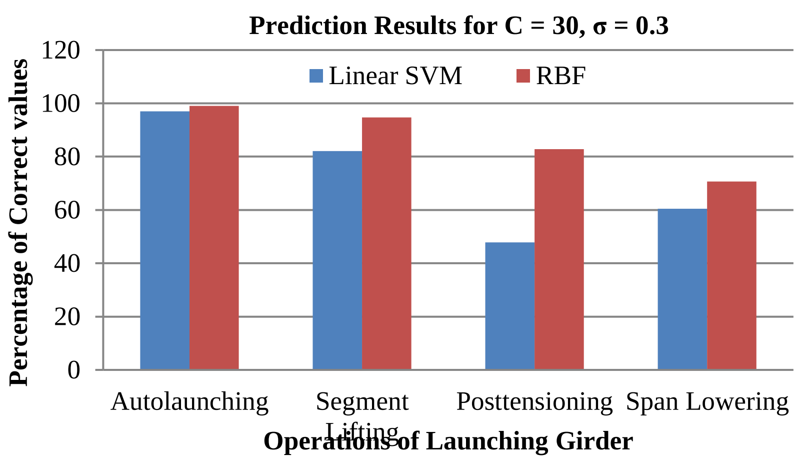

Figure 6. Percentage of correct values in linear and nonlinear SVM classifications.

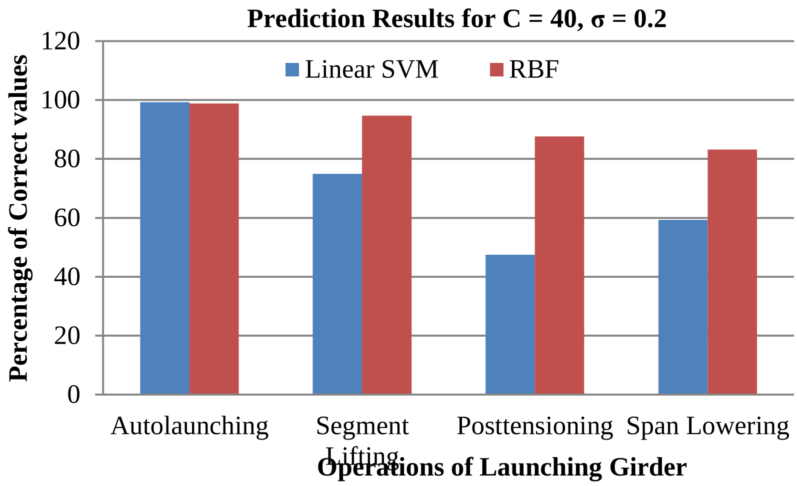

Figure 7. Percentage of correct values in linear and nonlinear SVM classifications.

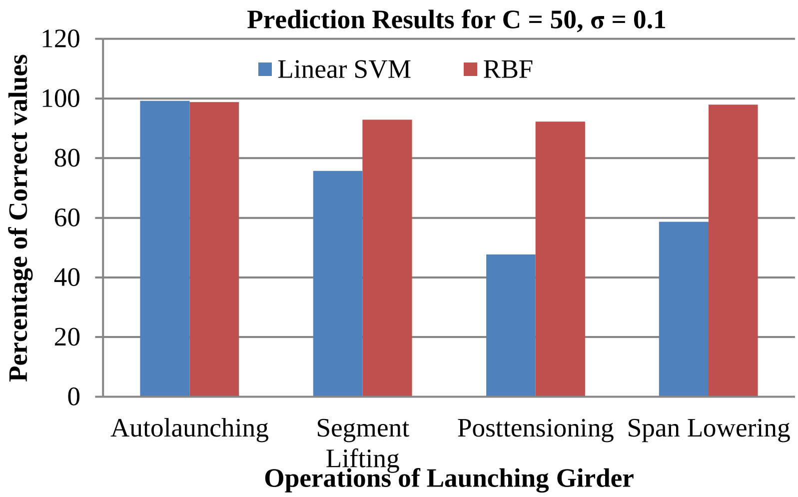

Figure 8. Percentage of correct values in linear and nonlinear SVM classifications.

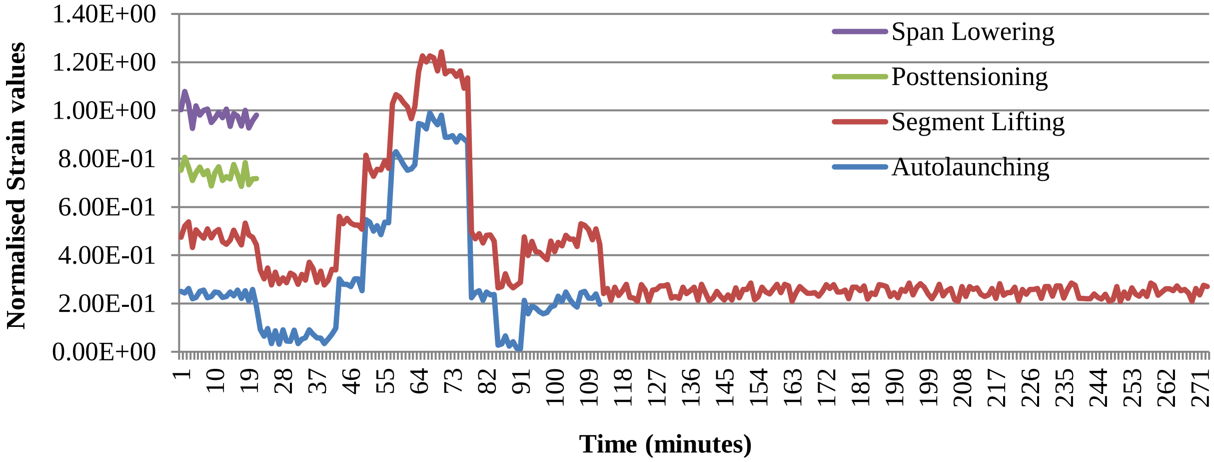

Figure 9. Instantaneous variation of strain at sensor location near middle span of the launching girder

Table 2. Comparison of prediction results of linear and nonlinear SVM classification with modified system identification method based on heuristics [10]

Method of Prediction	Prediction Results					
	Worst Prediction		Medium Prediction		Best Prediction	
	Predicted operation and details of prediction method	Percentage of correct values	Predicted operation and details of prediction method	Percentage of correct values	Predicted operation and details of prediction method	Percentage of correct values
Modified system identification method based on heuristics	Span lowering, with modeling error	79	Segment lifting, without modeling error	81	Auto launching, without modeling error	95
Linear SVM classification	Post tensioning, C = 10	37.39	Segment lifting, C = 40	74.89	Auto launching, C = 50	99.23
Nonlinear SVM classification with RBF	Span lowering, C = 10, σ = 0.5	44.24	Post tensioning, C = 50, σ = 0.2	87.09	Auto launching, C = 20, σ = 0.5	99.23

Strain data alone is not enough in such cases. We might have to include additional sensors like accelerometers to obtain more details about the operations. Strain data from one location is not sufficient to identify operations. Some locations give better strain variations compared to others. Therefore location of sensors should be carefully chosen.

In linear classification, error penalty C is having significant influence. However, accuracy of prediction increases with increase in C only up to certain extend in each operations. There is an optimal value of C for each operations which comes in the range of 20-30.

Nonlinear SVM classification with RBF is mostly governed by width of the Gaussian kernel, σ. Except in auto launching operation, increase in σ value gives better results. Changes in C value for constant value of σ have not much effects on certain operations such as auto launching and segment lifting. Interestingly, both of these operations follow similar strain variation pattern in the initial stage. Post tensioning and span lowering have optimal values of C for a constant σ value. With careful selection of the values of the parameters, SVM classifications can produce better results compared to modified system identification method based on heuristics.

Inferring construction activities from structural responses using support vector machines is possible with optimal values of C and σ determined for each operation. With the help of heuristics and additional types of sensors at best locations, prediction results can be improved.

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Integrated, automated and robotic process for building upgrading with prefabricated modules

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Abstract –

Adding manually thermal insulation onto an existing building is an inefficient and labor-intensive process. To avoid such manned labor on site, recent approaches have been developed for installing prefabricated modules onto existing buildings´ envelopes. However, the monitoring and the analysis of these approaches expose that these procedures are still time-consuming and inaccurate. In mass manufacturing industries, robots facilitate time reduction while ensuring accuracy. Nevertheless, the main challenge for adopting robotized manufacturing and installation processes in building renovation relies on the constant customization of the prefabricated modules, both off-site in the factory and on-site in construction. In pursuance of improving such situation, the authors conceived a novel process that automates the customization, the manufacturing and the installation processes of the modules. The solution integrates and links systems such as accurate coordinate acquisition, parametric design, digital manufacturing of elements and robotic assembly and installation of the modules. The main body of this paper describes the structure of this novel conceptual process. This process has been initially proofed, addressing mainly the feasibility and the correct sequence of each of the steps. The results show that this novel process, after further development, can be a solution for gaining efficiency on the building renovation processes.

Keywords –

Renovation, robotic, parametric, prefabrication

1 Introduction

Achieving a zero-energy consumer building stock is a goal of the European Union [1]. Currently, the most used and “traditional” method comprises the addition of an insulating layer on the exterior wall or facade of the building. After that, the operators spread mortar or place a waterproof material to protect this insulating layer. This procedure is time consuming and requires scaffold installation in front of the building´s façades [2]. In order to gain efficiency of the process, the European Union prepared a research call [3] defining the next main requirements for the applicant proposals:

- Use prefabricated modules with integrated energy efficiency devices and renewable energy sources.
- Use advanced computer based tools for integrating the value chain over the life cycle of the project.
- Move from individual manufacturing to mass-customization.
- Reduce the installation time by at least 30%, compared to a typical renovation process for the building type. For that purpose, high accuracy is needed

The BERTIM project (2015-2019) [4] was selected within this call. The main challenge relies on using timber-based prefabricated modules to cover existing buildings´ envelopes. The results of a preliminary demonstrator [5] of this research project showed that improvements in manufacturing and installation were still required in order to obtain a more efficient process.

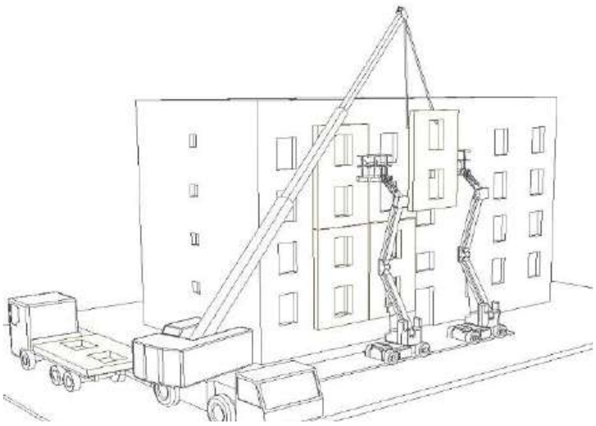

Figure 1. View of current installation process techniques of prefabricated modules for building refurbishment with mobile cranes.

The remainder of this paper is to explain and verify an integrated process that ameliorates the procedures of the demonstrator of the project [5]. For that purpose, some points have been outlined. First, the main challenges of the research are presented in chapter 2. After that, a solution that spans the research gap is defined in chapter 3. The verification process is described in chapter 4. Finally, in the last chapters, the future necessary works are outlined.

2 Multi-Aspect research gap

According to previous studies [5], the procedures used for adding a 2D module onto existing buildings are still excessively time-consuming. Time consumption affects different aspects: the design or layout-planning period, and the manufacturing and installation processes. This yields an increase of cost and therefore prefabricated solutions lose competitiveness in comparison to manual procedures [2]. As outlined in previous papers [5], it affects especially to the on-site installation phase. In other industries, a solution to these problems is the use of robotic and automated technology in order to improve the performance. There have been advances in product flexibility and flexible automation [6]. But normally, robotic manufacturing requires a standardized product. Moreover, building renovation requires fully bespoke products, adjusted to the existing geometry and function. The product´s size shape changes constantly. Therefore, a flexible robotic manufacturing process is needed for a customization. There are already some experiences where the linkage between a parametric design and a robotic control was developed [7],[8],[9]. These studies are focused on complex geometries more than the assembly of fully prefabricate units.

Besides, preliminary research [5] determine that the existing manufacturing processes produce 2D timber modules with excessive tolerances, with around 10+/- mm of deviations. For a highly prefabricated module in the rest of the construction industry, i.e. curtain wall modules, the tolerances cannot exceed 1 +/- mm. In previous studies, it was determined that the accuracy of the modules and the placement of the connector was crucial for a proper fasten. Furthermore, in the BERTIM project, it has been concluded that the insertion of services, and therefore, pipes and ducts must fit. This requires high accuracy.

Between the 2D module and the existing building, there is a connector that consists in two parts. This was further explained in previous publications [10]. One part, (Part 1) is fixed onto the existing building and the other part (Part 2) is fixed onto the 2D module. This way, the 2D module is supported on the connector, which in turn is supported on the existing building. With current techniques, accurately locating Part 1 of the connector is time consuming. Prior to this research, an interfacing Matching-Kit [1] has been defined and proved, which corrects the possible deviations of Part 1. The problem arises with the placement of Part 2 onto the 2D module; the location differs from case to case.

2.1 Information workflow, data acquisition and layout-planning,

In current processes, there is a lack of a continuous information workflow. This situation leads to errors and misunderstandings. The potential benefits of an integrated process were highlighted before [11] and considered BIM as a starting point for integrating the whole process. But in this case, the link between the robotic tasks and BIM needed further development.

Normally the process of building renovation with prefabricated modules starts with the existing building´s data acquisition. Progress has been made to implement 3D laser scanning for acquiring the data of spatial environment [12]. The question arises, if this technique is accurate enough for manufacturing and installing parts onto a previously built environment with high enough accuracy. Besides, the point cloud management might gather too much information to handle, at least for the façade renovation. Moreover, a faster and more efficient procedure for building renovation is to prioritize key points. This is based on the selection of only necessary information and the discrimination of the unnecessary geometrical information. This technique is already developed [13]**.** At this point, the problem relies on the location of the connector; it is also necessary to determine the location of the connector, which might be placed in a non-expected or undesired location. If the location of this connector is not measured accurately, or it is not placed accurately, the 2D module does not fit [10].

Finally, the re-design or layout-planning of the 2D modules needs to be used by a dedicated parametric software. Software such as Dietrich´s and RenoBIM [4] are developed (or are being developed) for a fast adaptation of the modules´ geometries. Recent studies suggest that the software information can be integrated [14] in the manufacturing and the installation processes. Addressing this, it is necessary to define a specific programming system that integrates the process.

2.2 Off-site manufacturing phase

The manufacturing accuracy of single elements can be gathered currently with CNC machines and even with robots. However, the automation level is limited on the following assembling phases. Currently, the assembly process is a purely manual procedure. Besides, there is a growing complexity of the 2D modules. This

[1] Publication under review process

means that more and more components and elements are included during the assembly process. This negatively affects the sought automation of the manufacturing system.

2.3 On-site installation phase

With current techniques, excessive re-work is necessary after the modules are placed and fixed onto the existing building´s façade [5]. The prefabrication degree of the 2D modules is, depending on the case, around 50% - 70%. This means that the rest of the tasks need to be finished on-site.

In any manner, there is no dedicated machinery for installation processes. Currently, the cranes and scaffolding systems are not suitable to this specific purpose. In previous research [15][16] there has been a study of different options for a robotic installation of modules. It must be mentioned that experiences such as the Hephaestus project [17] are relevant to carry out the installation process of the 2D modules efficiently.

2.4 Objective

For reducing the overall time, the main objective consists on integrating all phases, from existing building´s data acquisition to robotic 2D module installation. It is necessary that, from the acquisition of the key point coordinates of the existing building, the information for manufacturing and installing processes is linked. The solution should enable high prefabrication degree and accurate production and installation of modules. For that purpose, robotizing the off-site assembly and the on-site installation process of the 2D modules is desirable.

Since the 2D modules are customized products, in principle, the robot path and grasping for the assembly process should be programmed specifically for each 2D module. Importantly, there is one point to take into account. The 2D modules follow a pattern, they have many common characteristics and their layout changes according to some parameters. Therefore, the robotic programming could respond also to that parametric characteristic, and subsequently, if the controlling algorithms were arranged adequately, it would not need to be adjusted specifically for each 2D module.

3 Integrated process

In order to address the gap stated before, a solution was drafted. The proposed solution relies on a parametric software based on a visual programming language (VPL). This VPL functions as an integrator of several main points: the data acquisition of the existing building, the 2D module design/layout planning, the robotic manufacturing, and the robotic installation phases.

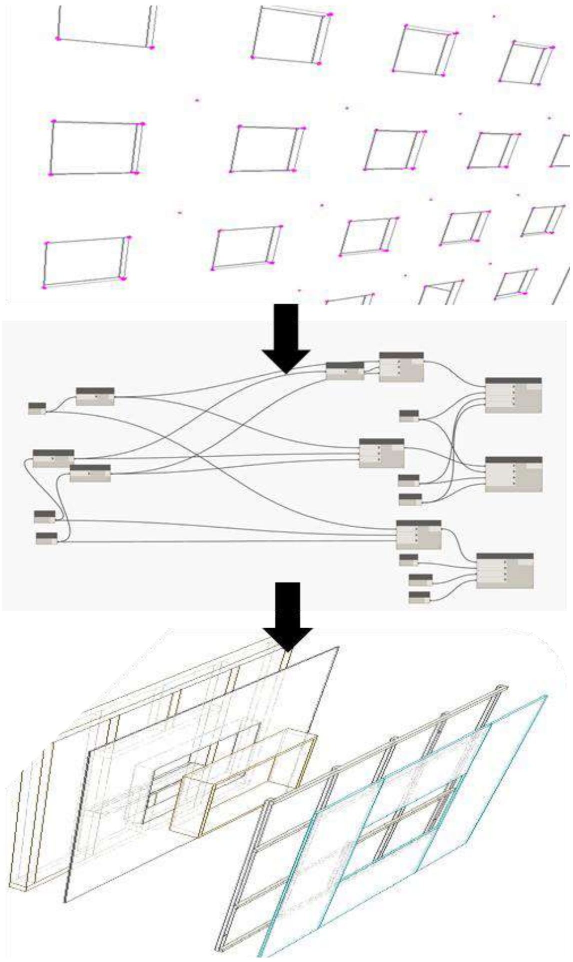

Figure 2. Necessary points´ coordinates in a façade for being inserted in the VPL and definition of every element of the 2D module by using the VPL.

As a primary input of the solution, only the twelve key points of the existing building would be necessary for defining each of the 2D modules. Four points would refer to the perimeter corners of the 2D module, and the other eight would be correlate to the window and its sill. In the case of a regular façade, that would mean that a grid similar to Figure 2. For now, the scope of the solution considers only very simple facades without terraces and balconies. As an output, the VPL would produce the necessary scripts for guiding the path and grasp-planning of the robots. The robotic environment used in this novel integrated process relies on Robotic Operating System (ROS) [17] and implies both off-site manufacturing processes and on-site installation processes.

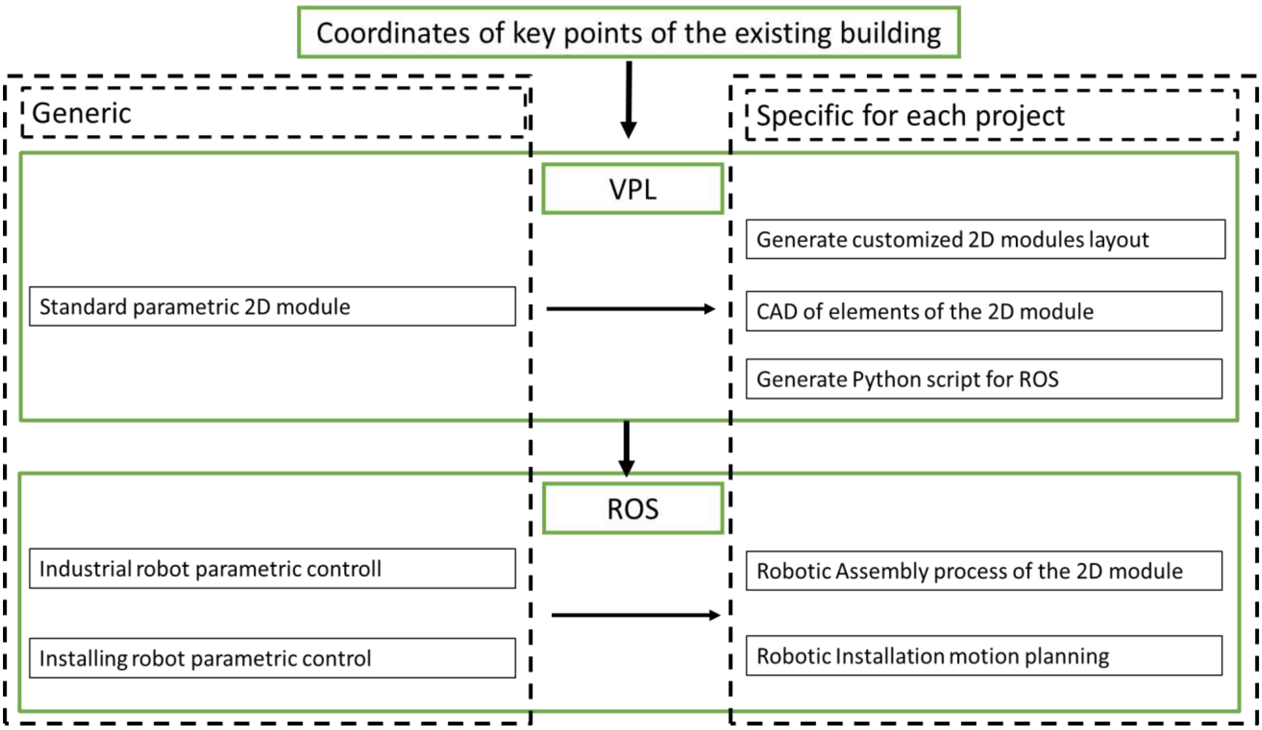

Figure 3. Scheme for the integration of the process.

3.1 Setting out of the standard 2D module

The term “standard” means that there is a library of solutions for the 2D module, with parametric variables regarding the size, shape and outer finishing material. In the case explained in this paper, the 2D module was defined to cover only flat facades, with no terraces or balconies, only with flat windows. The design of the 2D module was based on different layers. The inner layer of the wall was a flexible insulating material that adapts to the irregularities of the existing wall. Then it was followed by a flexible moisture barrier layer. This was to prevent the humidity of the interior of the building from damaging the 2D module itself. The main part of the 2D module was a timber frame, which was filled with insulation. After that a board was placed for rigidizing the timber frame. Following the criteria of previous research, the services were allocated into this timber frame, with extra insulation on the outer surface of the timber frame. For protecting the module from outdoor weather, a waterproof layer fully covered the outer surface. With current techniques, the overlapping of this layers is achieved manually on the site and after that, a finishing layer is placed and windows are inserted in the voids of the timber frame. But the layout and design of this research defined a prefabrication degree of 100%, including the services for RES. The studs and the battens have a maximum separation of 600 mm.

3.2 Setting out of the robots motion and grasp planning

In this integrated process, two types of robotic systems were conceived. On the one hand, there were the already commercialized industrial robots for the assembly of the 2D modules on the factory. On the other hand, there were the installation robots on the construction site.

In the off-site structured environment in the factory, the robot and the automated manufacturing machines and the 2D module´s elements are in recognizable positions. Therefore, an open-loop control system without sensory feedback is foreseen. The visual programming node generates a sequence of the assembly process for each of the elements and the 2D modules. For the assembly process off-site, as defined already before [11], the VPL generates also different types of files such as CAD or STL for the CNC machines and robots.

Besides, on the site, the situation is different. This is an unstructured environment, where the robot needs a calibration and guidance. In first considerations, the closed-loop control system was chosen as the best situation, since it is presumed the robotic system will need a feedback of its location. For that purpose, the selected key points of the building (the points that were acquired during the data acquisition) can be used as a reference for calibrating the robot. There are currently no marketed robots for the full installation of 2D modules. Several options have been envisaged [15],[16],[17]. As a first approach in this research, a stacker crane or Cartesian robot was defined. This Cartesian robot would host a Modular End-Effector similar to the one defined by the authors [19]. This system resembles the already commercialized systems for Automated Storage and retrieval Systems [20].

3.3 Proposed sequence

A building renovation project with prefabricated products requires parallel processes. On-site and off-site tasks need to be synchronized. The integrated on-site process sequence is defined with the next points:

1. The process starts with preliminary data collection of the wall-façade. Basically, it consists of the measurement of the façade´s key points by a digital total station. If the façade is planar, without balconies, the task can be achieved from the ground of the building. The key points are located in the window sill and perimeter of the façade.
2. These coordinates are listed and inserted in the VPL to recreate the façade and the layout of the modules. This step is not attached to the site nor the off-site factory, so it can be carried out in any location.
3. The installation of the robot body. For this research, the robot would be based on a vertical stacker crane. This robot must be calibrated properly according to the 0,0,0 or origin point selected within the building.
4. At this point [2], the onboard tools place the connector´s Part 1 with an accuracyof 20 +/-mm.
5. The onboard measuring device detects the location of Part 1.
6. The Matching-Kit (MK) is fixed by the robot and a planar, known situation is generated.
7. The 2D module is fixed onto Part 1 and the MK.

In parallel, the 2D modules are manufactured using the generated information by the VPL.

a) The data is introduced into the variables of the VPL. Automatically, the layouts of the 2D modules are generated.
b) The CAD and/or STL files are exported by the VPL for manufacturing the parts of the 2D modules. The generation of a CAD file out of parameters is not a novelty; it is used by other processes [11].
c) Every single part is machined and routed in a CNC machine. This way it can be guaranteed that the parts are contoured and milled accurately.
d) The Matching-Kits are produced as an interface. This MK can be produced on-site or off-site.
e) Finally, the assembly of the parts of the 2D modules is performed by the robotic tools. The scripts from the VPL defines the trajectory planning of the desired task, as well as the manipulator control system.

As stated before (ISARC 2016), the process sequence is modifiable depending on some concepts. The arrangement of the on-site sequence (1, 2, 3, 4…) and the off-site sequence (a, b, c, d…) steps presented in this chapter are variable. For instance, if the placement of Part 1 is performed accurately (step 4), the MKs (step c) would not be needed.

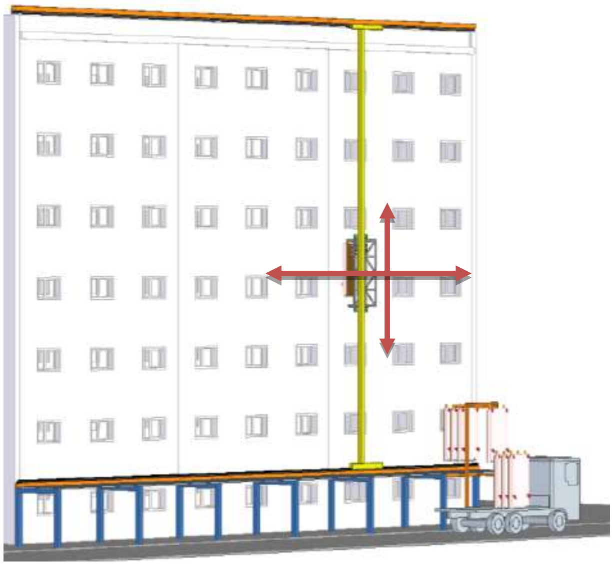

Figure 4. Installation process by a stacker crane (also known as vertical bridge crane).

4 Verification of the integrated process

For the verification of the process, some tests were achieved. The tests consisted of a laboratory experiment and a virtual simulation. The main objective of the tests was to verify the correct sequence of the process.. The verification was achieved in two main scenarios: (1) the robotic assembly of the 2D modules off site with a real robot, and (2) the installation phase on site, virtually. The VPL, Dynamo© [21], was used as an integrator. Dynamo© is a Visual Programming system developed by Autodesk used mainly for Design of parametric objects.

For this test, a sample of a 2D module was used. This sample was a scaled and simplified mock-up of a 2D module, based on timber frame. The 2D module was defined in Dynamo© environment and was parameterized depending of the 4 points of the perimeter of the 2D module. The module was based on eight different timber elements and four different

[2] Points 4, 5 and 6 are described more extensively in another publication under review process.

connectors. For the test, the 2D modules did not have any window, and therefore the eight points referred to in the previous chapter were not necessary. In a previous publication[3], it is explained how the key points of the location of Part 1 were measured.

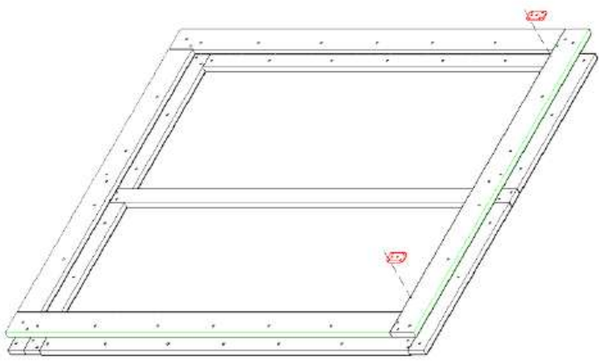

Figure 5. Definition of the 2D module for the Test.

The module was dependent to the existing wall´s key points. During the customization stage in Dynamo©, the data from the coordinates were listed in data sheet file. From here, the sorting node of Dynamo© first generated a solid that defined the façade or the wall, in the case of the test. The STL files generated by Dynamo© were used by a 3D printer for generating the the Matching-Kit interfaces. Finally the CAD model-.dwg file of the timber-frame element are used for routing and milling each of the elements.

Once the elements were accurately produced, the assembly process started. For the controlling system of the robots, ROS [17] was used. ROS comprehends and integrates a set of robot software frameworks. In the case of this research, ROS was used for the industrial robots in the laboratory, in addition to the installation robots in a virtual simulation.

4.1 Off-site robotic assembly of the 2D modules

For this test, the lightweight Jaco© robot by Kinova was used. The Jaco© robot can be installed in ROS environment. Prior to the performance of the robot, the robotic workstation was structured according to the base 0,0,0 origin coordinate. The parts of the modules were also placed in a known location according to this point. The task consisted on moving these elements to a pose goal within the 2D module, according to the 2D layout. The Python script generated in Dynamo© was taken by the Gazebo-Moveit application within ROS environment. The script sequenced the assembly of each of the elements, from the first element to the eighth element. An advantage was that the operator did not need to check the location of the elements, since the task was given directly by the robot.

Figure 6. The Jaco© robot operating with MoveIt ROS.

On this test, only the pick and place task of a relatively small and lightweight element was achieved. For this test, the screwing process was carried out manually. To achieve this robotically, another robot with higher payload and torque capacities would be necessary.

4.2 On-site robotic installation of the 2D modules

This first verification of the installation phase has been achieved virtually, since the robotic stacker crane is not operative for buildings and outdoor conditions. An URDF file that replicates the stacker crane was generated. This URDF was introduced to the ROS-Gazebo environment. Then, the stacker crane robot performed a task that simulated a simple drilling operation according to the given poses by the script.

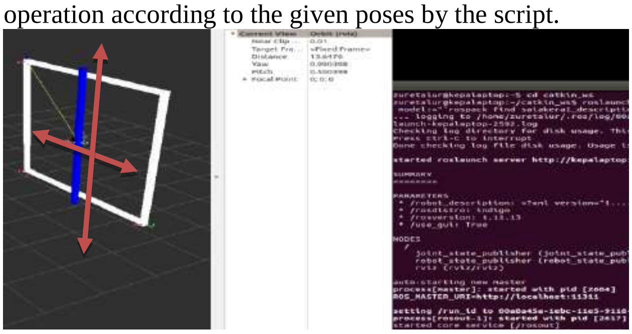

Figure 7. The stacker crane or Cartesian robot in Gazebo ROS.

For now, only the task of the drilling process has been tested and the results are satisfactory, but this process needs to be further developed.

3 Publication under review process

5 Future work

The results of the laboratory verification suggest future work considerations. For the assembly process, the some issues have been foreseen. For instance, the robotic assembly would require sequencing coordinately with the on-site works. The start of 2D module manufacturing depends on the size of the building, the bigger the building is, the earlier the manufacturing process needs to start. Related to that, the authors have envisaged two sequences within the manufacturing process of highly accurate 2D modules. The first is based on the prior routing of every single part of the module and the assembly of them. This is the process that has been explained in the paper. On the contrary, the process can be inverse, by assembling the elements first and then complete final routing of the entire 2D module. In other words, the 2D module can be produced with high tolerances, and then inserted and routed in a CNC machine to get the required contour with precision. Besides, regarding the assembly process, The center of gravity of each of the 2D module´s element should be calculated and taken into consideration before inserting the data on Moveit and Graspeit applications. This way, it should be possible for the robot to grasp the elements in the right position, close to the respective center of gravity. In this research collision detection hasn´t been approached and definitely it is an aspect to take into consideration. The unstructured workplace in the industrial settings must be considered, so the assembled elements are disposed in an aleatory manner.

For the installation process, some other issues must be taken into account. If the stacker crane (or Cartesian robot) system is used, it will depend on the accuracy of the carrier and the linear and rotary encoders. If these devices are not precise enough, another device or sensor would be necessary for positioning. Based on the previous point, a repeatability of the pose will need to be tested. The stacker crane can be up to 30 meters high. At this height, the carrier suffers some balancing and therefore, counter measures will be necessary, such as suction cups for holding the end-effectors.

Finally, this very first approach is limited to simple facades, thus it does not include facades with balconies or terraces. In the future, standard libraries for covering such building parts will be necessary. Depending on the complexity and the size of the building to be renovated, the robots´ controlling system might not be able to handle the data, therefore, splitting the renovation project might be necessary.

6 Conclusions

The existing techniques for manufacturing and installing prefabricated modules for upgrading building facades needs to be raised to a more efficient and automated method. The integrated process presented in this paper offers possibilities for reducing inefficiencies and increasing accuracy on the building renovation process. The proposed process or sequence, based on VPL and robotic assembly and installation, has been verified in a laboratory environment with satisfactory results.

The 2D modules are in general very similar, but they have many particularities; size and location of elements. These peculiarities are demanded by the geometry of the existing building. This means that the robots, both in the industrial settings and on the construction site, need to perform similar operations, but depend on specific parameters each time.

During the verification, with only the given input of the existing building´s coordinates, the VPL processed the data for the assembly robot that performed the assembly of the 2D module. Furthermore, in a simulation achieved in ROS environment, it has been tested that 2D module installation robots have a big potential. Both assembly and installation robotics still need more improvement. In the future, each step of the proposed sequence can be further developed and tested separately.

Acknowledgments

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BIM-BASED DECISION SUPPORT SYSTEM FOR THE MANAGEMENT OF LARGE BUILDING STOCKS

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Abstract –

While on the one hand the BIM methodology is an essential reference for the construction of new buildings, on the other hand it is receiving particular attention and interest also from owners of large building stocks who want to take advantage of the benefits of Building Information Modelling so as to have a coordinated system for the sharing of information and data.

This, especially in a process that concerns the management and maintenance of a large building stocks, involves the processing of uncertain information in BIM, particularly when dealing with existing buildings, due to the lack of and/or incomplete documentation, entailing a significant investment in terms of time and additional costs.

Therefore, to represent the reliability of existing building data, we suggest introducing a tool based on Bayesian Network that offers a valid decision support under conditions of uncertainty and is used to evaluate the compliance with the latest standard.

This paper presents a process to provide an integrated database defined by a minimum information level that can be used both to extrapolate and query specific information from a digital building model and populate the decision model in order to evaluate the performance parameters of existing buildings which is based on a Multicriteria decision making approach (AHP).

Keywords –

Building Information Modelling; building stock; data management; Bayesian networks; Multicriteria decision making

1 Introduction

In this work, attention has been given to the role played by public administrations in the management of large building stocks, focusing specifically on school buildings, the majority of which is outdated and lacks of compliance with current legislation.

The purpose of this paper is to propose a decision support model that can be used by public administrations, such as provinces and municipalities, which need to define the priorities of refurbishment actions among the school buildings they own.

This Decision Support System (DSS) concerns multiple regulatory areas in which evaluation is performed, namely Accessibility, Energy Efficiency and Acoustics. In addition, the DSS makes it possible to manage the uncertainties deriving from the scarce availability of necessary data on existing stock. The DSS was conceived so as to be able to obtain the necessary information directly from the Building Information Modelling (BIM) database. In addition, the decision support model includes a multi-criteria evaluation of performance indicators, each related to a determined regulatory area, with the aim of defining a final ranking of the schools assessed, in which the one with the lowest score shows the highest priority of intervention.

In conclusion, the aim of this paper is to develop a BIM-based Decision Support System for the assessment of building stocks which is able to perform the evaluation even in the case it has to manage uncertain or incomplete information. Our tool integrates networks that help evaluate the performance parameters of existing buildings, whose inputs can be retrieved from BIM models, and prioritise refurbishment actions through a multi-criteria assessment approach of some selected performance indicators.

2 Literature review

In many practical cases it is hardly possible to retrieve all the information about existing buildings through the query of the most relevant characteristics contained in a model in a reliable way. Even in the case of existing buildings for which extensive construction and operational documentation is available, some parameters might be uncertain or unknown.

Several research studies have been carried out to develop decision making systems to deal with the extensive and uncertain information characterising the existing stock. DSSs have been developed for a wide variety of engineering-related issues in the construction industry. For example, in [1] since the selection of curtain wall systems involves numerous technical, environmental and economic factors and impacts on all project stages from concept design and manufacture to installation and operation, a decision support system is proposed as a potential solution.

In [2] the authors presented the result of a research carried out with the purpose of establishing a multicriteria method for the assessment of architectural heritage to identify buildings with higher refurbishment priority. The author in [3] created and tested a multicriteria risk-based decision support model for investments in energy efficiency projects under uncertainty of building energy retrofits. In [4], a study was developed to provide systematic means for priority setting of maintenance activities in various hospital buildings as well as a Key Performance Indicator for building performance. Other researches focused on the choice of what information is needed to make models significant to maintenance and on handling uncertainty due to incomplete building documentation [5].

The above listed results are remarkable but do not deal with the compatibility between DSS and BIM models of existing buildings. Indeed, the modelling and conversion of captured data into semantic BIM objects, the updating of information in BIM and the handling of uncertain data, objects and relations in BIM, which are typical challenges in existing buildings [6], must be analysed.

Hence, this paper deals with the development of a BIM based decision support tool based on the use of Bayesian Networks (BNs) for the evaluation of building stock compliance with technical requirements and its ranking according to selected performance indicators.

BNs are an effective representation of knowledge uncertainty, because they provide the possibility of constructing an estimated probabilistic model, since not all information can be accessed. In addition, they make it possible to update the network inputs when new evidence is collected and updates results accordingly. BNs are composed of elementary parts (separate fragments) and recall their outputs in a larger network. They make it possible to reverse reasoning and can manage variables of different types (e.g. Boolean, numerical, interval or label nodes). BNs work with as many data as are available to give accurate results. Moreover, within each iteration, they learn more and refine their model to give updated results.

A great advantage of BNs is that they allow us to combine prior knowledge with new data even if they come from different sources. Once the model is compiled, we can get very quick results by using the already established conditional probability distribution tables.

Many organisations, especially in the public sector, own a large variety of buildings and other types of constructed facilities. These buildings need regular maintenance, as well as occasional renovation, rehabilitation or, perhaps, complete reconstruction [7]. Multicriteria decision making analysis arose to model complex problems like these [8]. Multiple criteria decision making (MCDM) is a generic term for all those methods that exist to help people make decisions according to their preferences in cases where there is more than one conflicting criterion to be taken into account [9]. Following a research throughout scientific literature, it was found that the majority of the methods used are based on AHP, ELECTRE and PROMOTHEE approach [10]. As outlined in [10], AHP can provide decision makers with a robust solution. The most important part of this method is that it puts decision makers' preference first and helps elect a method for their decision making in maintenance management without considering uncertainty rate and problem complexity.

For these reasons, the AHP methodology was applied according to what suggested by Saaty [11].

3 Modelling of school building stock

Although a detailed set of information about existing buildings would be necessary to carry out a reliable assessment of real estates, most of the buildings were built in the pre-digital age [12].

Some public administrations are developing preliminary BIM models of their stock, but they are willing to limit the complexity of these models within the lowest amount of information needed for management and maintenance purposes, in order to make that process affordable. For the reasons stated above, we selected two case studies of school buildings which are particularly complex. In the selected scenarios, there is a clear need to adapt the existing buildings to current legislation in terms of different aspects such as accessibility, energy performance, acoustic etc.

3.1 The case studies

In this paper two school buildings located in Melzo (Milan, Italy) were studied. The first one is the "Ungaretti" primary school, whose surface area measures 4528 m^2 and is arranged on four levels, one of which is the basement and the remaining three floors are above ground. The gymnasium is accommodated in a separate building, which communicates with the main one through two horizontal connections in the basement and one placed on the ground floor. The basement houses the canteen, the kitchen, laboratories, archives, refreshment areas and infirmary. On the ground floor there are classrooms and offices, while on the first floor there are just classrooms and on the second floor classrooms and auditoriums. The restrooms are distributed throughout the building and the gym.

The second case study is the “Mascagni” secondary school located in Melzo (Milan, Italy), which is as large as 5736 m^2 and is composed of three functional blocks. One block holds the classrooms and laboratories located over two floors above ground, the other two blocks hold the cafeteria/auditorium and the gymnasium.

3.2 BIM models

Developing BIM models of existing buildings implies, first of all, a thorough study of available documentation and then an accurate analysis of the real state of the buildings.

The next step involves the construction of three-dimensional BIM models of the buildings (developed through the Autodesk Revit™ platform) containing all the technical elements identified and the organisation of collected information. The models become the materialisation of the technical information related to the element or system they refer to. Each element of the models is “informed” of all parameters, specifications and characteristics of the real elements [13].

Nowadays, buildings information is often incomplete or obsolete, hence, during operation “an inordinate amount of time is spent locating and verifying specific facility and project information”. This is the case of the two BIM models of the two schools selected as case studies: the Ungaretti primary school (Fig. 1-a) and the Mascagni secondary school (Fig. 1-b).

Sometimes not all the information needed to perform a complete assessment is available in the BIM models.

a.

b.

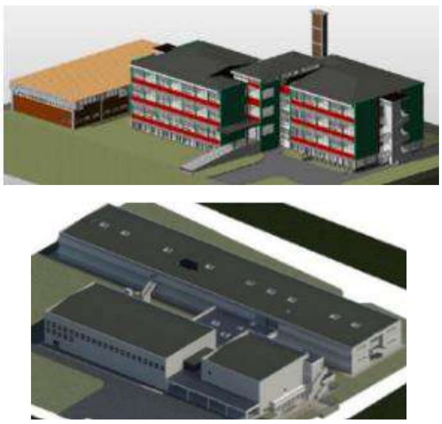

Figure 1. BIM models of the case studies a) Ungaretti school b) Mascagni school.

4 Methodology

Owners of any large building stock, such as public administrations, usually have to manage a huge variety of buildings with a limited budget. For this reason, targeted refurbishing actions are needed to ensure that those buildings comply with the latest standards and public administrators have to make important decisions regarding what part of their stock should be refurbished first.

Hence, the work developed in this paper is made up of several parts (Fig.2):

- A BIM database of the building stock;
- A set of Bayesian Networks for the evaluation of stock compliance with technical requirements and its ranking according to performance indicators;
- An interface between the BIM database and the Bayesian Networks, which automatically picks out relevant inputs from BIM models and transfers them to BN;
- A multi-criteria decision system, which ranks buildings according to the BN outputs;
- A further set of BN that estimates the budget needed to improve the status of any building.

DSS tool based on BN will be shown with the aim of assessing what buildings must be refurbished first.

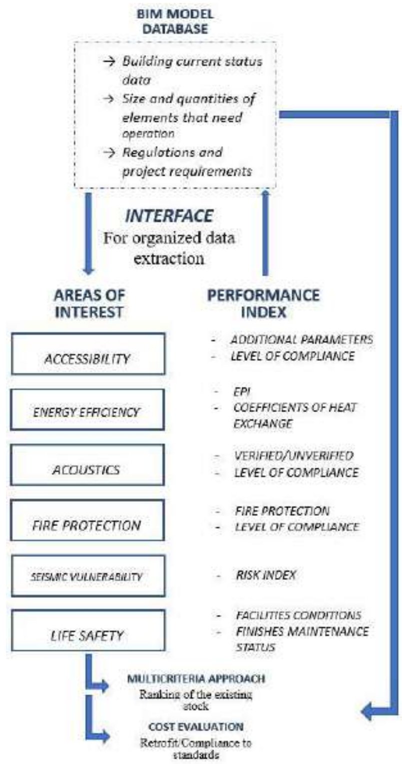

Figure 2. Schematic diagram of the structure of the decision support system.

4.1 Decision support system based on Bayesian Networks

A BN is a directed graph whose nodes are the uncertainty variables and whose edges are the casual or influential links between the variables. Associated with each node there is a set of conditional probability functions that model the uncertain relationship between the node and its parents [14]. Each variable may take two or more possible states of numerical (i.e. discrete), interval (i.e. subdivision into ranges), label or Boolean types. An arc from any set of n variables, called a_i, to another variable b denotes that the set a_i causes b and a_i are said to be the parents of b (b is evidently their child). The strength of those relationships is quantified by conditional probability tables (CPTs), where the probability of observing any state of the child variable is given with respect to all the combinations of its parents' states. In our example this probability is labelled $P(b|a_1, a_2, \dots, a_n)$, where any variable a_i is conditionally independent of any variable of the domain that is not its parent. Thus, we can obtain a conditional probability distribution over every domain, where the state of each variable can be determined by the knowledge of the state of only its parents, and the joint probability of a set of variables E can be computed by applying the "chain rule" [15]:

$$P(E) = P(E_1, E_2, \dots, E_n) = P(E_n|parents(E_n) \qquad (1)$$

That is: the joint probability of a set E_n of variables is equal to the conditional probability of the variable, given only its parents. Other relevant benefits are: the DAG provides a clear understanding of the qualitative relationships among variables; every node can be conditioned by new information (e.g. evidence about the features of a building in our case study); the same belief that updating is supported from consequences to causes, also known as diagnostic reasoning, and can be applied when the budget for renovation is limited and inference must be conducted from child nodes (e.g. cost of renovation) back to parent nodes (e.g. status of a building sub-system); finally, CPTs can describe the relationships among variables of different types (e.g. Boolean nodes, interval node, etc.), even within the same network.

Presently, every local administration performs separate evaluations of existing stock to decide where to focus the intervention first and there is no coordinated assessment at the national level on a proportional distribution of efforts. To that purpose, informed planning according to real priorities is needed, which means detecting any lack of compliance with respect to current legislation, in terms of comfort, energy performances, accessibility, seismic vulnerability, etc.

4.2 Multicriteria ranking

The methodologies for Multi-Criteria Analysis can be divided into two main groups: (i) Multi-Criteria Objectives Analysis (MCOA) and (ii) Multi-Criteria Attributes Analysis (MCAA). In the case of MCOA, the decisional process consists in the selection of the best solution within a group of infinite alternatives, implicitly defined by the problem boundaries. On the contrary, Multi-Criteria Attributes Analysis (MCAA) is a multidimensional evaluation method subset, whose final purpose is to locate the best strategy among a restricted number of alternatives, which are ranked according to their preferences [16]. MCAA can act as a support in the decision-making process [17], which leads through a systematic analysis of the solutions.

As a first step, the hierarchy is defined as follows: the top level is "stock value", the second is composed of all the areas of interest such as accessibility, energy efficiency, acoustics and others; instead, the third level is made up of the outputs from the BN "Level of Compliance" (LoC) node for Accessibility, "EPI" and "Heat Transfer Coefficient" nodes for Energy Efficiency and "Level of Compliance" (LoC) and "Compliance of acoustic requirements", as reported in Section 5. The second step consists in the pairwise comparison between the different areas of interest. As a result, the final ranking is inferred as a combination between the values obtained from the BN and the weights determined by means of the pairwise comparison [18].

4.3 Analysis of the minimum Information level

The next sub-sections show the necessary information to evaluate the level of compliance for the different regulatory areas, particularly the Accessibility Bayesian Network, the Energy Efficiency BN and the Acoustics BN.

4.3.1 Accessibility Bayesian Network

Italian legislation (D.M. 236/89) defines all the requirements and the related technical standards that are shown in the Accessibility Bayesian Network.

The output node 'Level of Compliance' is a child node of several parent nodes, each concerning a specific sub-area [19]-[20]:

- "Accesses": e.g. width, handle height, maximum opening force;
- "Doors": e.g. width, handle height, maximum opening force, maneuvering clearance;
- "Parking spaces": e.g. parking space width;
- "Lift": e.g. car elevator dimensions, car control keypad height;
- "Floors": e.g. floor frictional coefficient, floor joint

width, floor ridges, changes in level;
- "Stairways and Ramps": e.g. handrails, tread and riser size, stair width, maximum slope;
- "Toilets": e.g. water closet position, grab bar location and size, lavatory position;
- "Routes": e.g. clear width of an accessible route, passing space interval;
- "Windows and balconies": e.g. railings, maneuvering clearance, window opening force, handle height;
- "Facilities outlets": e.g. facilities outlet height.

The ratio of verified technical prescriptions (e.g. at the building component level) was evaluated in order to fill in the conditional probability tables of all the ten aforementioned Boolean-type intermediate nodes (admitting "true" and "false" states only).

4.3.2 Energy Efficiency Bayesian Network

The whole Energy Efficiency Bayesian Network was derived from previous research on reduced-order models for thermal simulations of buildings [21]-[22].

With the purpose of learning the CPTs of the BN from data, the reduced-order model was repeatedly run to generate a database containing more than 100 records which was used as a dataset to estimate the CPTs, while casual dependencies were quantified by means of the EM-learning tool implemented in the Hugin™ software program [23].

This network estimates two performance indicators:

- Heat Transfer Coefficient (HTC);
- Seasonal Energy Performance (SEPi).

In this case, the nodes represent the variables of the reduced-order model, while arcs were determined according to the casual relationship between the variables of the same reduced-order model.

4.3.3 Acoustic Bayesian Network

New and existing buildings must be characterised by specific noise insulation performance. The legislation (DPCM – 5 December 1997 "Determination of passive acoustic requirements of buildings") defines all the requirements and concerns:

- Insulation from airborne noises between different real estate units;
- Insulation from external noise (façade insulation);
- Insulation from trampling noise;
- Insulation from the noise of systems;
- Reverberation time of classrooms and gyms.

For each type of noise, the DPCM indicates:

- The indicators to use;
- The threshold values to be met depending on the intended use of the building.

Acoustic BN is divided into two sub-networks, the first of an analytical nature, as it reflects the Sabine equation for the calculation of the reverberation time, the second for the control of the remaining parameters.

4.3.4 BIM semantic enrichment

BIM models must comply with a minimum information level to be able to automatically retrieve information from them and transfer it as inputs in the BN. The management of this information is an extremely important issue from two points of view:

- The kind of information to be entered and how/where to enter it;
- How to extract information from the model in order to be able to carry out successive processing.

After reading the legislation, the verification network was created by taking into account all the aspects that can be evaluated through available information from BIM models. Tools such as SQL and Dynamo, were used to manage data transfer in order to automate the minimum level of information transfer between the BIM models and the networks system.

For both schools, the necessary data were extracted from the respective BIM models related to each requirement of the Accessibility BN, Energy Efficiency BN and Acoustics BN. If the data are not present in the model, they must first be added, if known, and then extrapolated. In the absence of applications that automatically extrapolate information from the BIM model, information must be extrapolated manually.

Table 1 reports the necessary information (available in the model, not available but derived from the models and after post-processing information) for the Accessibility network, Energy Efficiency network and Acoustics network:

Table 1. Necessary information for the networks

Available	Not available	After post processing
Access door width, internal door width, door handle height, ramp width, stairs railing height, stair flight width, hand rail height, tread depth, window parapet height,	Opening doors force, path width and length, door space check, Internal setpoint T, number of floors, lift car depth and width, door clear span, lift platform length	Average transmittance of the opaque and transparent elements, useful floor area, S/V ratio, air-conditioned gross volume, average global irradiation, average external

balcony parapet height, thickness and material of the various constituent layers, intended use, wall type, wall thickness, floor type, layers, floor thickness, internal wall type, window thickness	and width, sink height, toilet lateral wall distance, wc hand rail height, wc nominal height, slope, opening window force, window handle height, balcony operating space, friction coefficient, threshold height	temperature, Ce, Cm, Rm, Rea, Rie, Cih, Irradiation, conduction, gains, Q_op, envelope, power, efficiency, gains_tot, infiltration, forced_ventil, Qh, Epi/EPe, reverberation time, Las_{max}, La_{eq}

5 Results and discussion

These networks were implemented on two schools case studies (Fig.3). For both schools, the necessary data were extracted from the respective BIM models.

a.

b.

c.

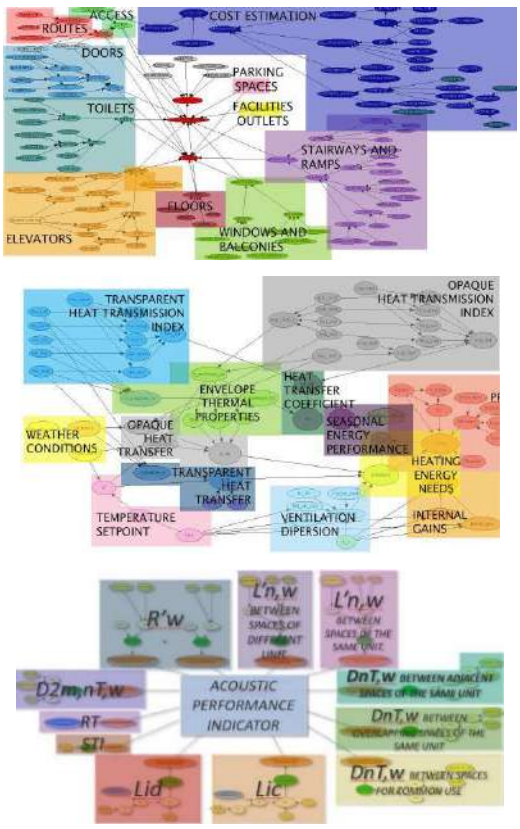

Figure 3. Accessibility Bayesian Network (a), Energy Efficiency BN (b) and Acoustic BN (c).

The Accessibility BN requires 62 inputs, the Energy Efficiency BN requires 32 inputs, while the Acoustics BN requires 30 inputs. Out of the 124 required inputs, 8 and 20 (respectively accessibility and acoustics) were directly available from the BIM model and 39 (regarding accessibility) were available because the BIM designer performed a customised modelling procedure. The remaining data were obtained through combined analyses of several parameters. As for acoustics, the compliance was checked room by room obtaining as output an acoustic performance index for each of them, an arithmetic average between the KPI obtained for each school was calculated.

In Table 2 the values of the BN output nodes are listed. The output “Level of Compliance” (in the second column) represents the ‘true’ percentage value of the node according to the information entered in the network. The other two columns represent the outputs of the Energy Efficiency BN. The rightmost column shows the percentage of ‘true’ of the “Level of Compliance” node of the Acoustics BN.

Table 2. BN outputs for the two cases studies

Case Study	Accessibility	Energy Efficiency		Acoustics
Output	LoC	HTC	EPi	LoC
Units	%	W/m^2K	KWh/m^3y	%
Ungaretti	54,9	2,39	47,04	49,44
Mascagni	55,73	2,55	45,87	55,41

After having obtained the values of the BN outputs nodes, a multi-criteria analysis was applied using the AHP approach for the classification of the two schools to evaluate them in the three regulatory areas.

As a first step, the hierarchy was structured where the first level (goal) is “Intervention Priority”; Accessibility, Energy Efficiency and Acoustics are on the second level (criteria); the third level (sub-criteria) includes the outputs of the nodes “Level of Compliance” for accessibility, “Level of Compliance” for acoustics and “SEPi” and “HTC” for energy efficiency; the fourth level (alternatives) includes the Ungaretti primary school and the Mascagni secondary school.

The second step consisted in the pairwise comparison between the different areas of interest and the different indicators within the same area (e.g. energy efficiency). As a result, the final ranking was inferred as a combination between the values obtained from BN and the weights (Table 3) determined by means of the pairwise comparison, as follows:

$$R = W_A * A + W_{EE} * EE + W_{KPI} * KPI \tag{2}$$

Where A is the "Level of Compliance" for the accessibility and KPI is the "Level of Compliance" for the acoustics reported in Table 2; W_A, W_{EE} and W_{KPI} are the weights (Table 3) and EE is computed as follows:

$$EE = W_1 * HTC + W_2 * SEPi \tag{3}$$

Table 3. Weight values

	W_A	W_{EE}	W_{KPI}	W_1	W_2
Weight values	0.63	0.26	0.11	0.17	0.83

As a result, Ungaretti was assigned {HTC, SEPi}={1, 0.975} and Mascagni was assigned {HTC, SEPi}={0.937, 1}. The application of Equations (2) and (3) to the cases of the two schools gave the following ranking results: R is equal to 0.66 in the case of "Ungaretti" school and 0.67 in the case of "Mascagni" school. Hence, Mascagni is ranked higher, the refurbishment should be prioritised for the Ungaretti school.

More remarkably, the use of Bayesian Networks allows us to draw attention to input nodes even in the case of uncertainty about the selected parameter in the BIM model, or in the case it is completely missing. For example, considering the Accessibility BN, when some information is not available, all the states of a node can be set at the same probability value (e.g. 50% false and 50% true in the case of a Boolean node). A hypothesis was made to show how the outputs can change (Fig.4) depending on the level of uncertainty of the inputs (e.g. door width and handle height) in the BN of the two school case studies, as Table 4 shows:

a.

b.

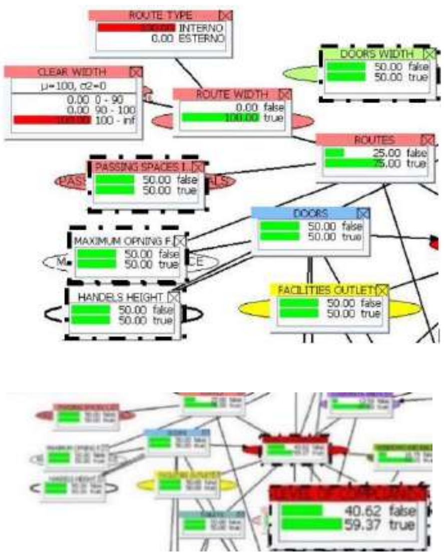

Figure 4. Accessibility Bayesian Network with a level of uncertainty (a) and related results (b).

Table 4. BN outputs of the two case studies with new inputs for Accessibility

Case Study	Accessibility	Energy Efficiency		Acoustics
Output	LoC	HTC	EPi	LoC
Units	%	$W/m^2 K$	KWh/m^3y	%
Ungaretti	59,37	2,39	47,04	49,44
Mascagni	60,21	2,55	45,87	55,41

Table 4 shows the new values of Level of Compliance of Accessibility. The application of Equations (2) and (3) to the cases of the two schools gave the following new ranking results: R is equal to 0.65 in the case of "Ungaretti school and 0.69 in the case of "Mascagni" school. Despite the changes made, the overall assessment remains always coherent, showing that the Ungaretti school is still the school that gets the minor score, so the first to require intervention.

6 Conclusion

To validate the Decision Support System proposed, an actual case project involving two existing schools in Melzo (Milan) was used. The system proposed incorporates 3D BIM models and Bayesian Networks that are capable of semi-automatically evaluating the level of compliance of existing buildings. BNs are a useful means to handle uncertainty due to the lack of some information about existing buildings, because they are capable of dealing with several types of variables and because inference propagation can be inverted. BNs can also consider multiple aspects linked to different regulatory areas simultaneously.

The whole decision support system includes a multi-criteria assessment of some performance indicators, each of them relative to a specific area of interest. The ranking of buildings was performed by means of the AHP approach. Considering the limited budget available to Public Administration, this makes it possible to carry out the evaluations of existing buildings with reduced time and costs.

This paper reported the application in terms of "Accessibility", "Energy Efficiency" and "Acoustics" networks, which were shown to give back reliable results, once interfaced with the BIM models of the case studies. In addition, the development of the BN and the detection of the necessary inputs through the interpretation of regulations give back the amount of information that must be provided by BIM models to perform those analyses.

The methodology detailed in this article can be extended to other regulatory areas such as seismic risk, safety and fire safety.

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Development of Application for Generation of Automatic 2D Drawings based on openBIM

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Abstract

This paper describes the development of an automated stand-alone application for generating 2D drawings using information from an IFC file, independent of existing BIM authoring tools. Using the application described in this paper, plan, section and elevation drawings can be extracted with no additional effort. The approach described in this paper, which is based on openBIM technology, will have a strong impact on the construction process especially from the perspective of enhancing productivity by providing a trade-off between conventional and new approaches.

Keywords –

Building Information Modeling (BIM); Industry Foundation Classes (IFC); 2D Drawings Generation

1 Introduction

With the increasing popularity of smart devices and the application of artificial intelligence and other automation technologies, technical applications for business innovations are being implemented in a wide variety of industries. In an attempt to improve productivity and quality in the construction field, openBIM was introduced for business innovation. openBIM can improve efficiency through construction cost reduction and work automation. Therefore, stockholders in the construction industry expect positive effects from the use of this technology. However, the high cost of facility investment and the re-education of users are hindering the introduction of BIM-related technology. In addition, compared with the expected effect, technology based on openBIM is still in the preliminary stages. In order to use BIM technology effectively throughout the construction process, the technology must be more advanced than its current state. Despite the high degree of interest and expectations for openBIM, there is a wide variety of BIM technology deployed in the construction industry because different groups introduced BIM at different periods and the use of BIM is still in the preliminary stage. In the actual business environment, the construction process is changing from the use of 2D drawings to 3D BIM, but the BIM model and 2D drawings are expected to be submitted at the same time during the permit process. In countries where BIM is mandatory, the BIM model is submitted as an IFC file. The generation of drawings that do not rely on commercial software and that follow international standards (IFC) is very important.

Therefore, there is a need for openBIM-based automatic 2D drawing generation technology to avoid duplicating the work of creating both the BIM model and 2D drawings as well as to overcome limitations due to technical gaps, which are the current economic and technical difficulties hindering the adoption of BIM. However, the drawing generation module included in existing BIM authoring tools can only be used with specific tools. This makes it difficult to use BIM in the current environment, and leads to difficulties in BIM facility investment as well as technical gaps between users.

The purpose of this study is to analyze the architectural elements required to generate 2D drawings with the aim of developing an openBIM application capable of generating 2D drawings automatically. The goal is to maximize the effect of BIM to enable individuals undertaking the permit process in a design office to create IFC-based drawings for permit submission after completing the model. Permit officers can also generate the drawings they need and work efficiency can be improved by reducing duplication during the transition period of BIM introduction.

2 Literature review

2.1 openBIM

BIM is based on the concept of using electronic information to generate and express building information. BIM refers to the process and technology of acquiring and managing information electronically, which is important throughout the life cycle of building planning, design, engineering, construction, maintenance, management and demolition [1]. Through BIM, information related to a building can be managed and used electronically, enabling application of the many advantages of computers, such as accuracy and storability. However, the construction industry is huge and complex and a wide variety of software is used by different groups in the industry to handle computerized information. The omission of information and errors in transmission can occur in the process of information exchange between these different programs [2]. To address this issue, buildingSMART proposed the concept of 'openBIM'.

openBIM is a concept focused on independence from specific software or product groups and ensuring interchangeability and interoperability of information between different kinds of software. For this purpose, the IFC format was developed as an international standard data format in buildingSMART and is actively being developed. In 2013, IFC was adopted and published as an ISO16739 standard [3]. IFC is an international standard neutral file format for BIM data exchange and information exchange between the BIM software used in many fields in the construction industry. In the IFC data structure, information about the building is expressed based on the relationship of the objects and the relationship of attributes owned by the objects.

2.2 Necessity of automatic generation of 2D drawings

Unlike the predicted disappearance of 2D drawings with the introduction of BIM, the requirements for 2D drawings have remained consistent. The results of a survey on BIM introduction status in Korea showed that "duplicate work due to creating BIM model and drawings separately" was the primary factor impeding BIM adoption, with 80% of users selecting this response. When introducing BIM to non-users, the ease of generating different sections, facades, and perspectives should be taken into consideration, as this factor has the highest influence on adoption with 62% of responses [4]. In the early stages of BIM introduction, though the duplicate work of generating 2D drawings simultaneously is necessary, it presents an obstacle to BIM adoption. The primary reason for the duplicate work is the difference in the technical levels of the participants in the construction process. Many participants are involved in different stages of construction, from design, permission, and construction to maintenance. However, when BIM is implemented from the design stage, all participants must use this method to complete the project.

Consequently, even if the BIM contract is expanded and the design work is performed using a BIM model, the current contract situation requires 2D drawings and duplicate work remains a necessity. An application capable of generating 2D drawings automatically is needed to solve this problem. Such an application can eliminate the negative elements of BIM introduction by reducing the workload of users, improving productivity and reducing the technical gap.

2.3 2D drawing automatic generation application and research status

There are various methods for generating 2D drawings from BIM models. Drawings can be generated in combination with a 2D drawing generation module in commercial authoring tools. Choi et al. pointed out the limitations of having to use a 2D drawing module in BIM authoring tool to generate drawings. The problem lies in creating an execution design drawing at the same level as CAD, an inability to match the details with the construction level, and lack of a modeling function that can add detailed content [5]. Chae et al. noted that problems will occur in the process of generating 2D drawings using BIM authoring tools, so this method should be applied in parallel with the existing method of creating 2D drawings [6]. Lee et al. stated that drawings generated with a BIM model cannot meet the standards for construction sites. He proposed developing a module to create steel reinforcement construction drawings and process the schedule accurately according to the relevant criteria by using a 3D structure model and taking the architectural structure as the object [7].

The results of previous research on automatic 2D drawing generation using a BIM model show that most of the previous research stays on the stay at those stages, such as instructions to generate 2D drawings using BIM authoring tools, changes in the design process using templates and a module for automatic generation of drawings for use at construction sites. However, methods for generating 2D drawings using a standard such as the IFC optimization criteria or generating a BIM design document are nonexistent. There is also a lack of practical research on solving the problems of 2D drawing generation.

2.4 Summary

BIM can improve business efficiency by embodying real buildings in virtual space. In the initial phase of BIM introduction, both the 2D and 3D processes coexist, resulting in practitioners performing the duplicate work of creating both a BIM model and 2D drawings [8]. Although the practitioners are burdened by the additional work, existing methods for generating 2D drawings from BIM models are incapable of producing detailed technical drawings. The drawings generated currently cannot be used because they do not meet the standard. In addition, there is no complete study evaluating the use of optimization criteria to improve productivity or a standard format to create drawings. In this study, the structure of the standard IFC format was evaluated to develop an application for automatic generation of 2D drawings based on openBIM that can be used for viewing the BIM model regardless of the type of authoring tool used. The goal is to enable users to generate drawings of required parts from the IFC model without inconveniences resulting from the level of BIM introduction and technical gaps.

3 Implementation of 2D drawing automatic generation application

3.1 Overview

3.1.1 Process for 2D drawing generation based on IFC

The process for 2D drawing generation based on IFC is shown in Figure 1. First, in order to visualize the IFC file, the IFC information must be parsed to distinguish the information for model shape expression and the object attribute information. After separation, the information is stored in memory. Solid shape information is generated using the shape expression information, then converted to mesh for 3D shape expression using the Open Cascade library. To visualize the transformed mesh information in 3D, the Direct X library is employed. For the generation of plan and section drawings, visual images for 2D drawings are generated using a mesh cutting algorithm. The remaining lines on the opposite side of the section generated by mesh cutting are unnecessary and are deleted by a removal algorithm before vector information is generated for output. To create annotated elements (such as dimension, grid, level, etc.) in the generated drawings, the information is first extracted from the IFC model and visualized in the generated drawings.

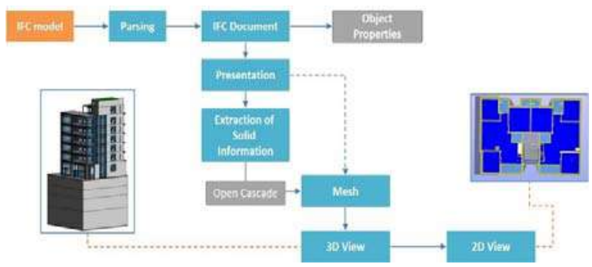

Figure 1. Process diagram

3.1.2 Structure of the application

The information generated from the IFC model is visualized according to the following structure. The structure refers to the classification of the basic structure for IFC. The application was developed in C#, an object-oriented C language, and encapsulation was implemented to use information effectively. During classification, the part needed by Solid calculation calculated through the modular solid calculation is operated as data for visualization. Through the visualization module, the information can be visualized on a computer screen.

To generate a plan drawing, elevation drawing and section drawing with the 3D model, the appropriate data structure for the model should be accurately defined. Section cutting must be applied effectively on the structure based on the cutting plane, and the section cutting results should be expressed accurately without errors. To express the 3D shape information, the structure of the object is mainly used in the triangulation mesh. In this study, we performed section cutting and the generation of section lines in the corresponding plane. However, a relatively complicated computation is required when using a triangular mesh and unnecessary lines may be generated in addition to the section lines. In this study, we mostly needed to generate the section shape. Consequently, we created the object structure as shown below, so that the related work can be completely effectively.

The basic structure of the object was defined as a polyline-made polygon with a hole. The example below shows the shape of one hole in the quadrilateral, but the method presented in this study involves several holes in the polygon. This method can be used to generate a mesh by using a triangulation network after cutting based on the cutting plane.

3.2 Automatic generation of 2D drawing

3.2.1 Generation of elevation drawing

The elevation indicates the elevation shape on four sides (left, right, front, and back). The lines expressed in the elevation can be divided into two types. In the first type, the intersections of the object surfaces form the lines. In the second situation, the intersections of the surfaces form no lines, but the boundaries of a prominent position become the outline. For example, in a curved surface, although there is no line formed by the intersection of surfaces, a section will be presented along the direction of the elevation as a contour line.

When elevation is displayed on the interface of the application, it turns the direction of the camera to the X (Left), -X (Right), Y (Front) and -Y (Back) axes and selects the projection mode as a right-angle mode to display on the interface. In the visualization of the IFC model, when the elevation is displayed, the objects behind the objects shown in the related elevation drawing are presented in an invisible form. In order to represent the elevation drawing on a computer screen, the triangular faces of the obstructed objects are drawn using the background color. On the elevation drawing, the lines that are intended to be hidden should be drawn using the background color, which will make them appear invisible. Therefore, it is not necessary to use the delete calculus separately for obstructed objects. In addition, the elevation drawing can be displayed quickly and effectively.

3.2.2 Generation of section drawing

Generation of a section drawing is based on the plane of the user's desired section, created by cutting off the BIM model and creating an isometric projection in the vertical direction of the section. The section is made up of lines cut from the datum as well as uncut evaluation lines. The method of cutting the building by using the inference plane is as follows. This method is based on the coordinates of the cut-off reference plane, fixing the location of the camera, and truncating all the objects crossing the cross-section and perpendicular planes. The boundary lines of the cutting plane are marked as boundary lines on the screen. This is the same process used in generating the elevation drawing, in order to express section drawings quickly. When displaying a section drawing on the screen, a structure is needed to hide the objects behind the cross-section when the cross-section is displayed.

As shown in Figure 2, the cross-section provides an interface that allows users to set the reference line of the section drawing in the plan drawing for generating section drawings. Currently, the section line can only be created as a straight line.

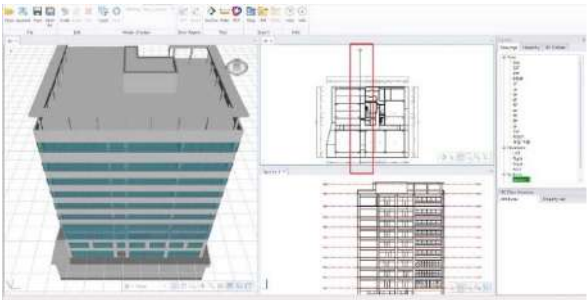

Figure 2. Selecting a section profile to generate any given section drawings of interest

3.2.3 Generation of plan drawing

The generation of plan drawing is a special method for generating the section drawing. It cuts off at the position based on the reference line which is 1.2 m in the upper direction from the surface of each layer, and uses the vertical downward projection method. In order to shorten the computation time for generating plan drawings, unlike the arithmetic method for generating section drawings, information about the object is used, such as the appearance lines on the bottom face.

There is some information in the plan drawing that cannot be expressed by a 3D shape alone. For example, in a swinging door, the direction of the door opening and the door trajectory should be represented. Information regarding the entrance and exit for the opening direction of the door can be generated in IfcDoor. However, IfcDoor only contains information about the location and the direction of the opening. To see the shape and type of the door in detail, the Profile representation in the IfcDoorStyle parameters should be used. In addition, the representation identifier can be used to generate the shape of the 2D accurately. IfcDoor has a separate attribute called Footprint. Although this attribute cannot be expressed in a 3D form, it contains information about the opening and closing of the door, which can be displayed in 2D drawings.

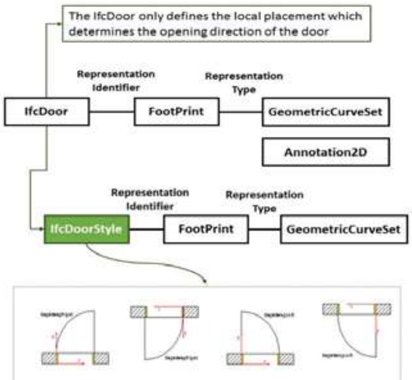

Figure 3. Derivation process to use IfcDoor data

The developed application makes use of related attribute information for creating the plan drawing for the door object. Details of the plan drawing generated in this manner are shown in Figure 4. It is not a 2D scene but rather a 3D Scene, which is created using the Direct X 3D library to express and display the information on the screen quickly. There are many limitations to the rich expression of 2D information, but significant improvements are anticipated in the future.

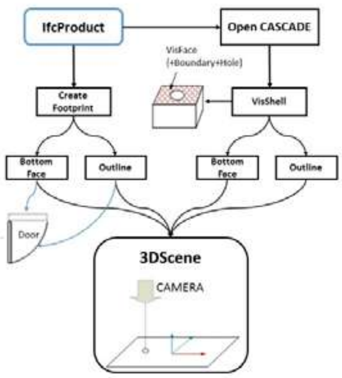

Figure 4. Fundamental algorithm to generate the plan drawing

4 Utilization of 2D drawing automatic generation application

4.1 IFC viewer and the confirmation of information specification

The application developed in this study aims to improve productivity by generating 2D drawings of required parts according to the needs of users after creating a BIM model. The goal is to reduce the duplication of design work and generate accurate drawings according to requirements to improve the efficiency of the work. The application in this study uses the international IFC standard format. The BIM model is based on LOD 300 for permits. The application can generate drawings of any position required by users without the need to consider whether specific authoring tools are available or not. Even if there are differences in the technical level of the users in different stages of the construction process, the IFC file can be used to generate the drawings of the desired parts.

Information in the IFC file can be confirmed using the IFC viewer. The performance of this study based on IFC can inform the users about the location and specification of the information for confirming the accuracy of the IFC files produced in the authoring tools. Therefore, errors in information transmission can be reduced by using the standard format. This is not only to meet the requirements for the permit and construction stages as well as to resolve difficulties because of technical differences, it can also be used to check the accuracy of information when using different kinds of BIM inspection tools to check design proposals at different phases of the design process.

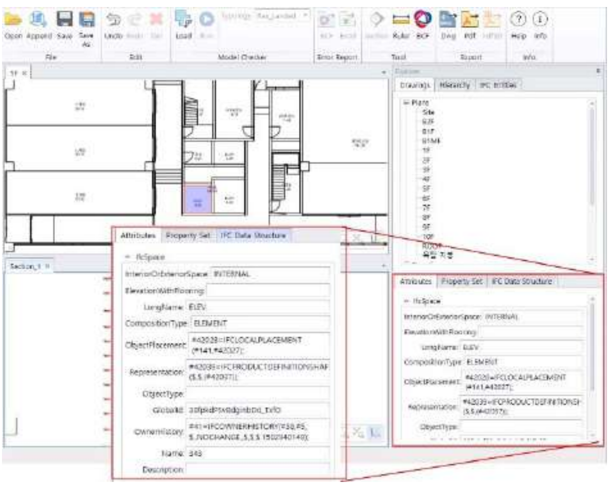

Figure 5. Fundamental algorithm to generate the plan drawing

4.2 Reflecting the optimization criteria of BIM design document generation

In this study, an application for generating 2D drawings based on openBIM was designed according to optimization criteria for BIM design document generation [9]. This means that the documents required in the future building permission process can be incorporated into IFC files using the application developed in this study. This application can generate 2D drawings automatically for submission according to optimization criteria. Therefore, users can utilize the application to generate the drawings necessary for the permit process without knowledge of the optimization criteria for BIM design document generation. This will reduce the amount of the work required by eliminating the duplicate work of creating a BIM model alongside 2D drawings for the permit. It can also reduce the time required to correct errors by generating accurate permission drawings automatically to shorten the time required to obtain permits.

5 Conclusion

In this study, an application for generating 2D drawings from a BIM model by analyzing IFC files was developed. The application can be applied not only in the design stage but also throughout the construction project. As the BIM technology matured, various authoring tools were developed. However, the data specification for each authoring tool is different, which reduced the efficiency of BIM [10]. To ensure that data from various BIM tools are compatible, a standard format must be used [11]. In countries where BIM is mandatory, the BIM model is submitted as an IFC file. The generation of drawings that do not rely on commercial software and that follow international standards (IFC) is very important.

In this paper, the authors use the concept of openBIM unrelated to specific authoring tools. In order to improve the usability, an automatic generation method for submission drawings was developed using optimization criteria for BIM design document generation. In this paper, the description was focused on generation of plan, section and elevation drawings from an existing 3D model. The generation of 2D drawings programmatically is achieved by using the background color for the part behind the cutting plane selected by the user to achieve a hidden effect. However, in order to extract the generated drawings in DWG or PDF format, the drawing lines corresponding to the cutting plane must be generated and an algorithm must be used to remove hidden lines to extract the drawings. In addition, for the presentation of the door object mentioned above, a cross-section of the 3D shape may not contain all the information provided by a 2D drawing (such as the grid, dimension line, expression of void, space information, etc.). Therefore, research on the generation of separate information in the IFC should be continued.

If the developed application can be used in the BIM environment throughout the process of design-permission-construction-maintenance to expand the application scope of BIM, the effect of BIM can be maximized. The application eliminates the need for duplicate or repeat work resulting from the type of authoring tools used or differences in BIM technical level. Unlike the previous process of using specific authoring tools or creating 2D drawings and BIM models separately, the developed application can improve the efficiency of the entire construction process under the BIM environment by generating 2D drawings using openBIM. Therefore, the application is expected to provide support for construction participants, facilitating efficient BIM usage.

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A methodological approach to implement on-site construction robotics and automation: a case of Hong Kong

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Abstract

The public housing construction industry in Hong Kong faces conspicuous challenges of high demands, safety, an ageing workforce, inconsistent quality and stagnant productivity. Compared to the manufacturing industry, the degree of automation in the construction sector lags behind. Based on the on-going consultancy project commissioned by the Construction Industry Council (CIC) in Hong Kong, the aim of this paper is to evaluate the current on-site construction operation and to identify the existing bottlenecks that can be enhanced by implementing robotics and automation. In the current housing construction field, the systematic and scientific method to approach this type of undertaking, especially when closely associated with the industry and authorities, has not been comprehensively discussed. Therefore, this paper highlights the activities that signify these objectives, which include five key activities: literature review, industry survey, on-site case study, co-creation workshops and potential pilot project. The key activities forming the backbone of the project and the outcomes will be illustrated. As a result, a range of proposed robotic applications that are tailor-made for Hong Kong public housing industry are recommended and hierarchically categorised. The results will epitomise the applicable methods that are required when executing the similar type of consultation project. In addition, the findings will inspire the construction industry to initiate and explore innovative, compatible as well as feasible solutions to the implementation of the robotic application in the future.

Keywords –

Construction robotics and automation; Methodology; Public housing construction; Hong Kong

1 Introduction

The Hong Kong Public Housing Construction (PHC) sector experiences three major challenges: first, to satisfy the increasing demand; second, to achieve affordable price, and third, to address demographic changes. In recent years, the manufacturing sector has adopted robotic and automation technology. This paradigm has achieved obvious implications in regard to increased productivity, affordability, constant quality, and improved safety.

In general, compared to the manufacturing industry, the degree of automation lags behind in the construction industry, and the implementation of construction robotics and automation may hold the key to solve the aforementioned challenges [1]. Therefore, the Construction Industry Council Hong Kong (CIC) commissioned the Chair of Building Realization and Robotics (br^2) at Technical University of Munich (TUM) to research and develop construction robots and automation strategies that are tailor-made for the PHC in Hong Kong. This paper documents the on-going project that demonstrates the research objectives, methods and evaluates the outcomes of the current project phase, as well as defines the remaining tasks.

2 Public housing construction (PHC) in Hong Kong

To gain a basic understanding of the Hong Kong PHC sector is decisively important when proposing tailor-made methods in developing construction robots and automation strategy for Hong Kong. Hong Kong is situated at the southern tip of the mainland China, which consists of three main islands, Kowloon, Hong Kong, and New Territories. The development of construction is always challenged by the hilly terrain and high population density [2].

Public housing in Hong Kong, which can date back 50 years ago, has a long history of overcrowding and growing demand. Over 48.8 percent of the population in Hong Kong live in public housing estates today [3]. According to the government census, the average living space per person is 13.2 m^2. Demographically, increasing numbers of retirees will impose more pressure on public housing demand. The government estimates that the housing supply target for the year 2017-2018 is 460,000 units. To make things worse, the housing prices have skyrocketed in recent years, and young people find it extremely difficult to climb up the property ladder. Therefore, the government needs to progressively response by closely working with the PHC sector to solve the aforementioned issues [4].

2.1 Challenges and hypothesis

To be able to catch up with the increasing housing demand, the PHC sector must improve its productivity and speed up the construction lead-time. As a result of the high housing price and construction cost, the quality and standard of the final finishing has to be high to avoid any criticism or even rejection from the Housing Department (HD) or the tenants. As a result of population ageing, skilled workers are scarce in the construction market. The construction industry has to transform its traditional public image from a dirty, dangerous and demeaning industry to a safe, attractive and prosperous one. Subsequently, implementing construction robotics and automation technology will potentially increase productivity, enhance construction quality, and improve on-site operational safety. In addition, it has the potential to transform the status of blue-collar construction workforce to the technology-focused and highly skilled workforce. With this paradigm shift the construction industry might has the potential to attract younger workers to engage in the construction trade [5].

2.2 Research objective and gaps

In general, construction processes are complicated, including many parallels, and sequential tasks are carried out seamlessly. Many stakeholders are involved in each critical phase to ensure that the project is on time and on a budget as well as satisfies key stakeholders' requirements. Despite what have been mentioned, many other factors could also influence the construction process, such as the technological, social, economic factors, and political measures. The main objectives of this project are: first to evaluate current status of the PHC sector by investigate existing construction operation, labour market, regulations and government legislation, then to identify the challenges, key stakeholder's requirements, and to validate key construction processes that can be improved by implementing on-site construction robotics and automation. Finally, a range of robotic applications will be tailor-made and proposed for the PHC sector, bearing wider audiences once the industry sector is reformed. For example, the future construction sector will expose a cross-disciplinary characteristic where many industries coexist and collaborate. In this sense, upgrading the performance of the construction industry not only has positive impact on one industry but also will grant much greater contribution to the prosperity of Hong Kong.

Research has been done on the development of construction robots. However, it has not been studied sufficiently in-depth, and often times only the design concept, hardware and software applications are demonstrated. Thus, limited research topics were particularly conducted related to the PHC in Hong Kong. Existing research does not emphasise issues related to the early stage of the construction robotics development. Therefore, the consultancy project fills the void and demonstrates a comprehensive method that emphasises research methodology in regards to the early stage of the construction robotics development. For example, how to structure an applicable approach that encourages the collaboration between the key stakeholders. It also explores how to interpret the accumulated data into universal requirements that can be further implemented as practical designs. Furthermore, the project explores to develop a practical design concept that reflects the research objectives and suits the practical market demands.

3 Methods

In order to systematically execute the consultancy project, the project has been divided into five phases (Figure 1).

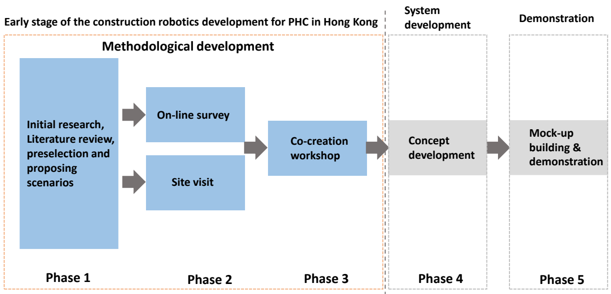

Figure 1. Project phases

The first phase includes initial research, literature review, preselection of the proposed robotics and automation strategies, and proposing use case scenarios. The second phase includes online surveys and site visits. The third phase is co-creation workshops. The fourth phase works on the concept development, detailing and finalisation of the selected system. The fifth phase includes a final demonstration of the system, construction of the demonstration mock-up, validation of the design concept, and planning for future work as well as recommendation for future development. This paper will methodically illustrate from phase 1 to phase 3 of the ongoing project and explore how to use applied research strategies in an early stage decision-making procedure when conducting this type of industry-related and technology-focused consultancy project [6]. The paper also presents current research findings and raises questions in regard to how to address the identified challenges with proposed feasible solutions.

3.1 Background development

During the 1980's, the Japanese construction sector put huge investments into R&D for developing construction robots and automated construction sites. At the time, a shortage of skilled labour, as a result of ageing society, has been a major concern in the Japanese construction industry [7]. Single-Task Construction Robot (STCR) have been developed to address this issue and to attract young workers to get involved in the industry. In general, STCR is designed to focus on executing one or several specific construction tasks in a dedicated working area. Due to the complexity of the construction project, STCR is very different from the robots in manufacturing in terms of the composition, kinematics, navigation, and function. STCR is normally tailor-made to suite all stakeholders' requirements rather than simply integrated into the construction project.

To be able to successfully adopt STCR, it is crucial to follow the notion of Robot-oriented Design (ROD) [8]. The ROD concept was first conceptualised in 1988 by Thomas Bock and later served as the principle for automated construction and robot-based construction sites around the world. This concept emphasizes the idea that during final on-site construction processes, all design parameters should have been considered at the earlier design and production stages. The building components will be designed to be easily handled by robots during the assembly phase. When developing robotic technology for the construction sector, it is far more diverse and complicated than the operation in manufacturing plants [9].

Nowadays, Hong Kong experiences a similar circumstance such as labour shortage, demographic changes, and the urge of increasing construction efficiency. By implementing robotics and automation technologies might be able to tackle some of the aforementioned issues. However, modern buildings consist of many complex structures, layouts, and subsystems. Also, the construction industry can be influenced by other attributes, for example, economy and policies, so that imposing huge constraints when applying robotic technologies in construction. Hence, in the early development phase, it is vital to be aware of key stakeholder's requirements, understand the existing construction operation, and analytically evaluate the construction process. This method helps the project team to enumerate the current demand, and distinguish the optimum strategy.

In principle, there are several hurdles or levels to achieve construction automation, which includes standardisation, semi-automation, and full automation. Standardisation can be achieved through prefabrication, and the prefabrication rates in Hong Kong is relatively high [10]. Prefabrication was introduced to the PHC projects in the mid-1980s in Hong Kong. Then the Hong Kong Housing Authority (HKHA) has promoted extensively the usage of prefabricated elements and standard reusable formwork in the public sector [11]. The most of the contractors are able to achieve 6-day-per-floor working cycle, thanks to the standardisation in design. Optimistically, due to a high degree of standardisation in the PHC sector, so Hong Kong has the potential and willingness to upgrade to the next level.

During the first phase of the research, the background study was conducted, which includes the typology of the building systems, and the labour market shortage analysis in Hong Kong. CIC has provided exclusive statistical information focused on the public rental housing development contracted by Hip Hing Engineering Co., Ltd at Ex-Kwai Chung Police Married Quarters building. The statistics indicate that the following professions will experience the most skilled worker shortage from 2017 to 2025, including carpenter for wooden formwork and joiner, plasterer, terrazzo and granolithic worker, interior/exterior finishing, stonemason, refrigeration, ventilation mechanic for assembly, inspection, and maintenance tasks. The background study provides an essential understanding of the current Hong Kong PHC sector as a whole, evaluates the weaknesses and strength, prioritises research objectives, and formulates feasible strategies.

An introduction booklet is produced during the first phase of research, and it was distributed among the selected stakeholders. The booklet serves as an eye opener for the construction industry due to the unfamiliarity of robotic technologies. It also assists the stakeholders in understanding the project objectives, and to demonstrate potential application which can be applied in the Hong Kong PHC sector. Based on the findings from the background studies and internal discussions between TUM, CIC and key stakeholders, there were 22 robotic and automation systems were proposed.

The 22 selected systems were also systematically distributed into three use case scenarios [12]. The scenarios were contemplated based on the evolution of degree of automation, and their ability to be integrated into industry during the course of the proposed development roadmap. The first scenario aims to demonstrate the potential of single task construction robots (STCR) to assist profession-specific, physically demanding and repetitive tasks on-site. Under this scenario, there are limited alterations which the existing building has to adopt. There is modest impact on the conventional construction industry and the structural performance of the building. It also serves as the backbone for the future development. The second scenario integrates automatic and semiautomatic construction systems. In this scenario, some of the proposed solutions may require alteration of the existing building design. For instance, a higher degree of prefabrication rate is recommended. The building method may need to adopt the use of robotics and automation. The third scenario illustrates the potential of applying fully automated construction system in Hong Kong. In this scenario, the proposed solution can be applied only if the building is designed in consideration of ROD. This scenario describes the ultimate goal that can be achieved when applying feasible automation and robotics technologies in the construction industry in Hong Kong. The scenarios also functioned as project use cases that allow the stakeholder analysis to be conducted [13].

A value matrix is dedicated to the proposed systems under each scenario to classify the functional, and non-functional requirements. For example, in this case, the functional requirements specify the technical specification of the system, the compatibility, the productivity, and the Technology Readiness Level (TRL). The non-functional requirements express the non-measurable function or quality of the system, the governmental policies and regulations, the legal matter, feasibility, and sustainability. The value matrix of the proposed 22 systems was distributed out to the selected stakeholders and scored with a value that measures those requirements fulfilling the stakeholders expectations. It also provides the background information for the online survey in the later stage of the project.

3.2 Online survey

In the first phase of this consultancy study, TUM has identified a series of automation and robotics technologies which has been proposed to PHC. In order to examine the feasibility of these automation and robotics technologies, as well as their potentials to improve productivity, safety, and quality of the industry, an online survey (powered by Google Forms) is conducted, and its methodology and results are described as follows.

3.2.1 The survey methodology

The aforementioned 22 robotic systems in three scenarios are listed in the questionnaire and these systems' technical details are described in the questionnaire. They include: T1 reinforcing bar fabrication positioning; T2 automatic climbing formwork; T3 concrete distribution; T4 concrete levelling and finishing; T5 logistics supply; T6 hoist and positioning; T7 installation and material handling; T8 façade cleaning and exterior finishing; T9 interior painting; T10 interior wall plastering; T11 automated bricklaying; T12 automated interior tiling; T13 robotic marking; T14 exoskeleton; T15 mobile on-site factory; T16 vertical delivery system; T17 building components positioning and handling; T18 façade element installation; T19 prefabrication in HVAC system; T20 sky factory; T21 ground on-site factory; and T22 integrated on-site assembling system.

The survey follows a two-round selection method (adapted from Nanyam, et al., 2015, see Figure 2) [14]. The first round is to examine these proposed systems' feasibility for the PHC in Hong Kong (the primary attribute). Once accepted, all attributes (e.g., feasibility, improvement of productivity, safety, and quality) of these systems are further evaluated. Each question is based on the Likert Scale [15]. In addition, survey participants can leave comments to each technology.

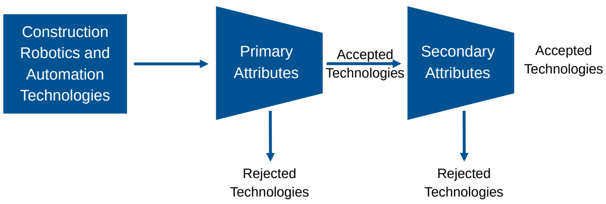

Figure 2. Survey selection method

Equation followed for calculating the TPS of the attributes of each technology:

$$\text{TPS} = \sum_{i=1}^{5} Pi \times Wi \qquad (1)$$

- TPS = Technology Preference Score
- P = Percentage of Preference
- W = Weighted Value (strongly agree=100; agree=75; neutral=50; disagree =25; strongly disagree=0)
- i = Likert Scale

3.2.2 The survey results

The online survey was sent out to more than 200 professionals/stakeholders from Hong Kong construction industry, and 36 effective survey responses have been received. Professionals are from various backgrounds: 36% of the participants are contractors, 28% are consultants, 14% are clients, 14% are policymakers, 5% are academics, and 3% are NGO members. 82.4% participants have more than 10 years of experience in the construction industry.

After calculating the survey data according to the aforementioned method, the survey results are listed as below. Technologies with a score above 70 are strongly/highly recommended; between 50 and 70 are recommended; below 50 are poorly or not recommended. Logistics supply and ground on-site factory are ruled out in the first-round feasibility examination according to the criteria (their feasibility scores are under 50) (Figure 3 & Figure 4).

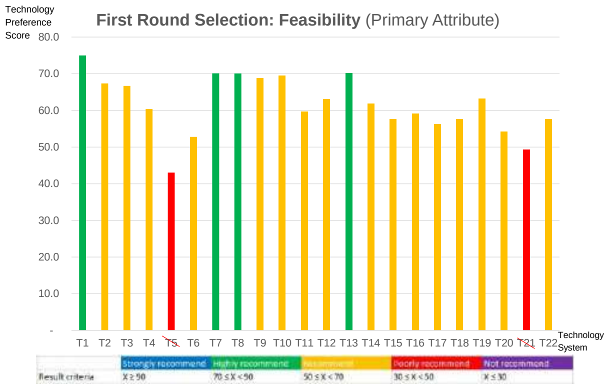

Figure 3. Survey scores of the first round selection

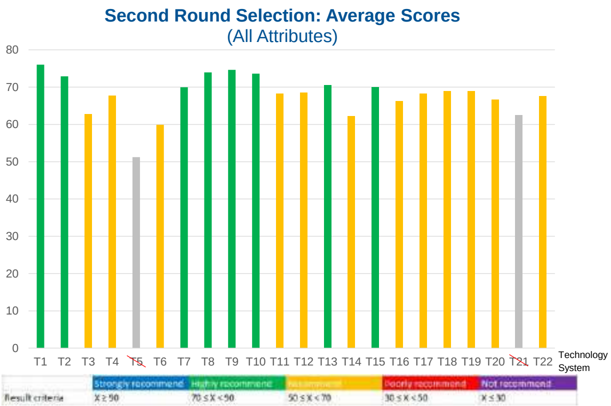

Figure 4. Survey scores of the second round selection

The result of the two-round selection summarised in Table **1** shows that in Hong Kong, the construction robotics and automation technologies are overall approved by the local professionals and stakeholders. The highly recommended technologies are of high priority and thus can be implemented in the near future. The recommended technologies are also demanded, but there is a long way to go before they can be fully implemented. However, due to the actual situation in Hong Kong, some technologies are not practical at the moment, such as T5 logistic supply and T21 ground on-site factory.

Table 1. Final survey results

Highly Recommended Technologies	T1 (Reinforcing Bar Fabrication/ Positioning) T2 (Automatic Climbing Formwork) T7 (Installation and Material Handling) T8 (Façade Coating, Painting, Cleaning and Exterior Finishing) T9 (Interior Painting Application) T10 (Interior Plastering Application) T13 (Robotic Marking) T15 (Mobile On-site Factory)
Recommended Technologies	T3 (Concrete Distribution) T4 (Concrete Leveling and Finishing) T6 (Hoist and Positioning) T11 (Automated Bricklaying) T12 (Automated Interior Tiling) T14 (Exoskeleton) T16 (Vertical Delivery System) T17 (Floor Slab, Beam, Column Positioning and Handling System) T18 (Facade Element Installation) T19 (Prefabrication in HVAC System) T20 (Sky Factory) T22 (Integrated & Automated On-site Assembly System)
Rejected Technologies	T5 (Logistics Supply) T21 (Ground On-site Factory)

3.3 Site visit

Shortly after the online survey, the TUM project team travelled to Hong Kong to conduct a comprehensive on-site case study, which was organised by CIC and Hip Hing Engineering Co., Ltd. The site is located at Ngan Kwong Wan Road in Mui Wo, Hong Kong, and it consists of two residential building blocks (one is 14-storey and the other is 16-storey) (Figure **5**).

Figure 5. Site visit at Ngan Kwong Wan Road

Both buildings are designed as Home Ownership Scheme project. The main objectives of the on-site study are summarised:

- To understand current workflow, techniques, regulations, and tenders process of the PHC.
- To identify the Key Performance Indicator (KPI) that measures construction success of the project.
- To discuss and exchange ideas with the site manager, skilled labour, and contractors in regards to the implementation of construction robotics in Hong Kong.
- To determine which working process is worth automating.
- To map out feasible concepts and roadmaps for the future development.

The site visit focused on the following key areas:

- Reinforcing bar fabrication/ positioning
- Self-climbing formwork or conventional formwork

erection process
- On-site logistics and material handling strategies
- Shear wall component hoist, positioning, and installation process
- Prefabricated bathroom component hoist, positioning, and installation process
- Interior finishing process
- Façade coating, sealing, painting, cleaning, and inspection.

Since the case study building was close to the completion stage, limited site activities could be observed. The construction diary and imagery collected throughout the construction process became a valuable resource to analyse the intended key areas. Detailed interviews were conducted with the site manager, engineers, and skilled labour. Interview questions and answers were documented in the site visit report. Potential areas that can be optimised by implementing construction robotics and automation were identified, which include reinforcing bar fabrication, positioning, formwork erection, prefabricated wall assembly, drywall assembly, façade painting, and interior finishing. One interesting finding is that before the site visits the project team considered on-site logistics and material handling as an integral part of the whole construction process, which has huge potential to be automated. However, during the site visit, the project team realised that the construction site is orderly organised yet extremely congested due to the limited on-site space. Therefore, it is challenging to implement robotic delivery systems, such as automated guided vehicle, allocated docking station, and dedicated loading bays on-site. The project manager also mentioned that it is crucial to test and refine the proposed robotic application in a pilot project, in which the biggest challenge is to introduce construction robots into an on-going project without causing any delays.

3.4 Co-creation workshop

After the online survey and on-site visit, a number of workshops were organised. These series of workshops were a key milestone of the consultancy study. The workshops aimed to seek practical input from industry experts to 1) evaluate the technical feasibility of adopting construction robotics/automation technologies in actual construction sites, and 2) map out pragmatic action plans for the Hong Kong building industry. Consequently, two Technical (T) Sessions and two Policy (P) Sessions were organised. The workshop participants comprised of a broad range of stakeholders including governmental representatives, developers, contractors, consultants, and industry experts. In total, more than 40 participants joined the two-day workshops. The outputs from the workshops were summarised and presented to the CIC Committee on Productivity. The data were used to form a roadmap on adopting advanced construction technologies in Hong Kong.

The main objectives of the T session were to identify the specific tasks and constraints within the on-site PHC that have the potential and are necessary to be upgraded by construction robotics and automation, then to determine the key organisational, technical, functional requirements when implementing construction robotics and automation in the selected on-site tasks. The priority tasks identified from the T sessions include façade/exterior work, interior plastering/painting, automatic formwork, hoist/positioning system, and welding. Detailed sequences of the sub-tasks were identified based on the existing operation of the tasks. For example, the sub-tasks of façade/exterior work include the installation of gondolas, cleaning and preparing the external wall, skim coating, exterior painting, installing the exterior piping, inspecting façade paint quality, and dismantling of the gondolas. Understanding the detailed work sequence will help the project team to identify the general requirements for the specific tasks, which are:

- The proposed system needs to be flexible and easy to install in the confined space on-site.
- The proposed system needs to be compact, lightweight, and easy to manoeuvre.
- The proposed system needs to be easy to adapt to the different designs of the building.
- The proposed system should avoid using temporary fixtures that will increase installation time.
- The proposed system should consider human-robot interaction. The robotic system hardly completely replaces on-site labour but can work together with labour to enhance overall productivity.

Based on the outcomes from the T session, the P session aimed to formulate strategies and action plans on how to implement appropriate technologies for the selected on-site tasks, in which socio-technical issues, work organisation, safety concerns, financial implications, skills requirements, and regulation-related topics were discussed. In conjunction with the potential concerns and opportunities during the implementation of the proposed systems were examined. Subsequently, guidance and potential approaches were forthrightly discussed in terms of how to address economic, managerial, social and political issues when introducing automation and robotics to PHC sector. As a result, industry policies encouraging the adoption of automation and robotics are necessary, which means the government and CIC should consider creating incentive programs for the contractors to adopt robotics and automation in their projects. It is crucial to establish a construction robots supply infrastructure including manufacturers, distributors, training facilities, and maintenance services.

Moreover, the degree of complexity and automation of the robotic system has to be considered during the early design phase. In addition, feasible business models have to be developed based on the scopes of the key stakeholders.

At the end of the co-creation workshops, a number of key performance indicators were identified, which include safety, labour shortage, improve quality, adoptable, compact and flexible design, acceptance, and improve productivity. A key performance study of the selected system was conducted by TUM project team with a spider chart (Figure **6**). The spider chart is used as a metrics to demonstrate a dynamic trend of the influential key performance, and each one is rated by lower to higher variables. For example, in this case, 5 point indicates a better performance score than 4 point. There were 5 finalists chosen for the evaluation, which include façade work and exterior work system, interior painting, plastering system, hoist and positioning system, automatic formwork, and automated welding system.

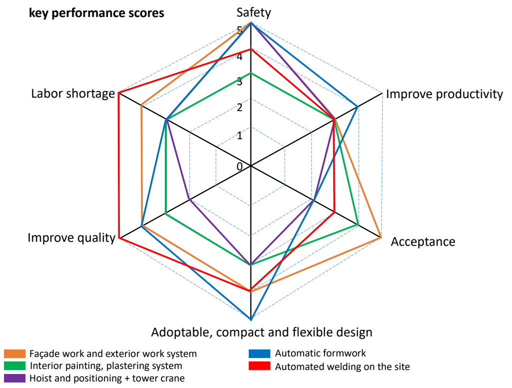

Figure 6. Key performance scores spider chart

The detailed description of the key performance indicators are as follows:

- Safety has been identified as one of the most important criteria for façade and exterior work system, automatic formwork and hoist system, positioning, and tower crane operation.
- The adaptable, compact and flexible design has been identified as the second most dominant measure. It is also pointed out by the participants during the workshops that the proposed system has to be adaptable to the changes in the on-site environment, building layouts, and design features.
- The proposed system needs to address the increasing trend of labour shortage and to improve the finishing quality as well as productivity.
- In general, the acceptance scores indicate that the construction industry is open to the implementation of automation and robotics.
- To convince the stakeholders to adopt automation and robotics on-site, the project team has to carry out a compelling pilot project with attractive incentives with the help of the government.

After discussion with the stakeholders, the project team decided to conduct the next phase of research based on the façade and exterior work system, because 1) it addresses the identified challenges, 2) it achieved balanced key performance scores based on the spider chat, 3) it can be constructed as a scale model in an early development stage with given budget, and 4) it can be implemented in a real construction site with minimum disturbance, hence suitable for future pilot project.

4 Results

During the project, the initial research identified the main requirements of the stakeholders, as well as the proposed strategies and scenarios for implementing construction robotics and automation in Hong Kong. The initial research forms the academic foundation for later phases. The online survey determined the potential systems that can be developed. However, the result is less conclusive, due to stakeholders' experiences and expertise. Nevertheless, the result has paved the way for the on-site visit. The on-site visit validated the requirements of the frontline workers. The feedback from the on-site visit was consecutive, pertinent and knowledgeable. Thus, the accumulated information helped the project team to build up a convincing argument, and draft research evidence and directions during the co-creation workshop sessions, which systematically formulated technical and practical strategies for further developing the project.

As a result, the façade and exterior finishing robot were chosen to be developed as a stimulator to the PHC industry. The proposed system will be a revelation that demonstrates how to adopt robotics and automation in the conventional construction process. In general, the robot will be highly modularised, which can form various configurations based on the design of the target building. Three application modes were proposed based on a ring concept (Figure **7**).

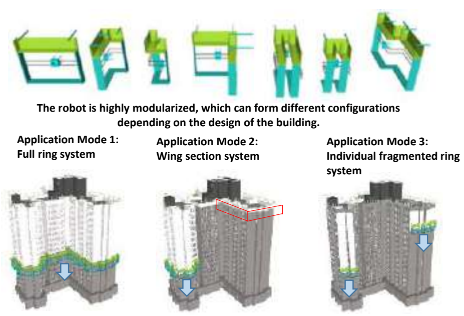

Figure 7. Proposed concept

The first mode is the full ring mode in which the system can be operated as a whole/partial ring up and down along the building surface according to the project schedule. The second one is the wing section mode in which the system can be operated to cover one wing of the building and then be reassembled to the other wings according to the scheduled work plan. The third one is the individual fragmented ring mode in which the system is only designed to paint a specific surface type. For example, the system only paints flat surfaces without any window openings, indentations or protrusions. Currently, the project team is working on the detailed design of the systems where the degree of automation, kinematics, and end-effectors will be finalised. However, due to intellectual property protection issues, the detailed design cannot be revealed at the moment.

5 Conclusion

The consultation project offered an opportunity to perform the systematic study in regard to how to implement robotics and automation technologies in PHC sector from the ground up. Through the initial research, online survey, site visits, and co-creation workshops, the project team have successfully identified the industry demands, stakeholder requirements, yet, narrowed down the research scope and now focuses on the system development as well as real-world implementation. The research findings indicate that the PHC sector in Hong Kong has the potential and willingness to implement construction robotics and automation technology. However, there are also challenges imposed by the existing industry. Many issues and questions cannot be verified at this moment in time, such as the construction industry's reluctance to change, limited understanding of automation and robotics, and lack of robotic infrastructures. How to generate more research incentives, make changes in the government policies, and initiate appropriate business models also need to be taken into consideration. The next phase of the project will be focused on detailing system design, constructing scaled functional mock-up, and disseminating the mock-up to the industry as well as to the public. The research methodology can serve as a guideline when the construction industry executes the similar type of project. In addition, the research will be able to inspire the construction industry to initiate and explore innovative, compatible as well as feasible solutions to the implementation of the robotic application in the future.

Acknowledgements

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Structuring information from BIM: A glance at bills of materials

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Abstract – Industrialized house-builders are moving towards an enhanced production where management of information along the value chain is critical in order to deliver housing projects on time and with the desired quality. Today digital tools and systems are used in both design and production to produce, deliver and instruct actors throughout the phases of a project. However, the information usually exists in different islands and manual transfers are required to keep the flow of information between IT-systems and individuals continuous. A key to improving the ability for the members in different stages of a project to work with the same information is to facilitate different views. One of the building blocks for creating bridges between the islands of information is to introduce bills of materials which can be used to organize information for different purposes. Uniting the use of building information modeling (BIM) with bills of materials (BOM) is therefore our focus in this paper. This is done in the context of industrialized house-building and the facets which it brings to the subject. The aim of this paper is to present an early endeavor into a BOM based approach for structuring information from BIM models. A demonstration tool was developed, and together with application in a case project from an industrialized house-builder, the generation of BOMs from BIM data is illustrated and discussed. The findings illustrates that we can apply different structures to the information located in our BIM models and that we can produce a BOM perspective on our products. Also, it is highlighted that we still need further studies to better understand how application of BOMs in the context of industrialized house-building is realized.

Keywords –

Bill of Materials; BIM; Industrialized; House-Building

1 Introduction

Within the realm of industrialized house-building the use of information and communications technology (ICT) is a facilitator providing conditions for an efficient production with accurate and reliable information [1]. Using ICT to share and provide up-to-date information along the value chain becomes an essential part in effective housing production processes. However, as a house-building project progresses, information is at risk to become fragmented into islands. Use of different tools by actors coupled with requirements on diverse views on information lead to implications where manual transfers between these islands becomes common in order to retain the flow of information. Solutions to this fragmentation has been discussed from angles including using a central repository to achieve greater integration [2] and using the common format of IFC to facilitate information exchange [3]. Within these, Building Information Modeling (BIM) is used as the overarching method and has been highlighted as an assistant in in solving these issues [4]. Furthermore, matters regarding integration, collaboration and information sharing in the context of BIM has also received increased attention in recent research [5].

It could be argued that as industrialized house-building companies retain more control of the value chain, leading to less fragmentation, there are greater chances of success when integrating ICT [6,7]. Despite this, issues exists including the overall management of information [8]. With characteristics from both the construction and manufacturing industry, adopting established practices from the latter has been of interest. As such, attention has been placed on adopting tools and methods, such as Enterprise Resource Planning (ERP) [7] and Product Lifecycle Management (PLM) [9]. However, ICT-tools adopted from other contexts have been targeted as one of the hindrances as these may not be optimal for their new context [6,8,9]. Issues that are present include divergent data structures that interfere with bridging of systems [6,8], and a dissimilarity in the view on projects [9] and construction objects [7]. For accommodating different views on information and to provide product structures through the lifecycle of a product, bill of materials (BOM) is described as a key facilitator [10]. The BOM carries product data between actors and systems, and is an essential part in the ICT toolkit. Previous research on information management within industrialized house-building has however paid little attention to the use of bills of materials as an approach to structuring information. Difficulties in managing information through the value chain, and requiring diverse views on information are however persistent issues. Better maintaining a continuous flow of information, providing accurate and reliable information between actors and tools, are aspects to strive for and to further explore. Therefore, the aim of this paper is to present an early endeavour of uniting the concepts of BIM and BOM in the context of industrialized house-building, suggesting a BOM based approach for structuring information. This approach is exemplified through a case study with a demonstration tool that extends a BIM capable platform to provide a BOM perspective on BIM data. The contribution of this study aim to start setting the groundwork for further studies regarding using BOM as a means to structure information in the context of industrialized house-building.

2 Background

2.1 Industrialized House-Building and ICT

The Swedish housing sector has been subject to an expansive development of industrialized methods. A strive towards shorter lead times, quality of deliveries, and customized buildings are driving forces for house builders to systemize work in their supply chains. Here, industrialized house-building is used to describe methods and principles of a process- and product-oriented alternative to traditional project-oriented house-building [11]. Constructs that constitute industrialized house-building includes management of components, processes and relations in the standardization of house-building platforms, as well as development of ICT for integration. Thus, the ability to provide up-to-date information [7], which is accurate and reliable [1] are key contributions from ICT to an efficient production. With characteristics from both the construction and the manufacturing industry, efforts to adopt patterns from the latter has been previously studied. Ekholm and Molnár [12] highlighted that information systems known from the manufacturing industry have been integrated in the industrialization of the building sector in order to reap from the benefits it has shown. Babič et al [7] investigated creating a link between an Enterprise Resource Planning (ERP) system and BIM. Holzer [13] investigated approaches to create links between Product Lifecycle Management (PLM) systems, together with BIM, to provide information to ERP-systems.

Through a perspective of BIM being used throughout a building's lifecycle, with the resulting information rich model, it becomes a facilitator for information management. With this, a growing interest has been shown areas of collaboration, information sharing, and integration [5]. Through this continuing expansion of BIM as an ICT platform, some research has surfaced investigating the relation between the areas of industrialized house-building and BIM. Lu and Korman [14] discussed benefits and challenges of BIM for modular construction from a perspective of pre-project planning and coordination. Moghadam et al [15] proposed a model for modular construction manufacturing that links BIM and lean. Lu et al [16] presented a BIM-based trade-off platform for industrialized housing. Nawari [17] proposed an information delivery manual for off-site construction. Ezcan et al [18] showed interest in BIM and off-site manufacturing and indicated that it would contribute in areas of IT integration, providing extensive information and improving lead times to mention a few.

2.2 Bills of Materials

At the heart of information systems within the manufacturing industry is the bill of materials (BOM) [19]. This includes systems like MRP (Material Resource Planning), ERP (Enterprise Resource Planning) and PDM (Product Data Management) [10,20]. Throughout the lifecycle of a product, it is used to accommodate different views on information and to provide data structures [10]. There are more than one way to define BOM and three different distinctions are described here: 1) as an organized collection of quantities, 2) as a means to structure information in systems, and 3) as a data repository.

When viewed in its simplest form the BOM provides a collection of the materials and components that comprise a product, together with the required quantities [21]. In a similar vein, and more commonly discussed in the construction industry, is quantity takeoff that offers the amount of materials and components which can be organized into a bill of quantities [21]. Further developments of the BOM exist where it is seen as a product specification, describing the composition of a product and how it is realized from its immediate components [19]. In these extended perspectives, more emphasis is put on the relationships between components (children) and their parents. As such, it becomes decoupled from being the sibling of quantity takeoff, and is instead transformed into a description of how a product is configured. Another take on the BOM exists where it is not only viewed as the underlying structure, but also as an information repository. Some authors describe the BOM as a "product structure data file" [23] or a "database" [24]. The scope of the BOM is thus extended to contain a wide variety of information, e.g. product specifications, part drawings, parts routing, manufacturing processes etc. [24].

A key part in the use of BOMs throughout multiple phases of a product's lifecycle is the different views that can be applied dependent on the use case and activities associated. The Engineering BOM (E-BOM) and the Manufacturing BOM (M-BOM) are two commonly discussed [20,21,24]. The E-BOM is used by designers [21], representing a product from an engineering viewpoint of how the product is functionally formed, however lacking sufficient information regarding manufacturing [25]. This is mitigated by the M-BOM which is a representation of a product based on how it is manufactured [25]. In a more practical sense, the E-BOM is usually managed through a CAD system, where support is provided for the designers to represent their product structure according to their desires. Furthermore, the M-BOM is the result of a transformation of the E-BOM where additional aspects are included such as manufacturing sequence [25], and adding interim assemblies to better depict the manufacturing process. As such, despite describing the same product, these different BOMs manifest themselves with different structures (see Figure 1), providing each phase of a product with the necessary information.

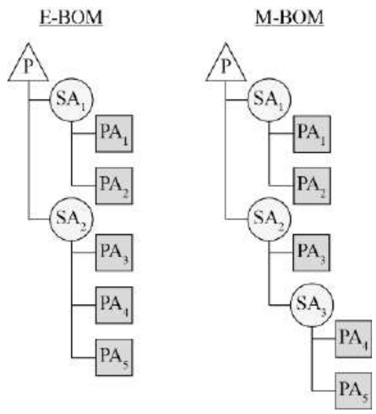

Figure 1. Example structure of an E-BOM and M-BOM, where P is the product, SA is a subassembly and PA is a part (adapted from [20])

Some authors (e.g. [20,26]) have also chosen to differentiate between the usage of BOMs, and the structural representation of BOMs. In these cases, the usage includes for example the E-BOM and the M-BOM. The structural representation includes for example the Traditional BOM, the Modular BOM [27], and the Generic BOM [19]. These different structures exists as Traditional BOM structures might bring issues to companies with large product offerings. As such, application of different structural representations is done to better support different production strategies, such as having high variety offerings or modular product compositions.

3 Generating BOMs from BIM data

3.1 Research approach

In this research, a review of earlier research was used to motivate the gap and to serve as input for the proposed approach. Following, a demonstration tool was developed in order to exemplify the restructuring of BIM data from a BOM perspective. In order to provide an illustration of the approach in a real-world setting, a case project was then used where an application of the demonstration tool is provided. The case project was chosen from an industrialized house-builder in Sweden, who focuses on production of residential housing. The company applies modular construction using lightweight timber frames, complemented with insulation materials and covered with sheathing. Each building is broken down into individual modules which are produced to an almost finished state off-site in a factory, to later be assembled and finished on-site. The case project in question is comprised of 156 modules, and the building ranges from 5 to 10 stories.

As a foundation, and for providing a BIM capable platform which provides a source for the necessary BIM data, Autodesk Revit was used. In order to enable representation of timber framed structures in Autodesk Revit, the add-in MWF Pro Wood [28] was used which in this instance provided design automation capabilities for framing timber walls. The demonstration tool was developed as an add-in to Autodesk Revit written in C#, utilizing access to Autodesk Revit's API to grant access to the data stored within the BIM model. The demonstration tool is composed of three main parts: configuration, generation, and delivery.

The perspective on BOM that is adopted in this paper is targeted towards providing a product specification, with focus on promoting the product composition [19] using product, subassemblies and parts as seen in Figure 1. Among the different views each BOM can encompass, this paper will concentrate on providing an engineering perspective, also denoted as the E-BOM [21]. This is done through using information found in a BIM model which is used as input to the demonstration tool. The underlying structure that is generated in the E-BOM is based on a Traditional BOM structure.

3.2 Demonstration of BOM generation

3.2.1 BIM model

With the demonstration tool in need for input data, A BIM model was created for the case project using Autodesk Revit (see Figure 2) based on 2D drawings provided by the case company. Using commonly available tools in Autodesk Revit, walls, floors, ceilings, doors, and windows were modeled. In addition, using the

MWF Pro Wood add-in, the specified technical solutions for each of the wall types was configured. Through that, studs and sheathings for the exterior and interior walls were automatically generated. As the case project in question is constructed using a modular production strategy, measures were taken in order to represent these modules in the BIM model. To achieve this representation spaces were used as objects to define and provide the boundaries of each module. Except for providing a possibility to include the modules in the BOM, these spaces are also later used in cases where relationships between elements and modules needs to be derived. The floors and ceilings did not receive joists and sheathing but were modeled using their corresponding element types in Autodesk Revit. Furthermore, elements not included in the BIM model was the roof (including trusses), the concrete foundation, and MEP.

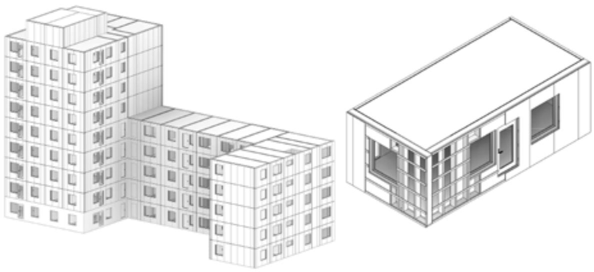

Figure 2. 3D-view of the created BIM-model for the case project with a close up of an individual module showing parts of the studs and sheathing.

3.2.2 Configuration

The first part of the demonstration tool is the configuration stage. Here, a number of options are made available regarding the composition of the BOM, and these choices will act as a basis for the generation of the BOM. The ability is provided to choose what categories will be included, which is this demonstration is bound to project, levels, modules, walls, floors, ceilings, windows, doors, studs, and sheathing. These categories correspond to some of the different categories provided when modeling in Autodesk Revit, and in extension also when using MWF Pro Wood. They also correspond to categories commonly used in timber frame modular construction. Besides selecting the categories of interest, a hierarchical structure can be decided upon by dragging and dropping objects in the tree view. This hierarchical structure determines the parent-child relationship between the categories which will be present in the BOM and describes the product, the subassemblies and the parts. As a category is placed as a child to another, the succeeding generation step will attempt to solve this relationship for each individual instance of that category.

Besides choosing objects and hierarchy, a selection of what attributes from each category should represent the tags is provided. These include using the instance name or family type that is automatically attached to each element in Autodesk Revit, or using the user-defined instance attribute Mark. These tags are later used as labels for each entry in the generated BOM. The purpose of them is to provide a human-readable designation, rather than just using the unique id of each element. It can also be decided if entries in the BOM should be grouped together. It might not always be necessary to include each instance of all categories, so grouping based on type or category is provided as an option. As such, it could be decided that e.g. instead of including each stud as separate entries, they are grouped together based on their type.

For the case project all available elements were selected and organized in a hierarchy as seen in Figure 3. Each category was given an appropriate tag, in this case mainly the type name. Furthermore, options for the groupings were configured such that the major categories are to be kept as instances whereas the individual components (such as studs) are grouped by their type. This configuration was selected with a modular design in mind. As such, with each module, and each wall, being produced individually, this configuration enables the tracing of the constituent elements.

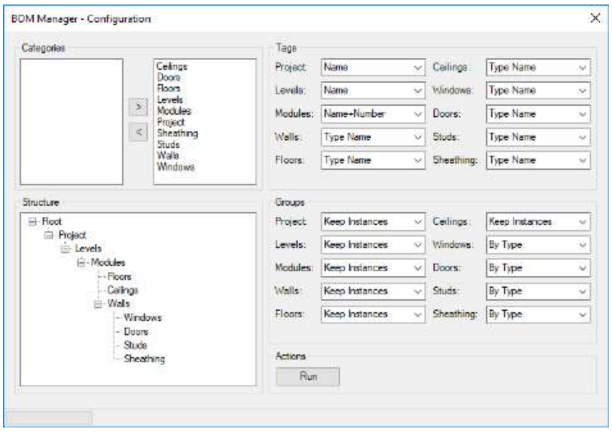

Figure 3. Configuration of the case study project within the demonstration tool.

3.2.3 Generation

With the configuration done, the BOM can be generated based on the input and BIM data available. At the start of the generation all elements are collected from the different categories that was selected. This entails using calls to Autodesk Revit's API in order to fetch each element instance of all selected categories. After the objects have been gathered, further calls to Autodesk Revit's API are made in order to extract the attribute values that correspond to the tags that were chosen for each category respectively, e.g. using the type name.

With the elements collected, it now needs to generate the hierarchy decided in the configuration stage. Depending on the specific relationship situation, this is done either geometrically or through attributes. Autodesk Revit already stores some of these relationships in attributes, for example what level a floor belongs to, or what wall a window is hosted by. The developed demonstration tool is however extending this to enable parent-child relationships between modules and elements, as well as between walls and studs or sheathing. As such, in the cases where there are no attributes to rely upon, a geometrical search is conducted. This is executed by taking an elements bounding box center point and iterating through the chosen parent category, searching for a match where that point is found within the boundaries of another element. If it is determined that a point falls within the boundaries of another element, it is established that a parent-child relationship has been found.

When all the relationships are found the elements are still represented as instances. The last step, if a configuration was chosen where certain categories are to be grouped based on their type or category, is therefore to process the groups. This is done by iterating through all levels of the hierarchy, gathering all siblings on each level and matching them by type or category. Here, it removes all entries of individual instances and replaces them with a group entry, representing a collection of instances.

3.2.4 Delivery

As the generation of the BOM is done, the last stage is to deliver it. A rudimentary viewer was therefore incorporated into the demonstration tool. In this viewer, the hierarchical structure is provided with a listing of the entries in the current BIM model. When an entry in the hierarchy is selected, the basic attributes of that entry is presented. This is done by accessing the attributes that was gathered during the generation of the BOM, but also by directly accessing attributes for the selected element in the BIM model. These attributes include the id, tag, and category of element together with a selection of category based attributes (e.g. dimensions of an element). Alongside this presentation of the BOM, an option is also provided to either export the entire BOM to an Excel-document, or a selection of it. The latter of these exports only the selected entries and its children, excluding the rest.

For the case project a representation of the BOM in the viewer can be seen in Figure 4. Here, the hierarchical functionality is displayed where the constituent elements in individual modules, and individual walls, can be examined. Each entry is also labeled according to their name or type name. Also, a display of attributes which are gathered from the BIM model is shown. The corresponding structure can be seen in the exported Excel document containing the entire BOM hierarchy (see Figure 5).

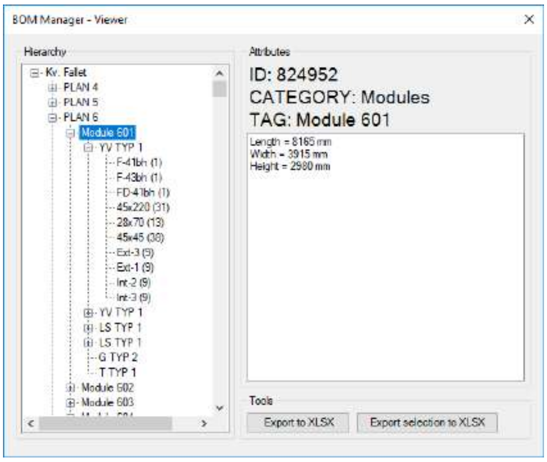

Figure 4. Viewer with the generated BOM for the case study project within the demonstration tool.

	A	B	C	D	E
1	Hierarchy	Tag	Category		
2	1	Kv. Fallet	Project		
3	1.1	PLAN 4	Levels		
4	1.1.1	Module 401	Modules		
5	1.1.1.1	YV TYP 1	Walls		
6	1.1.1.1.1	F-41bh (1)	Windows		
7	1.1.1.1.2	F-43bh (1)	Windows		
8	1.1.1.1.3	FD-41bh (1)	Doors		
9	1.1.1.1.4	45x220 (31)	Studs		
10	1.1.1.1.5	28x70 (13)	Studs		
11	1.1.1.1.6	45x45 (38)	Studs		
12	1.1.1.1.7	Ext-3 (9)	Sheathing		
13	1.1.1.1.8	Ext-1 (9)	Sheathing		
14	1.1.1.1.9	Int-2 (9)	Sheathing		
15	1.1.1.1.10	Int-3 (9)	Sheathing		
16	1.1.1.2	YV TYP 1	Walls		

Figure 5. Part of the Excel document exported from the generated BOM for the case study.

4 Discussion and conclusion

Issues of managing information and enabling diverse views on information are present within industrialized house-building. Using bills of materials (BOM) as an underlying structure for managing information during a products lifecycle has previously been seen in the manufacturing industry, where it is often built into CAD tools, and supported by PLM and ERP systems. With industrialized house-builders sharing some of the characteristics of the more product-oriented manufacturing industry, approaching information management from a BOM oriented perspective was of interest in this study. As such, this insight was adopted in an effort to generate a BOM based on BIM data. In a demonstration tool, using BIM data as the input, a parent-child hierarchy with links to attributes was generated based on a chosen configuration. This output resulted in providing an engineering view on the BOM, referred to as an E-BOM. This has also been presented when applied on a case of a multi-family residential housing project from an industrialized house-builder. The results shows how the BOM provides a view of a building based on its composition, and in the case study shows how individual modules and walls are composed.

Compared to approaching information management from a central repository [2] or IFC [3] perspective, the use of BOM is in this instance not seen as an overarching solution. It is rather seen from the viewpoint of being a method which can be applied to create an underlying structure to describe a product [19]. The question as such is not how we transfer information between systems, but rather how we describe our product in a way that facilitates this information transfer. Having a unified structure for our products is a step in that direction, and BOM is a method which could be used to aid this.

The presented demonstration tool shows an after-the-fact implementation of BOM generation. However, as more commonly seen in CAD tools from other industries, the use of BOM is an integrated part of the work flow for designers and engineers. As such, for adoption within industrialized house-builders, the questions of who creates the BOM and when are relevant.

This study shows a demonstration where an E-BOM is generated, using a traditional BOM structure. One of the strengths of BOM is however the ability to adapt to different views depending on the application. As such, further studies are of interest where the E-BOM is not only generated, but also transformed into other forms, such as the M-BOM to support manufacturing. Furthermore, with the use of product platforms and a product-oriented perspective, industrialized house-builders using predefined solutions could benefit from using alternative structures, such as the Modular BOM, in efforts to more efficiently derive products. Furthermore, the composition chosen for the E-BOM in this study is limited to only showing one structure. If we are to follow the view of an E-BOM as a functional decomposition of a product, then there is a need to identify what that entails for the context of industrialized house-builders.

The concept of implementing BOMs in the context of industrialized house-builders is seen as showing promise in the search for methods by which we structure information in our IT-systems throughout the value chain. Its use in the manufacturing industry is described by previous research but in the context of industrialized house-building it is more of a novel approach. This study shows how an implementation could be performed where BIM data is used as an information base, however, this study is only a glance at the topic and there is a need for further studies to better describe its use in the context of industrialized house-builders. As such, future research should include topics such as: identifying the owner(s) and user(s) of BOMs, in order to know who defines them and how they are consumed; what different representations of BOMs (e.g. E-BOM, M-BOM) could be used and how they should be structured; how BOMs could be used to bridge IT-systems (e.g. BIM and PLM) in order to support design and production of houses.

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Cost analysis of equipment in a building using BIM-based Methods

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Abstract –

The cost of the operation stage in a project life cycle is much higher than that of other stages in the building lifecycle. Efficient use of facility management can save money. However, the information of the traditional facility management cannot effectively be employed, which in turn affects the quality of the facility management. The emerging technology of building information modelling provides an opportunity to overcome the difficulties of utilizing the information stored by means of facility management. In this paper, the Revit@ platform has been used to build up a BIM model relating to the facility management. Through the Revit API, computer implementation has been developed, based on the programming language C#. This computer implementation can extract the information regarding the costs of equipment from the BIM model. Such information can be further analyzed to support decision making.

Keywords –
BIM; Facility Management; Secondary Development; Economic Analysis

1 Introduction

It has been well known that a significant part of the expenses of the life cycle of a building occurs during the operational stage. [1-3]. Almost all activities during the operations need considering the information of facilities. However, the information cannot be effectively employed by means of traditional facility management. Gallaher et al. [4] indicated that US$15.8B are lost annually in the U.S. Capital Facilities Industry due to the lack of adequate interoperability. As a matter of fact, the market of facility management in China faces the same problem. Hence, the effective use of detailed facility information in a building becomes the rising issue.

Meanwhile, with the advancement of the national development strategy in the informatization of civil engineering, modern technologies have been continuously applied to architecture, engineering, and construction industries in China. One of the promising technologies, Building Information Modelling (BIM), has been in the spotlight since it was introduced. The phrase "Building Information Modelling" is used to describe virtual design, construction, and facility management [5]. BIM provides one model that can store all building information for facility management.

Many research studies have shown the applications of the BIM technology to facility management. For example, Akcamete et al. [3] proposed an envisioned approach for integrating historical information in BIM to support visualization and spatial analyses of various maintenance activities in a facility. Wang and Zhang [6] demonstrated a case study of the maintenance activities for air conditioners in a building by means of a building information model. Liu and Issa [7] proposed a method that can automatically exchange the information of maintenance between building information models and Computerized Maintenance and Management Systems (CMMS). Yu and Li [8] combined the use of Revit@ and Access@ to establish a facility management system that can conduct not only the classification, assignment, and extraction of information, but also the query, location, and economic analysis of information. A case study has been carried out to verify the feasibility of their facility management system.

This study uses BIM technology for facility management along with the economic analysis of facilities. To take the efficiency of the analysis into account, the computer implementation was developed through the Revit@ API to give feedback on the cost analysis of a specific facility in a BIM under the same platform. A case study of a facility has been demonstrated in this paper. 3D building information model of the facility was first built from its 2D drawings. The computer implementation for the cost analysis was then applied to the 3D BIM.

2 Method

In this study, Revit@ was chosen to be the research tool, because it is one of the most popular BIM software in China. In addition, it equipped with a friendly and positive development environment. Based on the environment, the computer implementation was developed by using C# programming language. The flow chart of Revit@ secondary development is shown in Figure 1. Through an Add-In Manager plug-in which existed in the original installation package, the computer implementation was applied to the information of a BIM built in the same platform of Revit@ for the cost analysis of facilities. Results of the cost analysis can further help a facility manager in decision-making.

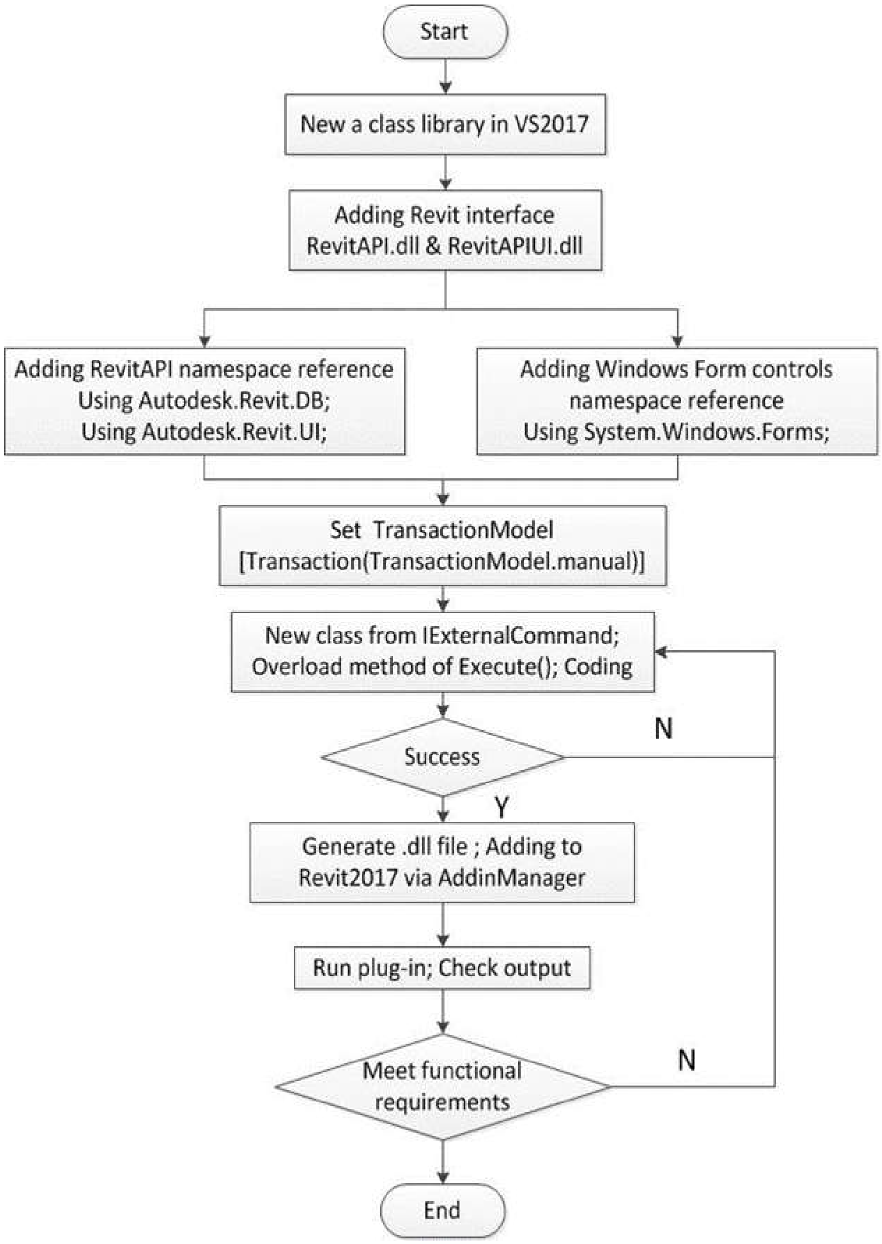


Figure 1. The flow chart of Revit@ secondary development

This computer implementation for the cost analysis is related to the principles of engineering economics, such as the economic life, the time value of money, and so on. A brief introduction is following:

In the first place, the following three points should be satisfied.

(1) The operation cost of equipment can be recorded and then statistically analysed;
(2) The annual interest rate is constant; and

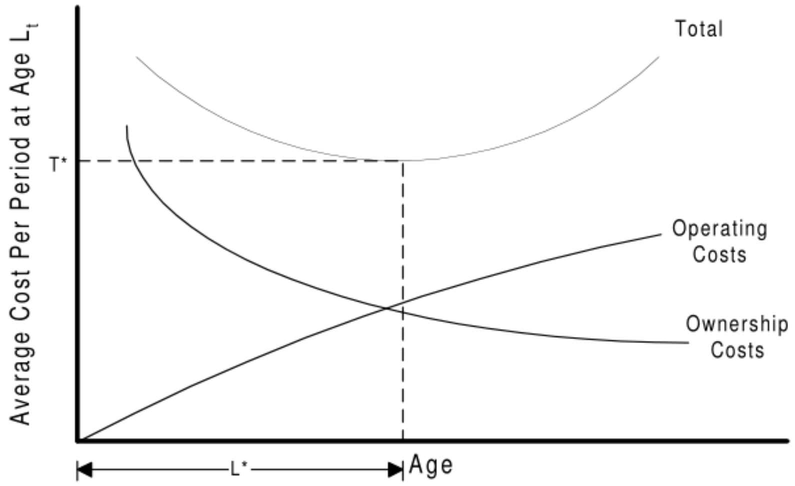


Figure 2. Economic life diagram

(3) The cumulative cost of the equipment in the future can be compared to a reference cost.

Mitchell [9] mentioned that economic life is based on decreasing ownership costs with the increase in operating costs. As shown in Figure 2, economic life gives the minimum value of the total costs on the curve at the point of an optimum age. The total costs consist of ownership costs and operating costs. Usually, the ownership costs merely consider initial costs and depreciation, regardless of salvage value, and the operating costs only take the costs of maintenance, repair, and operation into account.

Park [10] mentioned that "The time value of money means that a dollar today is worth more than a dollar in the future because the dollar received today can earn interest." Hence, the time value of money is one of the key factors in the economic analysis. Table 1 lists some important formulae used for the cost analysis of facilities.

In addition, Park [10] mentioned that the annual equivalent cost (AEC) criterion provides a basis for measuring the worth of an investment by determining equal costs on an annual basis. For the sake of simplification when using the life of various facilities for analysis, this study mainly used the two formulae in Table 1 to convert the original cash flows into the annual equivalent flows.

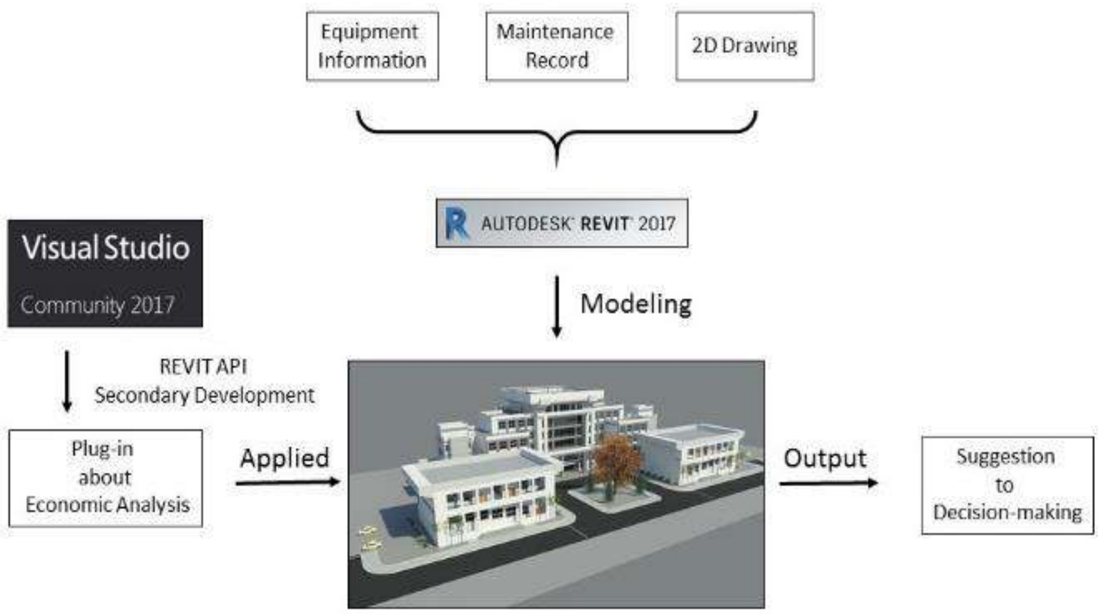


Figure 3. The application procedure of the computer implementation

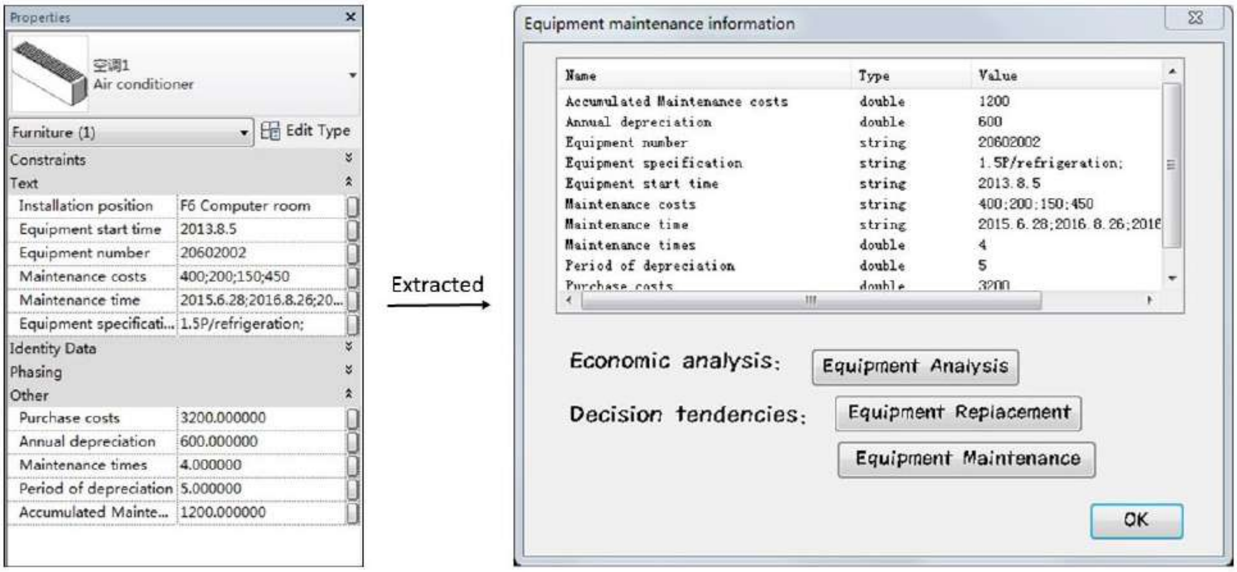
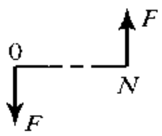
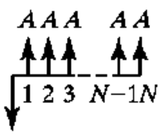


Figure 4. The main interface of the computer implementation.

Table 1. Some important coefficients related to economic analysis

Factor Notation	Formula	Cash Flow
Present worth (P/*F*, *i*, *N*)	$P = F(1+i)^{-N}$	
Capital recovery (*A*/P, *i*, *N*)	$A = P[\frac{i(1+i)^N}{(1+i)^N-1}]$	

3 Results

The application procedure of the computer implementation is illustrated in Figure 3. Once a building information model has been built, the computer implementation in the procedure can automatically extract the specific equipment information. Shown in Figure 4 is the main interface of the computer implementation. The left window of Figure 4 displays the partial information of the equipment in the BIM. The right window of Figure 4 displays the main interface of the computer implementation, on which the upper and the lower parts illustrate respectively the information extracted from the BIM and the functions of several application modules.

The main function of the "Equipment Analysis" module is to analyse the status of the selected equipment for supporting the maintenance planning decisions. In case the facility manager considers replacing the equipment, the "Equipment Replacement" module can help to make a right decision. When the equipment is broken, the "Equipment Maintenance" module gives rise to the analysed results based on the costs of the repairs and maintenance for the equipment. A window appears in Figure 5 resulting from the analysis of the "Equipment Maintenance" module for an example.

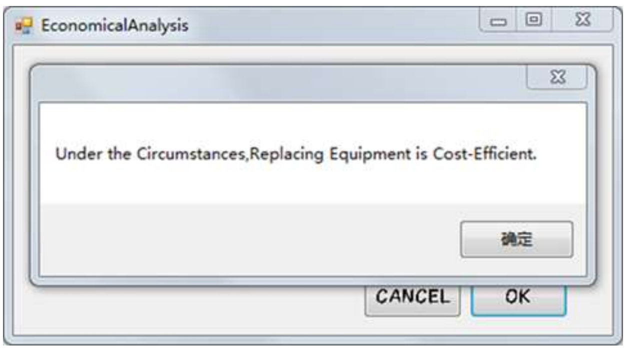


Figure 5. An analysis module result.

4 Conclusions

In China, most of the maintenance work in a facility is reactive. This practice is not effective from the perspective of facility management, because the reactive maintenance typically increases the costs of repairs and maintenance. To reduce the number of the reactive maintenance, there is a need for supporting the planned maintenance work. The emerging technology of building information modelling provides an opportunity to support such work. BIM can collect the information of facilities during their life cycles. As a matter of fact, the proposed method can be globally used unless the selected BIM software does not have an open development environment.

In this study, the computer implementation for the use of a BIM to analyse the costs of equipment was developed using the programming language C#. This computer implementation can simplify the process of the cost analysis to further improve the efficiency of decision-making. In addition, it can provide the secondary development of a building information model with some experiences in a future.

Acknowledgments

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Interactive visualization for information flow in production chains: Case study industrialised house-building

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Abstract –

Predefinitions in house-building platforms is developed as routines to manage project building information models over to production data by documents and digital drawings. Visualisation of the information flow in the industrialised house-building process is hard to track and information are often presented as islands, seldom described in the flow for the entire process. Interactive visualisation, using game technology, has open up for new applications of data -transformation, -visualization and -simulation of project information which is less studied in the context of industrialised house-building. This paper tries to address this issue via a combination of game engine technology and the predefined industrialised house-building process. The game engine technology allow development for end-user demands and functionality to express and visualise values for the daily planning and execution of processes. In a case study approach the development and analysis of four building projects were studied and chosen to the range of product platform predefinitions. Based on object structure for different views, models and the related metadata were visualised with an immersive virtual environment prototype. The prototype, based on game engine technology, was developed to manage incoming building projects variations that followed house-building platform predefinitions. As a visualising tool of engineering, on-site planning and production process the game engine technology simulates and visualize views on product structures, production information, assembling and operation instructions by interactive functions in the game environment.

Keywords –

Game engines; industrialised; house-building; information flow; visualization

1 Introduction

Industrialised construction companies are described in a range from high level of prefabrication to fully on-site construction [1]. The range of predefinition of the product affects how to manage a design process in construction and how information systems support the progress with human knowledge of the work. Visualising planning, as the artefact of planning construction projects in flow-oriented work, are used instead of traditional resource-planning with schedule techniques [2].

Using game technology in virtual environments has the potential as a communication tool for architects to customers to understand the house-building process [3-6]. By providing virtual models across extended supply chain representations Whyte et al [7] argue that combined visualisations are evolved through practices in reified and hybrid forms in fabrication, assembly and on-site work. Industrialised house-builders has developed their information flow using drawings and instructions in documents. BIM-software are used to speed up modelling of house-building projects, and design automation is used to provide template-based configuration functionality for example regarding the interfaces between wall-to-wall, wall-to-floor, and wall-to-ceiling. Other configuration in the BIM-software could be generation of studs, boards and stud-cutting around doors and windows. Automation between design and production has focused on robot and machine control since the beginning of the nineties [8]. Even if BIM-software with data for production has been around since the start of the millennium only a few applications for visualising information flow has been evaluated and implemented in house-building for factory production [1].

In the development of information systems for industrialised house-building processes the aim of this study is to describe how interactive visualisation could visualise the information flow for different views in the house-building production chain. To reach and confirm the research aim, the following questions about interactive visualisation in industrialised house-building has to be answered:

In the chain of information flow, how can progress be visualised by game technology through variation of different information views?

How can interactivity be used to visualise changing scenarios for BIM data in a factory production setting?

2 Frame of reference

Communication of building concepts is often based on rendered pictures, sketches, drawings and documentation by text where lights and movements is hard to compresence for decision makers in the early stages of design [3, 5]. Visualising the third dimension from 2D-descriptions demands experience and training [6, 9] and the static 3D-view do not enable expression of different perspectives for a specific place and a specific time [9]. Since the nineties the evolvement and application for building projects with virtual reality (simulated virtual environments based on physical environments), augmented reality (physical environments augmented by virtual input) and immersive virtual environment (user interaction supported within virtual realities) has become technologies that not only focus on design aspects but also on the life-cycle visualisation and simulation of a building project [10]. The immersive virtual environment enables possibilities for reviewing alternatives in the realisation process of a project before it becomes physical reality [6]. BIM-models are constantly becoming more detailed which opens up for opportunities to use game technology for VR visualization, but this also creates problems for a seamless use without further optimization. BIM-models are created to describe buildings in detail and many 3D models extracted from BIM models are too big and complex to be used directly in real-time visualizations [11]. Because of this, it is still difficult to integrate VR as appropriate tools during the design process [12]. The introduction of a new generation of VR glasses has made the situation even more challenging, though these new types of VR devices offer enormous possibilities in terms of realism and sense of scale they are also much more demanding when it comes to real-time rendering performance [12].

Industrialised house-building in Scandinavia has developed their processes from manual production to automated production lines in factories. Standardisation of house-building platforms that manage component, process and relations describing different market positions and relates to how the company organisation could arrange production planning [8]. Using design automation in industrialised house-building is described by Sandberg et al. [13] as a chain of engineering activities in the design work. By the use of software, configuration through parametrisation of building systems generation of components up to building is possible [8]. Balancing resource and flow efficiency is an important issue for industrialised house-building companies [14]. The use of standardised workflow with single unit flow is identified as efficient for operation in factory production [2, 14].

3 Methodology

This study was designed in a qualitative research approach based on interviews and collecting data by archiving data in drawings, documented rules in platform predefinitions, and production routines. The case study approach gives opportunity to reach value rich information from the combination of interviews and deeper knowledge from cases [16]. Semi-structured interviews give opportunity to follow answers from respondent and to develop the insight in for the research [17] where three technical managers at the studied company were chosen. Interviews with focus on both product concepts with predefinitions and IT-structure to manage object designations created the design phase in description documents and BIM-models. Industrialised house-building in Scandinavia is based on high levels of predefinitions in platforms or a combination of predefined products that are modularised in combinations. To reach the variation of predefinitions of house-building platforms two projects from two companies were chosen to facilitate the range from high levels of predefinitions to medium levels of predefinitions. The studied context is based on two volume-module production companies that has 15 years of experience of of-site production based on platform-products in their production.

Company 1 has a capacity of 2 000 apartments per year and a turnover of 100 million euro have reached a speed in production of about 60 volume units per week with two production units served by one design organisation. Company 2 has a capacity of 700 apartments per year with a turnover of 30 million euro and have reached a speed in production in about 40 modules per week with three production units served by one design organisation. Selection of building projects focus on volume module variation, general object selections and medium complexity for client choices. Volume modules with varies in dimensions from 3.1x6.2x2.8 meters to 4.2x9.1x3.1 meters in width, length and height.

Software selection were based on CAD software, databases and game engine platforms that are frequently used in general but also ones that enabled functionality of transforming object related information with relations. To develop the IVE, a prototyping approach was used. Development was done according to interview results, platform predefinitions and with one reference project in one production unit as a start. The prototype section of the study did not aim to find the most efficient application of software for an IVE, but rather to describe different scenarios of the information flow that could be developed further and as a foundation for flow oriented analyses of objects.

There is an increasing interest in articulating methods used in the field of IVE development for application in the construction industry [9, 11, 12]. Analysis of the

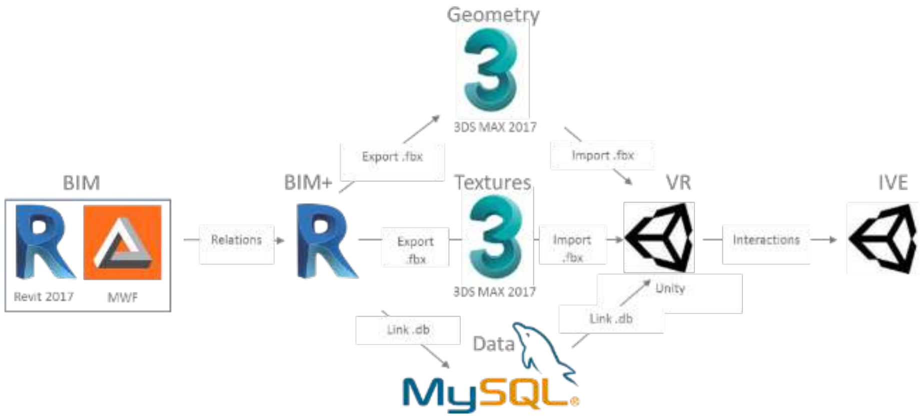

Figure 1. Transformation process of industrialised house-building BIM to IVE.

results were therefore made to provide insights to aspects included in visualising information flow using IVEs.

4 Game-technology for information flow

Describing the value chain of information was setup using game-technology to describe different process stages of managing information. BIM-models constitute an information base for communication of information between stages in the chain from design to production. The traditional use of drawings from design to different stages has until now been used as the primary communication from BIM-models. To enlighten the possibilities of managing information from BIM-models, without the transformation to drawings, the aim for describing a continuous flow of information was to set up a structure of product views and the communication of product transformation between these views. Game-technology was the enabler to visualise the transformation in the chain for the following views: engineering view, manufacturing sequence view, production process view, and on-site production view.

Implementation of game-technologies was achieved using Unity, a cross-platform game engine, which allows for the creation of applications with 2D and 3D graphics support with interactivity and functionality. Autodesk Revit, together with the add-in MWF Pro Wood for creating timber structures, worked as BIM-generators for the selected building projects (see Figure 1). Using a custom add-in for Autodesk Revit, written in C#, the BIM-models were developed further to BIM+, where extensions of the possible relationships between objects were implemented. The relations that were implemented for the house-building structures where the relations included-in and consist-of, e.g. a stud could now be described as included-in a specific wall, or a volume-module could consist-of specific walls, floors and ceilings. The add-in used calls to Autodesk Revit's API in order to extract data regarding the different elements in order to determine their relationship in one of two different ways: through attributes, or through geometrical analysis. As some elements already contain relationships, e.g. a window has an attribute which links it to its host, these relationships could be derived directly from the BIM model. Other relationships which are not already present, e.g. which wall a stud belongs to, were subject to a geometrical analysis. This analysis used the geometries of elements to determine geometrical intersections in order to identify relationships. These relationships were later used to give names to, and to track objects of buildings, volume-modules, elements, components and details in the visualization process.

In order to produce a 3D representation of the BIM models in the game engine, a solution where passing the geometry and materials from Autodesk Revit through Autodesk 3ds Max was used. This method was used as importing FBX-models directly exported from Autodesk Revit failed to provide the materials and textures found in the BIM-model. Using Autodesk 3ds Max as a middleware also provides the possibility to optimize the geometry and materials (see Figure 1).

Like with other game engines, Unity is limited in its ability to directly read metadata from BIM and CAD-tools. As such, to facilitate this transfer an information link was created through the use of a database. In this instance, MySQL was used as the database management system as it has the possibility to meet Autodesk Revit's database link interface and also to serve Unity with data through the use of custom scripts written in C#. In order to link metadata between the BIM model and the representation in the game engine, the unique element id that is generated for each element in Autodesk Revit was chosen as a common denominator.

As the geometry for the BIM model is exported, each object is given a name that contains the unique element id. Equally, the database that is populated from Autodesk Revit also contains a reference to this unique element id in each entry. Using this method, the geometry and metadata could be linked within the game engine.

The combination of the visual representation and a database containing the metadata, produces a virtual environment of the BIM model. The separation of geometrical representations, materials, and metadata as the three types of input sources became the method of transformation through the game engine development process (see Figure 1).

Linking design, manufacturing and production data from the BIM+ model into the virtual environment became the enabler of object structures that follow the building project through the entire life cycle. Geometry and material models were updated manually by traditional export/import using the format FBX. In this type of communication for information flow, the methods of combining transformation scripts through the use of unique object identifiers became central to the ability to first separate and then combine in the IVE prototype.

4.1 Interaction between and in building stages

The building stages in industrialised house-building with prefabrication of timber volume modules, when an order is set, is divided into the following visualisation views: engineering view, manufacturing sequence view, production process view, and on-site production view. The engineering view describes the building from its functional perspective with timber volume structures and space objects. Here, the interactivity in the game engine was programmed to give a variation of choices for changing between predefined views and fly-trough features and visualisation of combinations of space and physical objects. The transformation from engineering view over to the manufacturing sequence view visualises in which sequence each volume module were planned to be assembled on-site. Functionality was programmed here so that a user could select a volume module and get information corresponding to the current view. This can be seen in Figure 2 where data for the specific assembly sequence are presented, where the first number represents a sequence ID (23, 24, 25, 26) and the second number represents an object ID for each volume module (502, 503, 504, 505).

The production process view shows the transformation from the manufacturing sequence to a visualisation of the flow of volume modules and elements in a factory. In the production process view, interactivity were developed to visualize different product assembly lines with stations and visualising BIM metadata for the volume or element object at the station in the specific time (see Figure 3.). Alternative flows of assemblies lines were built in with Unity functionality based on a list of instructions and derived from the manufacturing sequence. From that list the both the main line (volumes) and sub-lines (elements) were programmed in C# for the specific flow. The number of elements in each volume and number of stations in the sub-lines gives the enter time

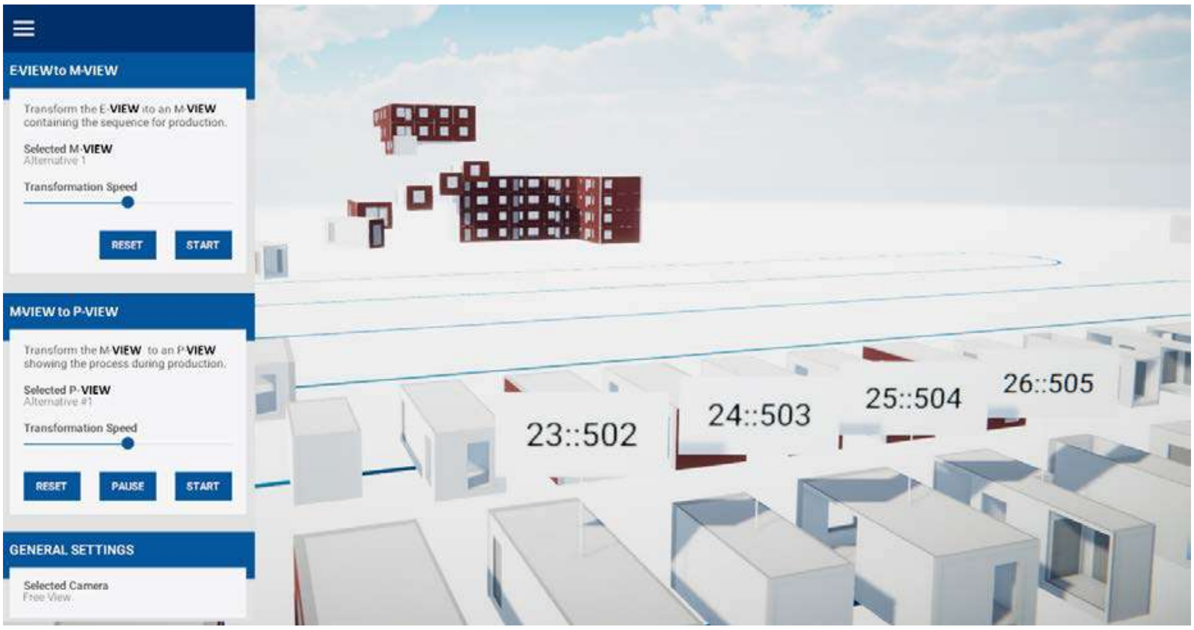

Figure 2. Visualisation of transformation from engineering view to manufacturing sequence view in the IVE prototype showing object ID and sequence ID.

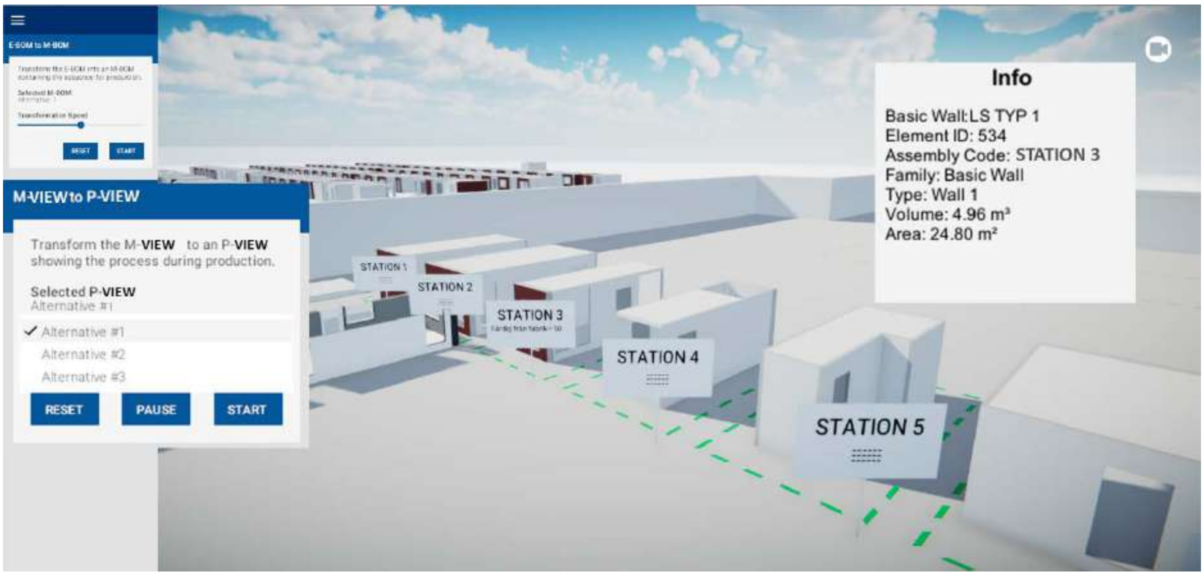

Figure 3. Visualisation of an alternative dialog and showing BIM information output with station related information in the factory production view in the IVE prototype

(instruction.Type==ProductionInstructionType.Enter) for each object for the flow. For a continuous flow from the list each object (volume, element) were asked to move to next station if they have entered the production line (instruction.Type==ProductionInstructionType.MoveTo) and ends with a general predefined pause for all stations in the main line. The entire flow of volume objects is then ended in the factory production process view if none of the two above conditions is not set (instruction.Type==ProductionInstructionType.Exit).

Lastly, the on-site flow shows the transformation of ready volume modules from the factory being assembled in the specified manufacturing sequence with a set site assembly time for each volume. In all instances of the transformations, interactive functionality was used in the game environment to combine object data and visualise different scenarios according to variation of projects, number of stations in assembly lines, production speed (pauses) and site assembly time. Possibilities to start, stop, reset and change the speed were provided. As such, the user is given the opportunity to control the events occurring within the IVE prototype.

The result shows that the use of game engine technology as a communication tool gives spatial understanding of both structural and space geometries, regardless of professional expertise. By exploring an environment in the IVE prototype, it comes very close to the experience of a full-scale model. The use of a game engine powering the IVE prototype provided the underlying tools to simulate and analyse processes in virtual environments. The environments allowed high interactivity and real-time performance, which meant that the goals for each stage could be evaluated before real production.

4.2 Building scenarios and metadata

Two building project scenarios of information flow were evaluated to the developed IVE prototype. The two projects were evaluated for two different assembly sequences and according to three production units (factories). Functionality with the Canvas tools in Unity gave the possibility to create user interfaces with controls such as buttons, dropdown menus, and sliders can be implemented to enable user-control over an environment. Interactive functionality for selection of assembly sequences were programmed in as drop-down menus with the two assembly alternatives in the Engineering to Manufacturing dialog (Figure 2). The three alternatives of production units were implemented using the same technique for the Manufacturing to Production dialog (Figure 3). Each building object in the IVE prototype were prepared with links to present object information for each view. An example is that the engineering view only visualise object ID, and in production view a number ofdetailed information were visualised that related to original BIM-data. If the Revit-model were to be updated with new metadata, the included links would facilitate propagation of the updated metadata to the IVE prototype.

5 Analysis and discussion of the results

Although the focus is primarily on resource efficiency, the significance of flow efficiency in house-building production is increasing [14] and systems that support and visualise the progress through production becomes needed. The open game engine technology, with a global network of solutions, gives possibilities to develop interactivity in the environment [12] and to visualize and simulate processes with product models for house-building through the entire production chain. The interactive visualisation in the case scenarios has to manage a variation of single project information to the variation of repeated process information. Simulation with IVE functionality has in this study shown possibilities for prefabricated house-building systems to visualise alternatives both for production units (factories) and also for the assembly order to prepare for building site. The spatial models with related data visualise the process in the IVE prototype as almost real objects, and as according to Heydarian et al. [10] the life-cycle perspective is important for all stages in the realisation of buildings.

Object structures with the relation of included-in and relates-of became a needed feature for the simulation of object flow in the visualisation. House-building processes with prefabrication of volume-modules uses the hierarchy in their planning of factory production in object assemblies from components up to volume modules. This serves not only the information flow but also the material flow that has to be managed in parallel.

Visualisation of different stages in different views of a production process gives an analytical method for planning production. By using both interactivity for input variables (as manufacturing sequences, production lines, and flow speed) the use of IVE enables a tool for analyse planning and simulate building process progress from a production perspective.

As the study shows, and also Whyte et al. [7] means, that total interaction and photorealism is not always necessary to make decisions through the process. The detail level should instead be adjusted according to the situation in which the IVE prototype is used. The study showed that platform predefinitions affects the information flow both on product and process information, which is central for how game engine could contribute by the interactive visualization in house-building production. A high level of predefinition of the product visualises the combination of object and process information in the IVE wile less predefinitions requires a lot more work before objects could be implemented in the IVE environment for flow analyses.

6 Conclusions, limitation, and future work

By highlighting the interactive functionality for flow it was concluded that game engine technology is applicable in industrialised houses-building on a spectrum from interactive visualisation in design, production and simulation of site assembly flow. To describe how IVE could visualise the information flow for industrialised house-building, the prototype presents the importance of alternative functionality for different views, as production processes in factory but also to the variety of assembling sequences. To visualise different views of the production progress, with game technology, the study shows how the combination of geometries, textures and data that are linked and could be updated by automation. Interactive functionality in the IVE prototype shows how the link between BIM and IVE could be updated to different scenarios by using extern databases and internal functionality in the cad and the game engine. To manage house building project for production a high level of predefinition of platform predefinitions speeds up the development of links between BIM and IVE.

The evaluated methods of IVE development for industrialised house-building could be interesting for on-site productions where standardised production work is applied and the need for visualising information flow. Limitations of two companies in this study constrain the generalisation of a prototype but enlighten the possibilities to understand possibilities to use BIM for IVE in a flow oriented production perspective. The transformation process of BIM to IVE describe a separation of geometry, textures and data with object tags as enablers for automated combination of models in the IVE prototype. This technology could be useful for other simulations, like supply chain flow of production materials or resource planning which are in relation to the studied scenario in our case.

Out of the four scenarios in the case two of them were modelled in ArchiCAD with the application Archiframe, for timber structures. Possibilities to evaluate the method for other cad-platforms is of interest for the API programming of relations and database connection, but not the purpose in this case.

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An information management framework for optimised urban facility management

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Abstract –

Information management for Urban Facility Management (UFM) is a key enabler for a more sustainable built environment [1]. This paper presents a further development of a case study research concerning the implementation an innovative UFM service. The UFM process is enabled thanks to a robust data engineering approach and Information Technology (IT) tools, based on Database Management Systems (DBMS) and Geographical Information Systems (GIS). The proposed methodology allows to streamline the survey phase enhancing the UFM services already in place, according to a continuous improvement logic. The scope of the research concerns the implantation of effective facility management methodologies, [2] through the use of current Information Communication Technologies (ICTs). The case study research concerns a business district in San Donato Milanese, Italy. After two years since the kick-off of UFM service, thanks to data provided by the UFM company operating in this context, authors aim at presenting advantages of adopting the proposed methodology. Information available concerns cost, technical historic datasets and budget CAPEX data until 2019. This information is georeferenced and processed through geo-spatial algorithms, in order to obtain spatial analysis and representation for monitoring and improving the UFM service. In conclusion, it can be stated that the proposed approach can improve UFM process fostering information management among stakeholders and reducing operational expenditure.

Keywords –

Urban Facility Management, Data engineering, GIS, Information Management

1 Introduction

Management of the built environment is characterised in the last years by the increasing of the complexity of physical assets, as well as the high number of stakeholders and the pervasive use of Information Communication Technologies (ICTs). Real estate is providing constantly a huge amount of information which must be collected, managed and exploited for the optimisation of the management process and for the achievement of a more sustainable built environment.

Facility Management can be intended as an effective strategy for restoring performance of assets to a proper level of quality, in order to provide a good environment for human beings, within the sustainability framework. This concept, despite being wide and opening to further specifications and insights, can be extended to the urban environment. Accordingly, Urban Facility Management (UFM) can be implemented to provide an integrated array of services supporting operation, fruition and valorisation of urban goods [3].

This paper presents an update of a case study research carried out in 2015 concerning the support for the implementation of an UFM service in San Donato Milanese, Italy [4]. For this purpose, an information system supporting the survey phase has been developed. Information are gathered and managed thanks to a Data Base Management Systems (DBMS) jointly with Geographical Information Systems (GIS). The outputs of the process are thematic maps, used for leading strategic decisions on prioritisation of maintenance and restoration interventions in the neighbourhood. The system has been employed in the kick-off stage of the UFM service. The survey and reporting tool has been applied and partially embedded in management procedures of the company appointed for the implementation of the UFM service.

In §4 a quantitative and qualitative analysis of data concerning the maintenance cost and investment undertaken on the management of the urban precincts is presented. These analysis, show that, thanks to the implementation of the system, cost for corrective maintenance decrease, despite a different trend can be highlighted in the last year of analysis (2017). The paper concludes with some insights and further development of the methodology and the whole research. Moreover, drawbacks and limitations are highlighted.

2 Data engineering for UFM

Urban OM&R can be intended as a set of actions carried out to keep or restore performances of urban goods to an adequate level [5]. Therefore, they are primary issues in management of the built environment. Moreover, OM&R can be encompassed in a wider framework, namely the Urban Facility Management (UFM), which comprehends a series of services, procedures and actions for enhancement of operation, fruition and valorisation of the urban goods in order to achieve a better quality of the built and open environment [3][6]. Considering an overarching strategy of resource saving, these issues acquire outstanding relevance, to foster sustainability of buildings and, more in general, of the built environment [7].

Different players in the real estate, belonging both to the private and public sector, contribute to the management and production of information. The public player on one hand assumes a role of legislator providing guidelines and frameworks concerning the types of information that must be collected, recorded and certified for validating building procedures and operations. On the other hand, it produces and preserve itself a great amount of data. Thus, it assumes a double characterisation. It can be considered a supervisor, since it has a responsibility in terms of compliance checking of reliability and accuracy of information requested to the private player during design, execution, use and management phases of buildings. While executing this role, it must be also compliant with the rules and codes developed for the purpose [8]. As a consequence, the public player plays both a proactive and coercive role.

In the same context, it is needless to say that private player is forced to produce compulsory documentation related to its real properties. Moreover, it is appointed for the management, updating, and conservation of this information.

Nevertheless, it is not always easy to assess and determine the responsibility and compliance with codes and laws. Therefore, in those situations where the uncertainty increases, tools for information management acquire a key role both at the building and territory level.

For reducing uncertainty in OM&R, the authors identified a set of information both for building and urban precincts that should be taken into account. These core information collections are called *Building Logbook* and *District Logbook* [9]. Table 1 and Table 2 list the main information contents of the tools cited above.

Table 1 information categories and contents of the Building Logbook [9].

Section	Information to be collected
Building registry info	• Concerning the urban registry information and the updated internal subdivision in sub-units.
Information about the property, management and tenancy	• Updated documentation on ownership, • updated documentation on tenancy and related contracts and agreements, • documentation concerning the management structure, appointed to the management of the building (concerning leasing contracts and technical management contractors).
Technical info on building elements	• Building breakdown, • description of technical, typological and functional characteristics of components,
Operative info for management and maintenance	• Documentation related to technical, administrative and economic management of the building, • safety and certification documentation.

Table 2 information categories and contents of the District Logbook [9].

Section	Information to be collected
Urban and building registry info	• General information about the neighbourhood, • quantitative data and reference to infrastructures, urban facilities and buildings, • urban planning info.
Population registry info, property management and tenancy	• Data on the population of the neighbourhood, • data on city users, • data on management entities.
Technical info on urban goods and elements	• Location, • ownership/responsibility/manager, • geometric info,
Operative info for management and maintenance	• technical condition, • instructions/procedures/guidelines for maintenance and management, • safety measures, • plan/program for maintenance.

As can be seen, the information required by the two core information collection is rather wide and complex. Moreover, it can be considered as dynamic collection of data, updating time by time whenever a changing at the building or at the district level happens. The Building and the District Logbook should be used for the reduction of the uncertainty in transaction and use phase, since they can be considered as risk prevention tools for technical, economic and legal issues in management of the built environment. Through their use, crucial information could be easily found used as proof of compliance with laws, building or urban performances etc.

When the scale of the intervention is the neighbourhood, the District and the Building Logbooks should be used jointly, in order to enable the stakeholders to timely access information. In the following paragraphs a description and update of a case study concerning the implementation of a UFM service is described. This experience must be encompassed in the framework described above, especially for what concerns the implementation and management of the District Logbook for the sections titled *Technical information on urban goods and elements* and *Operative information for management and maintenance.*

3 Case study

The system, has been applied, fostering the setup of an Urban Facility Management (UFM) service for Quartiere Affari in San Donato Milanese, Milan, Italy.

The purpose of the information system, concerns the speed-up of the survey phase. Thanks to its possibility to manage a great amount of information, a Geographical Information System (GIS) has been adopted. GIS potentiality is enhanced through the joint use of a Database Management System (DBMS). These tools are integrated with a survey module, mounted on portable devices (e.g. smartphones and tablets). Exploiting the aforementioned tools, it is possible to ease and systematise the urban environment's assessment process. Accordingly, the times for urban components' detection have been significantly reduced. In Table 3 key data of the survey campaign are summarised.

Table 3 Survey key data

Description	Data
Tot. failures detected	476 (297 failure forms)
People involved	4 people in 2 groups
Roads	Approx. 2.500 m
Square	Approx. 9.000 m^2
Average survey time for 100 linear meters	1:00 h
Duration of the survey campaign	1 week

The survey has been carried out on the neighbourhood, to collect data concerning the status of urban components, identified according to a breakdown structure previously defined [3]. Information collected concern:

- typology of the pathology detected,
- different levels of necessity of intervention (from long term to urgent),
- safety for users,
- pictures of the pathologies on the urban elements,
- comments [10].

Information are gathered thanks to the use of a mobile application developed for the purpose and stored in a web database (*Assessment* phase in Figure 1).

Figure 1. Survey process schema. Phase 1 Assessment

Data are then georeferenced using a GIS platform. In the *Data analysis* phase (Figure 2), information collected during the survey campaign has been processed and organised both through quantitative and spatial analysis. Combining these two types of analysis it has been possible to spot the most critical urban components and urban precincts (phase *Data output* in Figure 2).

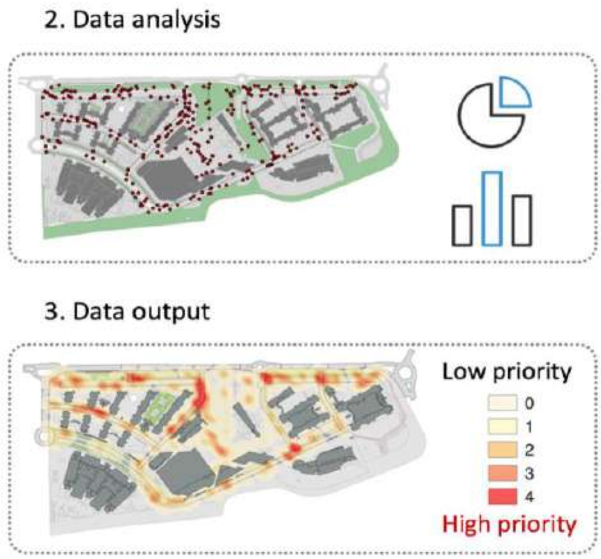

Figure 2. Survey process schema. Phases 2 Data analysis and phase 3 Data output

Identification of most critical entities, allowed to prioritise maintenance and repair interventions [4]. Most critical areas are highlighted in Figure 2 *Data output* thanks to a map showing the concentration of pathologies of components in a circle of 20m of radius.

Thanks to the analysis performed and described above, it was possible to identify that the crossroads are the most critical technological units presenting also issues related to safety for users (therefore, more critical). Following a descendent level of priority of intervention, urban drainage system is identified as second most critical technological unit. As for what concerns the crossroads, also this entity is subject to a high level of stress, especially if located in roadways characterised by heavy vehicular traffic. The third most critical technological unit is the walkway. Spatial analysis concerning the concentration of degradation in a radius of 20m has been carried out and combined with quantitative analysis. While the trends in degradation of technological units described before is confirmed, this data processing allowed to identify, the precise location where the degradation phenomena appear [4].

4 Maintenance costs analysis

The survey phase has been carried out in 2015, thanks to the information system described in the previous paragraphs. After that, the company in charge, developed the investment and UFM plan. Thanks to a collaboration with the UFM company, we could access the cost and technical historic datasets and budget data employed for the implementation of the intervention needed for bringing the maintenance and functional status of the neighbourhood in optimal condition. Moreover, the UFM company, partially integrated its management and survey procedure with the assessment and framework provided by the authors. Despite the complete adoption of new technologies and procedures, as recursive procedure to be carried out periodically, can be considered as a long term process, the cost trends in term of OM&R expenditure, confirm an improvement over the years.

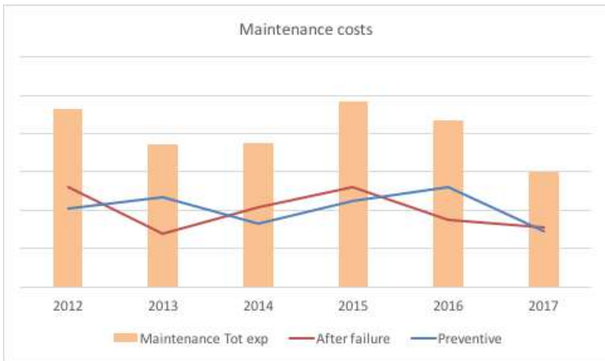

Figure 3. Maintenance expenditure trend from 2012 to 2017.

The cost chart in Figure 3, represent the trend of maintenance expenditure from 2012 until 2017, namely the period in which the UFM company has been appointed. As can be seen, the cost trend of the after failure maintenance (in red) and preventive maintenance (in blue) show a higher investment in preventive maintenance in 2012, namely the starting year of the UFM contract and in 2016, after the survey and assessment phase carried out by the authors. Nevertheless, in 2017 can be spotted an increase of the expense of the after failure maintenance. In 2017 can be also spotted an increase of the expense of the after failure maintenance, despite the total maintenance expenditure assumes the lowest value since 2012.

Lower investments in maintenance are compensated by high investments in CAPEX. Area in the neighbourhood identified through the survey as most critical in terms of safety for users, intensity and concentration of degradation phenomena etc. have undertaken a refurbishment process. In Figure 4 are represented the cost trends in term of investments for the rehabilitation of the areas described above and for maintenance (corrective and preventive). The trends depicted in the chart show that a higher CAPEX injection in rehabilitation of the urban areas, corresponds to a decrease in maintenance expense. Unfortunately, preventive maintenance expense forecasts for 2018 and 2019 are not available.

Figure 4, on the other hand shows an interesting trend for total CAPEX injection for years from 2016 to 2019. For privacy reasons, CAPEX, as well as the maintenance expenditure magnitude, is not reported in this paper as precise amounts but as a percentage of the total CAPEX injection during the investment period (2016-2019). The representations in Figure 5 and Figure 6 show a correlation between the localisation of failures, detected during the survey, characterised by the safety issue attribute and the urban precincts where more intensive investments have been dedicated.

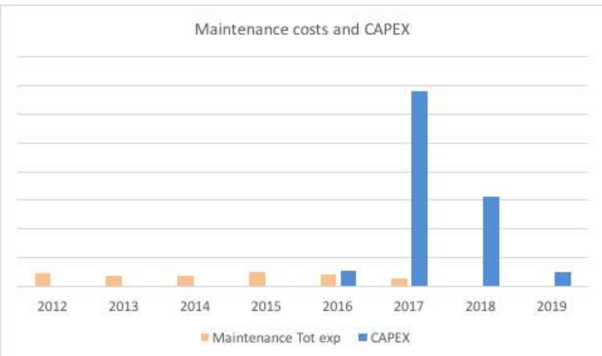

Figure 4. Maintenance expenditure (2012-17) and investment trend in refurbishment (2016-19).

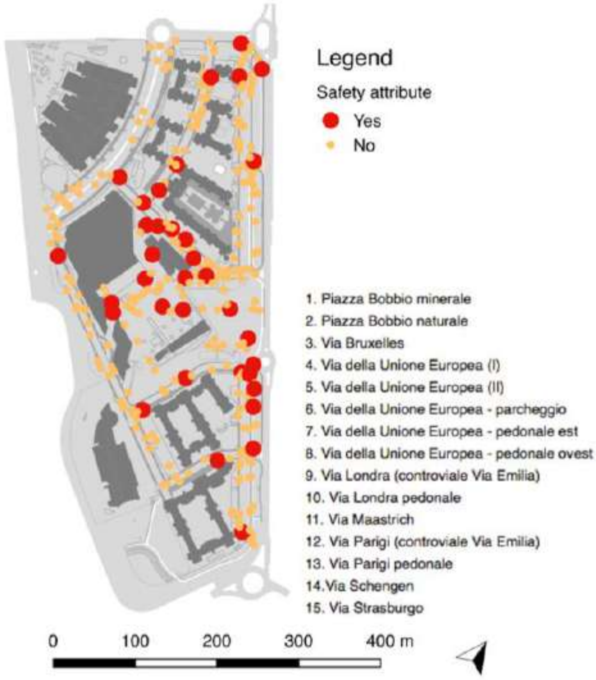

Figure 5. Localisation of failed components with safety attribute

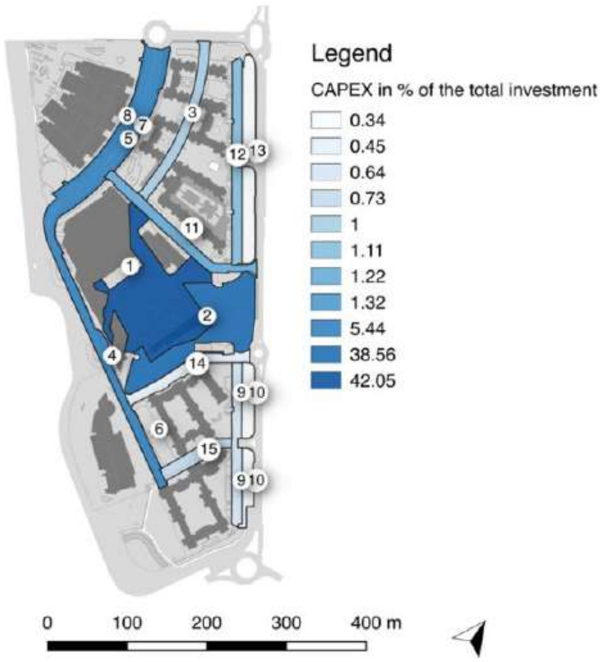

Figure 6. Localisation of CAPEX investments in percentage of the total

InTable 4 are summarised the number of detection of failed urban entities characterised by the attribute safety, in the urban precincts represented in Figure 6.

Table 4 Number of detections with safety attribute in the urban areas

Code	Area	Safety detections
1	Piazza Bobbio - minerale	9
11	Via Maastricht	6
10	Via Londra pedonale	4
3	Via Bruxelles	3
14	Via Schengen	3
2	Piazza Bobbio – naturale	2
9	Via Londra - controviale Via Emilia	2
12	Via Parigi - controviale via Emilia	2
13	via Parigi pedonale	2
4 – 5	Via della Unione Europea	1
15	Via Strasburgo	1
6	Park via Unione Europea	0
7	Via della Unione Europea - pedonale est	0
8	Via della Unione Europea - pedonale ovest	0

Among these areas precincts 1 and 2, corresponding to the neighbourhood's central square are receiving more than 40% of total investments on the period considered. This peculiar situation is due to the fact that being a spaces frequented by many users during the day, the degradation phenomena where more critical than other urban precincts, thus they required a higher injection of capital for the refurbishment intervention. Moreover, this higher amount of resources is due also to the extension of the area (approx. 9.000 m^2). Other peculiar situation can be highlighted for what concerns the precincts 4, 5, 6, 7, 8 Corresponding to via dell'Unione Europea. Despite in this area can be found only one detection presenting the safety attribute, it is the third more expensive precinct in terms of CAPEX injection (5.44%). This is due to the fact that though not affected by degradation with safety attributes for users, the number of detection is rather high.

Nevertheless, it must be taken into account that the only economic data, does not provide a dimension to the kind of refurbishment or restoration intervention carried out. Accordingly, it is necessary to combine these evaluations with others (technical, qualitative etc.) in order to obtain a more comprehensive picture of the whole neighbourhood's status. These further datasets could be obtained thanks to the recursive implementation of the survey phase. To conclude, it must be highlighted that Figure 4 does not represent the geographic representation of the total CAPEX. Values of investments on underground parking has been neglected, since they have been considered as separated entities for the whole development of the case study research.

5 Discussion and conclusions

Through the description of the case study research and thanks to the collaboration with the company appointed for the UFM implementation, it has been demonstrated how the precise definition of the information contents to be collected and management during the survey phase and for carrying out the UFM, it is possible to make informed investment decision of OM&R. This experience demonstrates that, adopting the survey system and the related procedure for assessment and data handling, UFM services can be better organised and performed faster, nevertheless, thanks to its modular structure, it allows the integration of different thematic modules [11]. Therefore, GIS software allowed to import information detected during the survey in thematic maps, exploited to define the level of degradation of some urban areas and to guide maintenance interventions. The system developed is dynamic and flexible and is updated through IT tools which take advantage of relational databases. Moreover, it can be considered as a risk prevention tool from both client and supplier point of view.

The system, despite being a powerful tool for data collection and analysis in the built environment, so far, lacks of integration with Building Information Modelling (BIM) editor software, even if it can be considered as compliant with the information management addressed by BIM procedure [12]. Thus, the system, can be considered as a first step toward the development of a more comprehensive Asset Information Model (AIM).

The methodology for economic assessment of the benefit in the adoption of the proposed system is based on the comparison between the quantitative data analysis against the spatial analysis allowed by the use of the GIS platform. This approach allows to describe and analyse cost performance trends in a wider and a more complete way. The economic expense for after failure maintenance and preventive maintenance can be related to the condition assessment of the neighbourhood, showing interesting trends before and after the survey has been carried out. Nevertheless, it was not possible to analyse the trend of the CAPEX injection, related to the current status of the urban areas. Only an assessment concerning the status as of 2015 compared to CAPEX budgeted from 2016 to 2019 has been possible. This is due to the fact that, despite the survey process to be implemented through the proposed system has been partially embedded in the procedures of the UFM company, it is not completely and periodically carried out. The process of adoption of new procedures in the well-established corporate practices is typically a long term process.

In conclusion, it can be possible to sketch an overlook of the proposed system concerning the integration of the core database with further modules belonging to different disciplinary fields. For this purpose, a case study concerning the possibility to exploit information collected during the survey for obtaining urban sustainability assessment is being implemented [11]. This case study demonstrates the possibility to exploit methodology underpinning the implementation of the system, within the context of the Neighbourhood Sustainability Assessment Tools (NSA) [13]. When management OM&R is addressed at the urban level, one of the keywords to be taken into account is complexity. For this reason, the system can be further developed, through the integration with a module for community involvement in urban maintenance prioritization [10]. Nevertheless, allowing users belonging to a given urban area to detect anomalies on the urban environment, requires robust data handling procedures, to be developed jointly with the implementation of the community involvement module.

This experiences show the potentiality of a structured data engineering for management and control of UFM service. Nevertheless, more testing and further validations in case studies are desirable. This will allow to integrate the proposed methodology and system in a more and more effective process for management of the built and open urban environment.

Acknowledgements

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Cable-driven parallel robot for curtain wall modules automatic installation

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Abstract –

Recently, the accurate prefabricated Curtain Wall Modules (CWM) used as building facade are gaining popularity around the world. However, the conventional manual procedure for installation of CWM is dangerous for labour work. More so, it is a time consuming and expensive task. Automation of the CWM installation using a cable robot is an alternatively faster and safer method. The cost saved due to shorter installation time would compensate for initial investment costs of the robotic systems. However, for CWM installation, the cable robot and its modular end-effector (MEE) need to perform several tasks such as positioning within 1 mm accuracy, drilling, installing bracket (connectors), and handling and positioning the CWMs. However, there is no such robotic solution currently available on the market. As a probable solution to CWM installations, the European project "HEPHAESTUS" is designing a cable robot-based automatic system capable of 1 mm positioning accuracy, while performing other tasks such as drilling on the building. Meanwhile, it could carry nearly a tonne in payload in an outdoor environment. As a design phase in this paper, five different conceptual scenarios for such complicated automatic installation process conducted by a cable robot are introduced. The possible concepts are assessed using the Delphi method. Finally, the accuracy, safety, and installation time of the selected scenarios are comparable to the conventional manual procedure of CWM installation. In the future, these systems further improve within the HEPHAESTUS project framework.

Keywords –

Cable-robot; Construction robotics; Automatic curtain wall module installation; Delphi method

1 Introduction

The construction industry plays an important role worldwide. Many countries consider it as a large part of gross product, which supports high employment rates [1]. Although construction companies use numerous apparatus onsite and offsite to enhance productivity, still several duties remain for manual workers [2]. One of such tasks that requires high labour effort in construction sites is the installation of curtain walls. This task poses serious risks for manual workers, since this task is done on the edge and on top floors of incomplete buildings. In addition, manual curtain wall installation is a slow operation. Numerous labour forces working long hours make the manual curtain walls installation highly expensive as well [1], [3], [4]. Therefore, automatic installation of curtain walls increases safety and productivity [5] , [6].

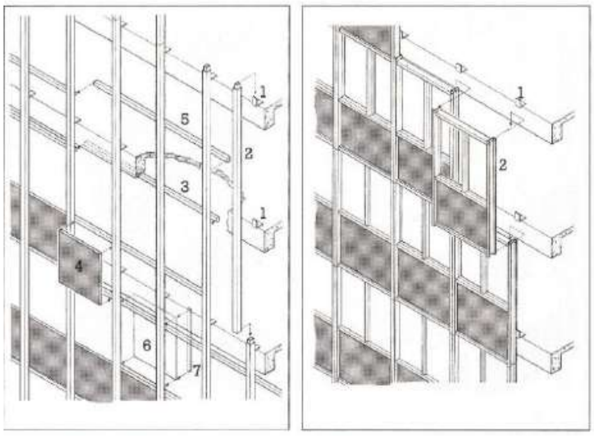
In the call for proposals from the European Union: *ICT-25-2016-2017 - Advanced robot capabilities research and take-up* [7], the *HEPHAESTUS* project [8] got founded in *innovation and action* scheme. The consortium of the project consists of three research institutes, one university and five companies. Nine members of the consortium are from different European countries namely Germany, Spain, France, UK, Italy and Norway. This project addresses novel concepts for facilitating the cable robots in the construction sector, which currently has a minor usage. The focus of the project is on curtain wall installation as a high risk and critical construction task. This paper is within the frame of the HEPHAESTUS project that aims to solve the challenges mentioned above.

In this study, we first discuss state of the art (chapter 2), followed by an introduction of the five possible scenarios for the automatic installation of curtain wall modules by cable robots (chapter 3). Next, the scenarios assessed using the Delphi method are highlighted (chapter 4). Finally, the assessment results leading to preferred scenarios are concluded.

2 State of the art

2.1 Curtain wall

A curtain walls is an exterior envelope of the building which does not carry the vertical loads of the building roof or floor. It sustains its own weight in addition to imposed loads such as wind, and transfers these forces to the building. It provides benefits such as daylighting and reduces the overall weight of the building [2]. There are two types of curtain walls shown in Figure 1.



Unitized and stick curtain wall system

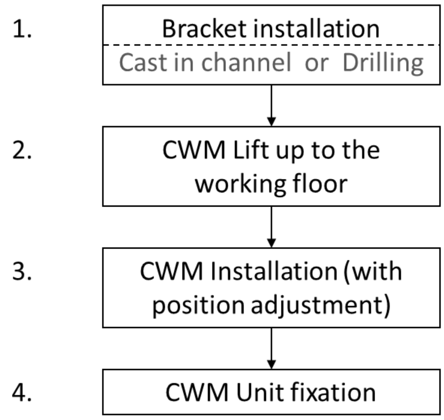
Figure 1. Left: Assembled on site, "stick". Right: Pre-assembled into rectangular panels, "unitized". [Picture rights: courtesy of AAMA [10]]

1. Type one is the stick system, where the installation of metallic frames and glass panels is carried out on site [9]. Most stick systems consist of horizontal rails and vertical mullions. When mullions and rails create such a grid on site, glass panels are often inserted, although other materials can also be used.
2. The second type is the unitized (modular) system. In a unitized system the curtain wall modules (hereafter called CWM) are pre-fabricated and assembled with pinpoint accuracy in the factory. The assembled module includes the rectangular aluminium frame and inner glass. A connecting part, i.e., bracket, will help to affix the module onto the buildings.

Figure 1 shows the two different types of curtain wall. The figure also shows that unitized system installation needs fewer steps on site. Therefore, the unitized system is selected for automation process and is the subject of this paper from now on.

2.2 Conventional CWM installation

The standard conventional CWM installation is a manual procedure, which occurs in four phases (see Figure 2). Step 1 of curtain wall module installations encompasses Bracket installation. There are two general ways of bracket fixation on the concrete slab of the building: cast-in channel and drilling. The Cast-in channel system is the most common technique for unitized system installations in new buildings.



Sequences of CWM installation

Figure 2. Conventional steps for a CWM manual installation process.

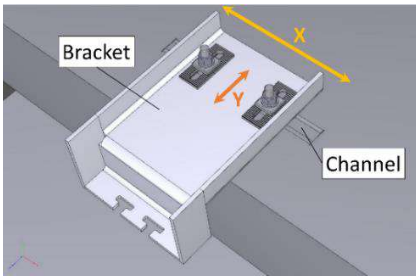
For the installation of cast-in channel systems, the first step is placing the cast-in channel on the framework, followed by welding it onto the steels bars before pouring the concrete (Figure 3 - up). The next step is manually removing foam from the cast-in channel (Figure 3 - bottom), followed by placement of the bracket (Figure 4). The adjustment of the bracket proceeds until its positioning meets the adequate pre-defined location.

Cast-in channel system

Figure 3. Preparation of cast-in channel system [Picture rights: courtesy of Focchi SPA [11]]

In a drilling system, the drilling points are first measured, and the absence of rebar under the aforementioned drilling points are checked before

drilling. If there is rebar under the drilling point, the drilling point will be changed accordingly while carefully considering the range of bracket adjustment allowance. Then, two holes are drilled in their proper positions. Finally, the bracket will be fixed using screws in the appropriate areas using anchors.
The bracket should be installed within an accuracy of 1 millimetre. In a cast-in channel system, the adjustment of the bracket position is possible in two directions (Figure 4). In a drilling system, the alteration is possible in only one direction because of the absence of a channel.



Bracket adjustment

Figure 4. Two possible direction of bracket adjustment while installing [Picture rights: courtesy of Focchi SPA [11]].

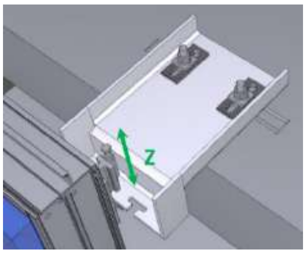
During bracket installation, its position will be controlled and checked by use of measurement systems such as a total station. In a manual setup, the placement of the bracket is critical because the final position of the CWM relies on the bracket location. The positioning of the bracket is likely not to be further re-adjusted.


CWM installation

Figure 5. Conventional installation of a CWM, possible dangers for labours - the number of workers involved in the installation process [Picture rights: courtesy of Focchi SPA [11]].

After the production, assembly, and control of the curtain wall modules in the factory, the modules are transported to the construction site and stored. At this step, it is assumed that the brackets are already fixed in their planned positions and are ready for hosting the CWM. In step 2, cranes lift the CWM to the working floor. The CWM can also be elevated to the working floor using an elevator (if available on site). Nevertheless, cranes handle the CWM’s weight during installation, while workers manipulate the CWM and adjust its position accordingly (step 3, see Figure 5).

Workers on the site guide the CWM into the bracket and adjust the CWM’s height via a specific part of the CWM (Figure 6). Finally, when the correct position of the CWM is confirmed, it will be fixed (step 4) and the installation of the next CWM starts.



CWM level adjustment

Figure 6. One direction of CWM adjustment during installation [Picture rights: courtesy of Focchi SPA [11]].

Each bracket hosts two adjacent curtain wall modules while bearing half the weight of each CWM, and each CWM is supported by two brackets, i.e., each bracket handles the full load of one.

2.3 Automated CWM installation

Multiple types of automated equipment for automatic curtain wall installation exist. One good example is a patented method by Brunkeberg Systems AB [12], which uses a dedicated railing system and a specially designed CWM to install the façade from the outside of a building. However, rail installation is conventional in this method. S. N. Yu *et al.* [2] used a mobile robot from the inside of a building to automate façade installation. However, they only managed to automate step 3 (Figure 2) of the standard CWM installation. J. Činkelj *et al.* [4] developed a telescopic hydraulic system that reaches the building façade from the outside followed by nailing of the façade panels to the building. This tele-operated system is specialised for sandwich panels, but not for CWMs. K. Iturralde *et al*. [13] proposed a Modular End-Effector (MEE) concept for use in automatic panel installation. Nonetheless, the proposed MEE is still at the conceptual level. These robotic systems, nevertheless, have some limitations.

In the HEPHAESTUS project (a subject of this paper), all the four steps (Figure 2) in CWM installation are considered to be fully automated, but not tele-operated. To reach this novel goal, a cable driven parallel robot (known also as cable robot) hosting a modular end-effector is the selected robotic system. A cable robot system has several advantages: (a) it could carry heavy objects based on cable load capacities, (b) the workspace is a design parameter and could be chosen big enough to cover the whole side of the building. Moreover, other features of cable robots such as the degree of freedom, speed, and adaptability could be beneficial [14]. In cable robots, flexible cables are used as actuators of parallel manipulators. One end of each cable is connected to a platform hosting the MEE, and the other end is reeled in or out by a motor-driven winch. The MEE is a specially designed mechatronic system, which moves to different floors of the building by the help of a cable robot. Briefly, a cable robot carries the MEE to the desired position and the MEE performs the rest of the tasks (e.g., drilling). Figure 7 shows a conceptual cable robot and the platform hosting the MEE. However, the Figure does not reveal the details of the MEE.

Cable robot

Figure 7. Conceptual view of a cable robot (Orange) working on a building. The platform hosting the MEE is coloured red.

2.4 Development process

In the HEPHAESTUS Project the requirements for the system together with existing technologies have been studied. The HEPHAESTUS Project revealed that the series of tasks in CWM installation is one of the critical issues that need to be addressed. Therefore, in this paper, mainly the sequence of the tasks is researched. In order to find the most suitable workflow procedure, first, five possible scenarios were defined and analysed by the Authors. Secondly, these five scenario were introduced to the whole project consortium. Next, based on the Delphi method for gathering expert opinion, all project partners participated in an assessment process. Finally, as a result of the assessment process, the preferred scenario is introduced in this paper.

3 Description of the installation Scenarios

The previously defined scenarios distinguish themselves in their different workflow of tasks. Although all the five different scenarios fulfil the CWM installation requirements, they require different technologies and provide various outputs. Table 1 shows the different steps to be taken in each of the five scenarios. All these phases are automated by the use of a robot unless mentioned otherwise.

Table 1. The sequence of tasks undertaken in the different Scenarios

	Scenarios				
	1	**2**	**3**	**4**	**5**
Steps					
Drilling the hole in precise location		1			4
Drilling hole with rough position			1	1	
Placing anchor in bracket	1	2	2	2	
Adjustment of bracket position	2	3	3		
Placing bracket	3	4	4	3	
Placing anchor in building					5
Fixing the bracket on the building	4	5	5		6
Measurement			6	4	
Creating interface bracket (Manual or by external device)			7		
Adjustment of CWM connection part (Manual)				5	
Mounting Bracket on the CWM(manual)					1
Placing and fixing interface bracket			8		
Placing CWM	5	6	9	6	
Placing CWM and bracket together					2
Adjustment of CWM and bracket together					3

Following, in this chapter, those scenarios are defined and their advantages and disadvantages are discussed.

3.1 Scenario 1

The first conceptual scenario follows the same workflow as the conventional installation process; for installing the CWM in new buildings, the placement of a "cast-in channel" before pouring the concrete is necessary. Afterwards, a bracket is accurately placed and adjusted. Finally, the curtain wall module is draped over the bracket. The accuracy of installing the façade relies on a precise bracket installation.

Advantage: This is the closest scenario to the existing installation methods. Therefore, solving this scenario would mean getting closer to the needs of the current market.

Disadvantage: The complexity of the tasks is considerable. The MEE system would need to achieve several tasks such as levelling of the bracket's nuts simultaneously.

3.2 Scenario 2

In the second scenario, it is considered that there is no cast-in channel available. Hence, drilling is required. First, the drilling position is calculated, then the robot will check if there is re-bar under this planned position. If this is the case, the position will be adjusted considering the bracket adjustment range. If there is no re-bar, the drilling process does not require an additional recalculating step. After this recalculation, two holes for each bracket are drilled automatically by the robot. From this point onward steps are similar to the scenario 1.

Advantage: It improves the adaptability and versatility of the system, because a cast-in channel system may not be provided in all constructions (assuming e.g., renovation process or steel construction), but drilling could be used in almost all constructions.

Disadvantage: There is some additional complexity. Attention to re-bar of the concrete, which should be recognized before drilling, especially if slabs are post tensioned.

3.3 Scenario 3

This scenario is based on using a correction interface for (mostly) each of the brackets. It is an alternative to have the adjustment flexibility in the fixing or drilling process. The idea is first installing the bracket roughly, and then with help of an interface, correcting any small misalignments. Considering the construction nature, (for example, concrete slabs are not always well aligned) some misalignments are hardly avoidable. Therefore, this scenario solves it by using a uniquely made interface for each bracket.

Advantages: This is a rapid installation case if the interface can be ready on-time. Furthermore, drilling position is selected roughly.

Disadvantage: It is Expensive. CNC or an additional machine on-site would be required. Other rapid prototyping methods such as 3D printing for the manufacturing of the interface may not be strong enough. Challenges of rebar recognition on drilling process exists, too.

3.4 Scenario 4

In this scenario, similarly to scenario 3, the hole is drilled roughly in range of a few centimetres. And the bracket is installed within that rough position precision. The adjustment for the exact position of CWM is handled by an adjustment module on the CWM. On the CWM, there is a part to be connected to the bracket. This part normally is fixed on the CWM, but in this scenario the CWM is re-designed to make this part adjustable. After rough placement of the bracket, its position will be measured and the connecting part on the CWM will be adjusted manually on the ground to correct the misalignment caused by rough installation position of the bracket. In contrast to conventional installation methods, adjustment capability transfers to a connection part of CWM. In conventional methods, adjustment happens directly on the bracket.

Advantage: The advantages are same as in Scenario 3.

Disadvantage: Adjustment module on CWM could not be mechanically strong enough to carry the load. It is better to have it fixed and not adjustable, considering mechanical stiffness. There might be a problem during the placement, hence non-parallel movement of the CWM may be necessary, which can jeopardize the fitting process. Challenges of rebar recognition on drilling process exists, as well.

3.5 Scenario 5

In this scenario, it is given that the bracket and the CWM first combine with each other, which could be considered as one module hereafter. Secondly, the combined modules are carried to the desired position by the cable robot, and next they are adjusted on their correct position within 1 mm accuracy. The further steps: drilling, placing anchor and fixing the bracket finish this scenario. When the bracket is installed on the building, it is carrying the CWM, which is the main difference of this scenario from the others.

Advantages: The CWM module is used as a physical pattern.

Disadvantage The slab's current geometry is unknown. Therefore, it may be impossible to level the bracket. Challenges of rebar recognition on drilling process exists, as well.

4 Assessment

After presenting five scenarios, one of them should be selected as the preferred scenario. To select the most profitable one regarding the requirements of the system, an assessment process is carried out in this research. In this chapter, first the assessment methodology is introduced then the corresponding procedure and results are presented.

4.1 Methodology

The assessment process and the selection of the preferred scenario in this project is a decision-making problem. In many decision-making cases, the decision needs to be taken based on multiple attributes to select an alternative from the feasible ones. This is the principle of Multiple Attributes Decision Making (MADM). It contains multiple decision attributes and multiple decision alternatives. The aim of the method is to make the decision considering all attributes [15][16][17]. One of the methods to do so is the Delphi method developed by Helmer and Dalkey [18] (around 1950s) to systematically use the expert's opinions. Decisions based on several experts' opinions are usually more precise than the individual opinion of each of the expert [19]. The Delphi method is a group communication process, which gathers the experts' ideas via survey letters or, in our case, via an assessment table. In contrast to other methods, Delphi applies multiple iterations (uses feedbacks) to develop a consensus of opinion concerning a specific topic [20]. The Delphi method begins with sending the same open-ended questionnaire to each of the Delphi participants (experts) and asking for their first thoughts and comments about the questionnaire. This is the first round. After collecting responses, this data will be converted to a well-structured questionnaire to be used in a second round. It is acceptable to start the method from round two if such well-structured questionnaire is already available [21]. In the second round, each expert receives a new questionnaire and is asked to review and sometimes to rank it in order of priority. In this round, area of diversity among opinions are identified and some consensus starts forming. In round three, each expert receives the questionnaires that includes opinion and rating of other experts in the previous round. They are asked to revise their rating and specify their reasons. In round four, usually the final round, the consensus of opinion, and any remnant of items exists, is presented to the experts. It should be mentioned that the number of Delphi iterations could vary from three to five.

In this paper, the Delphi method is used to assess the previously proposed scenarios. The group of experts as Delphi participants are project members. On behalf of each organization of HEPHAESTUS consortium, one person represents the organization's thought. So, nine experts are involved. First, an assessment table is provided as a questionnaire, where scenarios could be assessed by provided indicators.

In the first round, the assessment table and the scenarios' explanations were sent to experts and they were asked to share their first thoughts on the scenarios and indicators of assessment tables. After receiving the first comments, they were considered and included in the scenarios and the table. In round two, new well-structured table and scenarios returned to the experts. The experts shared their new revised ratings in the assessment table while they knew the others' opinions, as well. Finally, in the fourth round the final assessment table based on consensus of experts' opinions was presented. All experts agreed on that and it was accepted as the result of the Delphi method.

The following section presents indicators, which are used in an assessment table. The section after next describes the assessment table.

4.2 Indicators

The cable robot must perform certain tasks. The main task is to install a CWM in a building structure. For that purpose, some specific criteria for the cable robot were marked:

- **Cost of the proposed systems**
  Initially the presented solutions must rely on the possibilities of the end-users, the CWM installers and the contractor companies. It should compete with conventional manual installation.
- **Simplicity and ease of accomplishment**
  There are several ways to perform each task to make the overall system work. The simplest way is preferred, because it eases the design process and makes the job for an end-user simpler.
- **Technological availability**
  The proposal must rely on previously tested technologies. However, scientific development is required in cases such as a specific visual system for bracket placement. The extra developments should be avoided as much as possible.
- **Accuracy and Repeatability of the robot's path**
  The cable robot is responsible for the CWM installation. Therefore, its position accuracy plays a key role in installing the bracket and the CWM correctly.
- **Adaptability to different construction sites**
  The cable robot should be adaptable to multiple construction sites. The target buildings are commercial and office buildings. In such cases, they are made of steel or concrete structural frames with on-site concrete slabs. The cable robot system will be designed to install the curtain wall panels in facades without balconies, as it is the case of most commercial and office buildings. Indeed, a cable robot is well-known for easy reconfiguration, since pulleys and drums can easily be placed in different position and are adaptable to complex systems.
- **Matching to conventional unitized CWM**

products
If scenarios require major changes in the current product (the Curtain Wall Module and bracket) for being installed by the cable robot, this might be a problem for future marketing of the robot. Therefore, matching the system to the conventional bracket and the CWM system will ease the future marketing and is considered as an indicator of the most successful robot.

- **Possibilities of Multi-functionality (cleaning, repair, etc.)**
The cable robot should be configured for accomplishing multifunctional tasks, the project primary task (installation of CWM) plus possible optional tasks (such as cleaning or painting). The optional tasks are generally easier compared to the primary task.

4.3 Assessment result and preferred scenario

In order to assess each scenario quantitatively, each indicator has a specific maximum value as seen in Table 2 in parentheses.

Table 2 Assessment table of the Scenarios

	Indicator (max- value)	Scenarios 1	2	3	4	5
Demonstrators	Cost of the proposed systems (20)	15	15	10	10	15
	Simplicity of the system and ease of accomplishment (20)	10	10	10	15	10
	Technology availability (20)	15	15	10	15	10
	Accuracy and Repeatability of the robot´s path (20)	15	15	10	5	5
Future feasibility	Adaptability to different construction sites (10)	5	5	5	5	5
	Matching to conventional unitized CWM products (5)	5	5	2	2	5
	Possibilities of Multi-functionality (5)	5	5	5	5	5
	TOTAL (100)	70	70	52	57	55

The indicators are divided into two types: demonstrators and further feasibility. Since demonstrator is the primary goal of the HEPHAESTUS project, the respective indicators have a greater maximum value. If the project is successful for the demonstrator task, it could fit for simpler applications as well (e.g., cleaning). The weights (maximum value) of indicators are mentioned in parentheses. The maximum value represents the maximum score a participant could give a specific scenario. The higher the value, the better the project goal in terms of that indicator. For instance looking at Table 2; scenario two has higher value compared to scenario three considering first indicator, which means scenario two better fits to the project goal regarding costs. Simply it could be translated such that: scenario two is at the end cheaper by experts' opinion compared to scenario three. The sum of the weights is 100. Each scenario finally will gain a total value between 0-100, the closer to 100 the better the scenario fits the project goal considering all indicators. All consortium partners in the HEPHAESTUS project have participated in the assessment process by the Delphi method. Table 2 is the final table of round four using the Delphi method confirmed by experts.

5 Conclusion

The results in Table 2 show that scenario 1 and 2 achieved the highest value and are the preferred scenarios. However, the MEEs in scenario 1 and 2 need further development in the direction of modularity. Ideally, the MEE should be modular enough for both situations, despite the need for some modifications. Additionally, scenario 2 is interesting from a technical point of view; it makes use of drilling, and can therefore be used for renovations on old buildings with no cast-in channel. Another aspect of the preferred scenarios is to perform bracket installation and to carry the CWM, distinctively. The modules in charge of moving the CWM and the ones responsible for installing the bracket do not have to be run at the same time by the cable robot, therefore reducing the typical load carried by the robot.

In the next research phases of the HEPHAESTUS project, the authors will further improve and develop these selected scenarios.

It is worth noting that the details of the "detail how to do systems" will be defined in the next stages of the project, which deal more with the design of the system. After completion of the design, the system will be built and tested in a real world.

6 Acknowledgement:

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An Algorithm for Optimizing the Location of Attached Tower Crane and Material Supply Point with BIM

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Abstract

Attached tower crane is globally used in the high-rise construction to transport components vertically and horizontally. To reduce cost and improve overall efficiency, the tower crane should be well located to move heavy materials. This paper proposes an optimization algorithm to identify the optimal type and location of attached tower crane with proper location of material supply point. The algorithm concerns four main models:1) tower crane location generation model to define alternative type and area for allocating crane.2) supply point location model for selecting all potential area to establish supply point.3) tower crane optimization model to get the ideal location of tower crane and supply point. 4) 4D simulation model to evaluate and visualize the optimal layout scheme through BIM. Then, a practical case, in China, is described in order to demonstrate the outputs obtained by the optimization algorithm. Later, three typical situations of construction site are discussed based on the case. The results reveal the rule that the trolley sliding movement is weightier than the jib rotation movement when considering the optimal layout scheme.

Keywords –
Attached Tower Crane; Optimal Algorithm; Site Layout; BIM

1 Introduction

Construction site layout planning is a tough task that has to be determined at the early stages of construction, and suitable site layout can significantly improve the construction efficiency [1]. Equipment cost might be in the range of 10% to 40% of overall construction cost [2]. Therefore, having an optimal layout of equipment (e.g. tower crane) and material supply point will be conducive to shorten schedule period and reduce cost [3].

As for types of construction equipment, tower crane is the most prominent construction machinery in the construction market, not only for their large size, but also because they played a prominent role in transporting components vertically and horizontally [4]. In addition, tower crane is the most expansive type among these construction equipment types [5].

With the accretion of population during urbanization process, the number of high-building is increasing especially in China and this phenomenon leads to the widespread uses of attached tower crane. The crane, allocated close to the building boundary, significantly improves the lifting capacity of cranes. Therefore, the selection and allocation of attached tower crane has been the main concern of the construction of high-rise building.

2 Literature Review

Current study has put forward a lot of different ways to find the optimal position of tower crane, which is mainly based on simulation and mathematical algorithms. Based on achieving minimal collision of tower cranes, Zhang et al. [6] proposed the method of calculating hoist travel time firstly which laid the foundation for later study. C. Huang et al. [7] improved the equation by adding not only formulas to calculate vertical transporting time but also a parameter α to reveal the location specific effect in different construction sites. Subsequent study completed simulating the hoisting process and separated into load mode and unload mode [7]. In 2017, Justin K. W. Yeoh et al. [8] took multiple stages and the concept time into account to a better solution.

Most of previous researches prefer using mathematical algorithms to allocate optimal layout planning. C. M. Tam et.al [9] applied genetic algorithm to optimizing supply point and tower crane location. Later, GA-ANN model, combined genetic algorithms and artificial neural networks, was introduced to solve

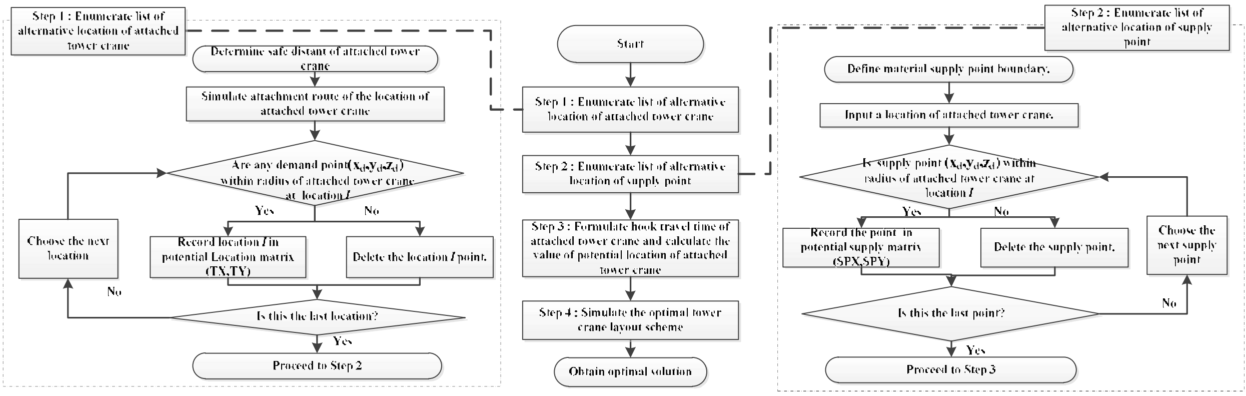


Figure 1. Flowchart of attached tower crane optimization

the same problem [10]. Another modern application for the problem, involving mixed-integer linear programing technique, was introduced by Huang et al. [11]. With increasing focus on construction layout planning, Javier Irizarry et.al. [12] applied geographic information system (GIS) and building information modeling (BIM) to solve the problem which visualize the potential conflicts. And Particle Bee Algorithm (PBA), combined particle swarm optimization (PSO) and bee algorithm (BA), involved to get the optimization location of demand points and supply points [13]. Then, Jun Wang et.al [14] used firefly algorithm for generate optimal layout planning and BIM technology to input data and visualize layout scheme. Mohamed Marzouk et.al. [15] developed a decision model for tower crane selection and location based on BIM and GA.

In previous study, scholars mainly discussed material demand point, supply point, location and lift capacity of tower crane that based on the object of minimal operating time, cost and collision between tower cranes. Practically, tower crane with high lift capacity means using less time to transport the same quantity components than lower ones. However, this also leads to increased costs which is proportional to the rent time. Thus, it is essential to select the suitable type and optimal construction layout planning in different construction which is the purpose of this paper

3 Attached Tower Crane Optimization Model

Finding optimal tower crane scheme involves four steps as shown in Figure 1. Firstly, a tower crane location generation model is introduced to produce all alternative tower crane location. Secondly, a supply point location model is generated, finding all potential material supply point. The next is an optimization model to search optimal exact location of tower crane and supply point. Finally, the outputs are evaluated and visualised through BIM.

3.1 Module A: Tower Crane Location Generation Model

To illustrate the constraint of selecting and locating tower crane, several analogies has been drawn on from the previous study. As shown in Figure 2, D1 and D2 represent two demand points where need the same type of components, while the component in D3 is lighter than that in D1, which means M1=M2>M3. And R1, R2 and R3 stand for the radiuses of the maximum area to ensure the crane lift the load of the demand points respectively. Ideally, each crane has its own fixed lift capacity and the radius of the component is inversely proportional to the component mass. The lighter the component is, the further the jib is, which leads to R1=R2<R3. In order to insure the crane to deliver all components to demand points, the crane has to be positioned in the overlapping region.

According for the attributes of attached tower crane, the crane needs a safe and short distance to be located and operated. This distance can be obtained by practical experience. Therefore, attached tower crane should be located in the junction of the overlapping region and attachment route.

3.2 Module B: Supply Point Location Model

Comparing with the tower crane location generation model discussing above, supply point location also has two limiting factors. On accounting for the distance between attached tower crane and the building, the supply point lays behind the crane. Another factor is similar to the principle discussed above. Each potential crane location can have its alternative supply area, as shown in Figure 3.

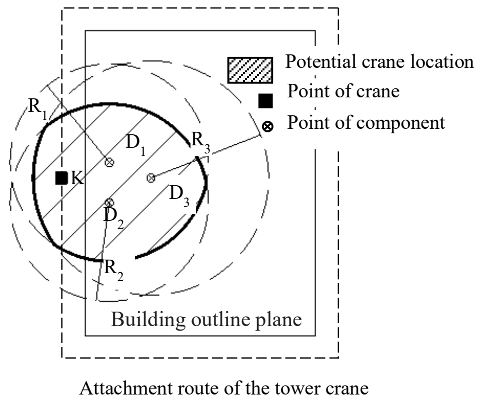


Figure 2. Possible crane location

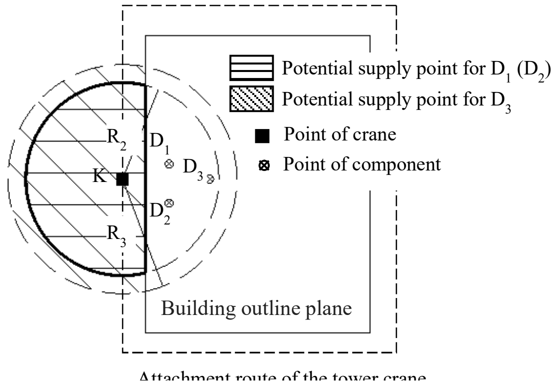


Figure 3. Possible supply point location

3.3 Module C: Tower Crane Optimization Model

Attached tower crane lift components in supply point S (x_s, y_s, z_s), transporting it to demand point D (x_d, y_d, z_d). This movement process of attached tower crane is consist of vertical movement and horizontal movement. On the other hand, the hoisting process can be divided in two main situations: (i)With load (ii) Unload.

3.3.1 Vertical Movement of Attached Tower Crane

Vertical movement can be separated into two parts, the vertical lift movement and descent movement. In order to avoid the collision between the components and building, there is a safe height h_0 above demand point. Eq. (1) and (2) calculate the travel time of vertical lift movement and descent movement respectively where v_{h1} represents hoisting speed of hook (m/min). When attached tower crane is back to supply point for starting the next delivery, the crane is under unload condition. The different between with load and unload is the velocity of hook.

$$T_{v_1} = \frac{|z_d - z_s| + h_0}{v_{h1}} \quad (1)$$

$$T_{v_2} = \frac{h_0}{v_{h1}} \quad (2)$$

3.3.2 Horizontal Movement of Attached Tower Crane

As mentioned in Zhang et al. [6] model, the horizontal movement contains two motions: (i) linear motion of the trolley;(ii) the rotation of the jib. Figure 5 shows the relationships among location of the crane, demand point and supply point, including the radial and tangential movements of the crane jib. The relationships can be calculate using Eq. (3) - (7).

$$\rho_D^K = \sqrt{(\mathrm{x_d} - \mathrm{x_k})^2 + (\mathrm{y_d} - \mathrm{y_k})^2} \quad (3)$$

$$\rho_S^K = \sqrt{(\mathrm{x_s} - \mathrm{x_k})^2 + (\mathrm{y_s} - \mathrm{y_k})^2} \quad (4)$$

$$\rho_S^D = \sqrt{(\mathrm{x_d} - \mathrm{x_s})^2 + (y_d - y_s)^2} \quad (5)$$

$$T_\omega = \frac{1}{v_\omega} \arccos\left(\frac{\left(\rho_S^D\right)^2 - \left(\rho_D^K\right)^2 - \left(\rho_S^K\right)^2}{-2 \cdot \rho_D^K \cdot \rho_S^K}\right) \quad (6)$$

$$T_r = \frac{|\rho_D^K - \rho_S^K|}{v_r} \quad (7)$$

$$0 \le arccos(\theta) \le \pi$$

Where T_ω= time for trolley movement; T_r= time for jib rotation; v_ω= slewing speed of jib (rad/min); and v_r= radial speed of trolley (m/min).

Practically, the movement of the jib rotation and the trolley sliding runs simultaneously to transport component efficiency. The parameter α represents the degree of synchronization between the movement of jib rotation and trolley sliding. The assignment of α is between 0 and 1 that stand for full simultaneous movement and full consecutive movement. The parameter β_r and β_ω represent the first movement of the

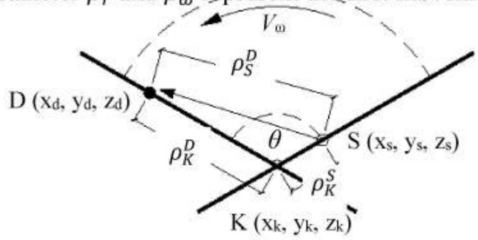


Figure 4. Horizontal operation process

$$T_h = \alpha[\beta_r T_r + \beta_\omega T_\omega] + max\{(1-\alpha)[\beta_r T_r + \beta_\omega T_\omega], \beta_\omega T_r + \beta_r T_\omega\} \quad (6)$$

When α=1， β_r=1， β_ω=1， or α=0， β_r=1, β_ω=0, or α=0， β_r=0, β_ω=1, the results of Eq. (6) are same as the results of that of Zhang [6].

3.3.3 Total Travel Time of Attached Tower Crane

In the same consideration of parameter α, the parameter γ is added to express the degree of synchronization between the vertical lift movement and horizontal movement. Furthermore, the hook travel time is determined by many factors such as site conditions and the proficiency of operators. Hence this paper adds the parameter μ_k to reveal the degree of difficulty in alternative crane location K for the operator to manipulate ranging from 0.1 to 10.0, which may be diverse in different combination of demand and supply points.

$$T_{i,j.l}^{o}(x_s, y_s) = \mu_k\{\gamma T_{v_1} + max\{(1 - \gamma)T_{v_1}, T_h\} + T_{v_2}\} \tag{9}$$

In conclusion, Eq. (1) - (9) define the calculation of hook travel time when delivering a single component. Besides, in practical, there would be loading time, unloading time and waiting time during the whole process of hoisting. Therefore, the total time of a building hoisting scheme could be defined as Eq. (10).

$$T_{t_n} = \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{l=1}^{L} T_{ijl}^{o} + T^u + T^w \tag{10}$$

Where I refers to the total number of the components, J refers to the total number of the floor, L represents the total number of type of the component.

3.4 Module D: 4D Simulation Model

Owing to the abstract outputs from above model, it is tough for site manager to fully understand the result and make wise decisions. Furthermore, conflicts and restrictions in spaces are difficult to display in 2D or 3D layout planning. Hence, the purpose of developing this 4D simulation model is to evaluate the credibility of the mathematical model outputs and space restrictions.

The inputs of this model come from three parts: 1) the outputs of tower crane optimization model including the location of attached tower crane and supply point with proper type of the crane.2) the coordinates of demand point and material comsumption.3) model library concerns 3D building model, construction schedule and 3D construction site model. The outputs of this model are the final layout scheme which will be implemented in reality.

4 Case Study

The proposed optimization model was used in the construction of a 23-story single apartment in Chongqing, China. The high-rise building is a footprint of 34.8 X 11.7m using attached tower crane. In addition, the types of the cranes used in this case are QTZ63, QTZ80 and QTZ125, and the numbers after "QTZ" means the max load moment of that type of tower (unit: KN/m). According to practical experience, the distance between the building boundary and tower crane is assume to be 4 meters which is the same between the location of tower crane and material supply points, as shown in Figure 5. Owing to the significant shape of attached tower crane and components, the possible position of tower crane and supply points is described in one-dimensional coordinate as particle distribution.

The results of module A, produced by MATLAB, displays in Figure 6. QTZ63 and QTZ80 are only able to deliver components to cover all demand points in part of the attachment route, while QTZ125 has potential location in all of the route. Depending on whether the attachment route, the situation can be divided into two parts: (i)full-filled which achieves the object; (ii) part-filled which attached tower crane locates in part of the attachment route. Practically, tower crane and material supply points locate on the basis of the experience that the tower crane should satisfied the farthest demand point with the heaviest component. And the full-filled situation simulates this realistic scenario. Thus, QTZ125 is the optimal type of attached tower crane in this project using practical experience. Meanwhile, QTZ63 and QTZ80 are another choice based on this mathematical model. As shown in Table 3, choosing

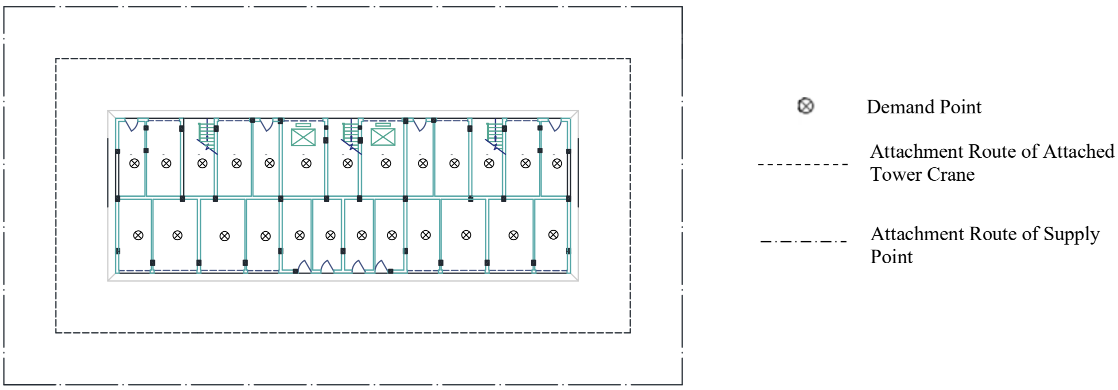


Figure 5. Site layout of case study

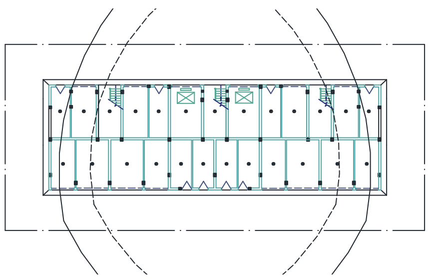
QTZ63 is a better solution that reduced the total cost of QTZ125 by 42.57%. Finally, the outputs are proved feasible in practice by Module D, and display in Figure 7.

Table 1 Coordinates of demand points and weight of the section to be transported (Standard floor)

Prefabricated Part	Demand Point	Coordinate X	Coordinate Y	Coordinate Z	Weight of the section to be transported(t)
Beam	D1	18.10	19.57	18.00	2.75
Floor	D2	21.20	19.57	18.00	3.25
Floor	D3	24.85	19.57	18.00	3.25
Beam	D4	27.94	19.57	18.00	2.75
Column	D5	30.55	19.57	18.00	2.50
Column	D6	32.89	19.57	18.00	2.5
Column	D7	35.35	19.57	18.00	2.5
Column	D8	37.69	19.57	18.00	2.5
Beam	D9	40.30	19.57	18.00	2.75
Floor	D10	43.39	19.57	18.00	3.25
Floor	D11	47.04	19.57	18.00	3.25
Beam	D12	50.14	19.57	18.00	2.75
Floor	D13	50.01	25.54	18.00	2.25
Floor	D14	47.60	25.54	18.00	2.75
Stair, Beam	D15	45.10	25.54	18.00	3.25
Beam	D16	42.37	25.54	18.00	2.75
Column	D17	39.93	25.54	18.00	2.5
Floor, Beam	D18	37.06	25.54	18.00	3.75
Stair, Beam	D19	34.12	25.54	18.00	3.25
Floor, Beam	D20	30.95	25.54	18.00	3.75
Column	D21	28.07	25.54	18.00	2.5
Beam	D22	25.63	25.54	18.00	2.75
Stair, Beam	D23	22.90	25.54	18.00	3.25
Floor	D24	20.40	25.54	18.00	2.75
Floor	D25	17.99	25.54	18.00	2.25

Table 2: The value of parameters used in the optimization model

Parameter	Unit	Type of Attached Tower Crane		
		QTZ63	QTZ80	QTZ125
v_h	m/min	41.6	43.3	51.4
v_{r1}	m/min	25	25	25
v_ω	r/min	0.7	0.7	0.7
v_{r2}	m/min	40	58	58
h_0	m	3	3	3
α	/	0.5	0.5	0.5
β_r	/	1	1	1
β_ω	/	0	0	0
γ	/	0.5	0.5	0.5



Note: QTZ125 is able to locate on any position of the attachment route due to its huge lift capacity.

Figure 6. Possible attached tower crane location

Table 3: Optimized total costs of attached tower crane on site using the proposed model

Results	Attached tower crane		
	QTZ63	QTZ80	QTZ125
Total material transporting time(min)	4215	4103	3910
Installation and dismantle costs(RMB)	39800	46200	74800
Foundation costs (RMB)	20250	24502.5	29160
Rental costs(RMB/d)	600	700	1200
Total cost(RMB)	65318.75	76686.04	113735

Figure 7. Simulation of the optimal scheme

5 Discussion

Each project has its individualism optimal layout planning because of the different constraint among the construction site. Exploring the main influencing factors and the changing rule of time in different situations is helpful to find the optimal layout planning. Practically, the supply point may be fixed in one position on account for the other facilities layout (e.g. steel cut machine), or there is no constraint of the allocation of supply point and tower crane. The experiments are based on the full-filled mode that is able to reveal the all-round output of the layout. In addition, the mass of the demand point distribution is symmetrical in left and right.

Situation I: Material supply point is right behind attached tower crane.

As shown in Figure 8 (a), the filled black pentacle refers to the optimal location of attached tower crane in the center of top attachment route. The line chart shown in Figure 8 (b) is the total delivering time of each attached tower crane location, and when the crane lays on the bottom and top of the attachment route, the total time will be shorter than that it in the right and left. The reason is that the high-mass component distributing mainly on the top line of demand points, so the distance to all demand points gets the minimal travel time.

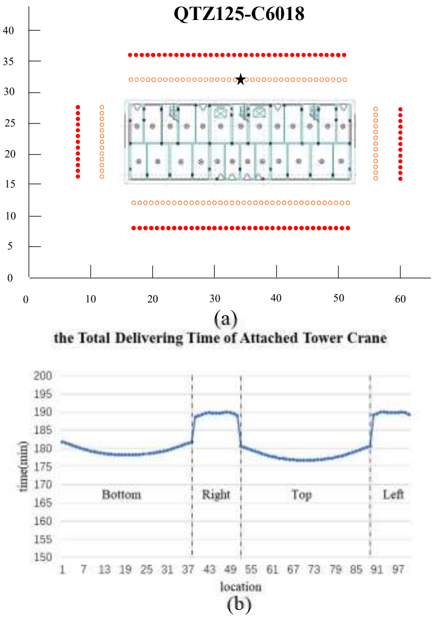


Figure 8 Results of situation I

Situation II: under no extra constraint when define the location of attached tower crane and supply point.

For this part, the layout planning reaches a state of relative ideal that may achieve in the early planning stage. As illustrated in Figure 9, the green triangle refers to the optimal metirial supply point when the tower crane located on the black filled pentacle. In addition, the left green triangle is corresponding to the left black pentacle.

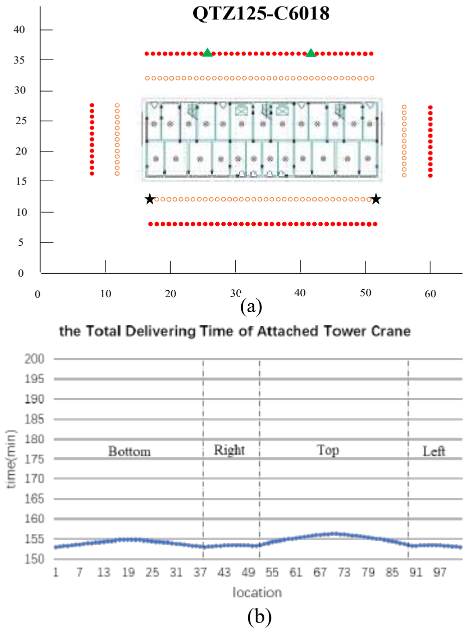


Figure 9 Results of situation II

Situation III: Supply point is fixed.

In order to comprehensive discuss this situation, this part is divided into three typical conditions:

1. fixed the supply point in the center at the bottom of attachment route;
2. fixed the supply point in the center at the left of attachment route
3. fixed the supply point in the angular point of the attachment rout

As shown in Figure 10-12, the optimal location of attached tower crane usually locates in another side of the attachment route, but not so far from the fixed supply point. The fixed supply point plays an important role in layout planning. Furthermore, when the crane lays right above the fix supply point, the total delivering time reaches the highest.

Among those situations, the line chart of situation II is the smoothest line and reaches the minimal time which indicates the importance of considering the layout planning in early stage. Meanwhile, it is a bad choice to lay attached tower crane just above the supply point that always leads to a costly result.

According to the proposed model, the mainly direct factors of the total travel time are the trolley sliding movement and jib rotation movement that influenced by the angle θ of ρ_D^K and the difference of ρ_S^K and ρ_D^K, respectively. And the optimization layout planning is to achieve a balance between the two factors.

Contrast with situation II and III, situation I is waster money which θ isn't able to less than 90 degrees while the difference of ρ_S^K and ρ_D^K is the same with others. Therefore, when solving the layout planning problem, the angle is a more important than the difference.

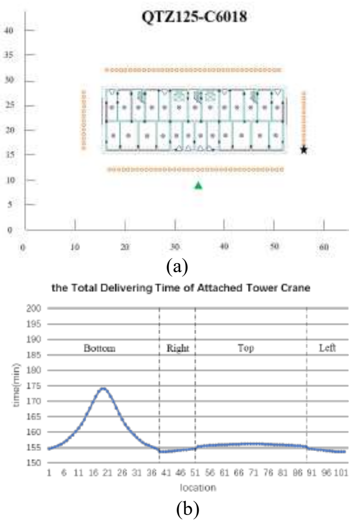


Figure 10 Results of situation III(i)

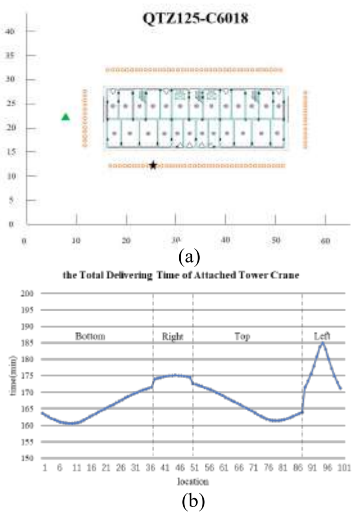


Figure 11 Results of situation III(ii)

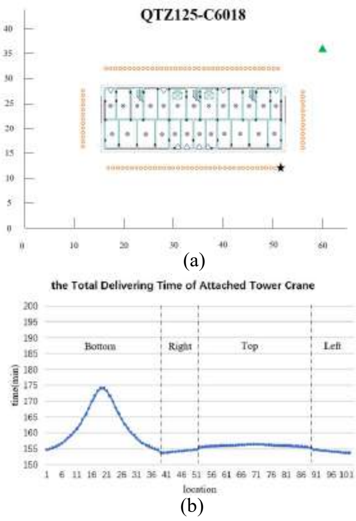


Figure 12 Results of situation III(iii)

6 Conclusion

This paper analyses the relationship among attached tower crane, demand point and material supply point, then simulates the movement of hook travel. Based on mentioned above, an optimization model is generated in order to select the type of attached tower crane and find the optimal location of the crane and material supply point based on finding the minimal cost. Furthermore, to evaluate and visualise the outputs, simulating the layout planning to ensure the optimal scheme is feasible and guide the site manager fully understand it. Finally, this algorithm leads to a more cost-efficient result than the traditional method that determined based on experience.

Compared with current study, the object of this study is attached tower crane, and this paper is more pertinent because it concerns the crane features as constraints when determine the layout planning. In addition, this paper discusses the main influence factors when positioning attached tower crane and supply point. Based on the practical case, many experiment has been done and reveals a few rules. The experiments are divided into three typical situations according to realistic site construction and aim to analyses the influence essential factors in layout planning. The results show that the angle between ρ_S^K and ρ_D^K is more important than the difference of ρ_S^K and ρ_D^K.

7 Acknowledgements

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BIM-based interoperable workflow for energy improvement of school buildings over the life cycle

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Abstract –

Simulation and predictive models to verify the energy performance of new or retrofitted existing buildings strongly need tuning procedures based on energy monitoring in the operational phase, thus to avoid performance gap concerns. The value chain of an uninterrupted information for energy models based on design data (e.g. for new buildings) or on paper documents and additional surveys (e.g. for existing buildings) is crucial to perform a reliable design optioneering process. The present research applies a BIM2BEM approach to provide a public administration with a model for facility management (i.e. BIM) and a model to assess energy improvement and check the choices (i.e. BEM), as a pilot project on school buildings renovation. Schools are frequently out-of-date buildings in harsh need of structural and energy refurbishment and public administrations require consistent economic evaluations considering the payback time of the proposed solutions. Additionally, O&M (Operation & Maintenance) costs should be included in a life cycle evaluation of the buildings. Two schools with different layouts and configuration adopted as case studies to compare energy simulation to actual consumption. The workflow empowers the energy simulation results highlighting the accuracy of energy modelling in different situations and it introduces possible tuning strategies to decrease uncertainty.

Keywords –

Predictive models; energy retrofit; BIM, interoperability.

1 Introduction

Nowadays, digitalization of design processes is BIM-based and allows an uninterrupted information chain [1] promoting a consistent energy model based on design data through BIM2BEM (Building Information Model to Building Energy Model) procedures enabled by gbXML interoperable format [2]. Furthermore, the possibility in existing cases to compare the predicted results with actual energy consumptions is imperative to identify suitable tuning criteria for energy models that always differs from real use [3]. The proposed BIM-based framework could empower in the whole life cycle an accurate evaluation of the building changes that are key factors to manage the asset and to guarantee the economic feasibility of renovation strategies [4]. The research aims at investigating how to use the BIM methodology for existing building management and how to implement energy retrofit strategies based on performance analysis by means of dynamic simulations accomplished through BEM. The main innovation and value is the interoperability of the models that allows to guarantee the conformity of the information in the design and evaluation environments. The possibility to extract the energy model from the BIM model is a step towards an optimized workflow that is not currently implemented in the practice when design and energy evaluation are always running on parallel tracks [5]. The performance gap that affect the energy simulation in comparison with actual performance in the running phase often heavily affects reliability of the models and time and cost are wasted to understand where is the misleading factor. Many factors collaborate on performance gap, however variability of occupancy, weather data, modeling assumptions and real performances of the building referred to designed and modeled ones are the main issues to be addressed [6]. The possibility to reduce the discrepancy of information and to define the reliability of simulation models is thus fundamental for AEC sector and to reach the nZEB goals. Different uses of the buildings are more or less prone to these errors and educational facilities are a very interested field of application because of the relevance of the thermal behavior of the building related to comfort conditions and learning performance of the users. At national level the school building stock is highly inefficient, as the 75% has been realized before energy laws [8][9] and thereby it is outdated and in need of retrofit and structural interventions [13] [14]. In the paper a new methodological approach is proposed defining BIM model for existing buildings and translating data to BEM models. A comparison of energy simulation and real consumption is used to understand the reliability of the model in different building configurations and to define tuning procedures that can be based on sensing and IoT.

2 Methods and tools

The use of the BIM methodology in combination with BEM energy analysis software for existing buildings is implemented in order to carry out preliminary analyses for renovation strategies and maintenance interventions to improve performance and reduce energy consumption. The data transmission between the two digital environments is guaranteed by interoperability which is the ability of a system to cooperate and exchange information with other different systems in a more or less complete and error-free way with the aim of optimizing resources reliably even between non-homogeneous information systems, both in software and hardware. This issue is becoming increasingly important when we talk about BIM-oriented design. The interoperability between BIM and BEM is a quite new issue and there are not many operational suggestions available for relocating data from architectural to energy models [7]. The data transfer process makes possible to keep the value chain of the information reducing discrepancies and possible inconsistencies contributing to exacerbate the performance gap, and increase time and cost of the realization.

2.1 Workflow

The analysis path uses Autodesk Revit as BIM authoring tool and IES VE as BEM dynamic simulation software (Figure 1). The architectural spaces defined in Autodesk Revit are defined as bounded analytical spaces and thus translated as thermal zones in the BEM. Analytical spaces are objects used to define and analyze of volumes that have thermal characteristics and specification allowing to store information about that thermal zone (e.g. occupancy rate, ventilation rate, temperature set points, etc.) to perform static and dynamic analyses on heating and cooling loads. The BIM model adapted for energy simulation should be enriched with data about thermal characteristics of the envelope, thermal specification for loads and parameters of the thermal zones and plants efficiency and typology. In this way it is possible to enable load calculation in the BIM environment or dynamic simulation in further simulation environments (directly into Green Building Studio or through *.gbXML file in IES VE, Design Builder, etc.). In the present research a workflow BIM2BEM through gbXML is adopted to eventually simulate the thermal behavior of two case studies.

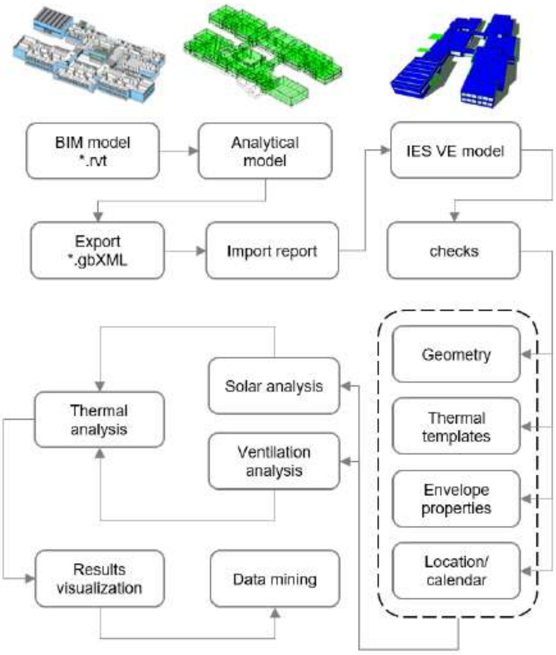


Figure 1. Workflow for interoperability BIM2BEM.

2.2 Scope and research problem

In the case studies the BIM methodology has been proposed to the public client (the Municipality of Seregno, Northern Italy) in order to manage the existing school building stock. The BIM2BEM path has been adopted to simulate different condition of the schools during time (and with refurbishments adopted in comparison with original situation) and to evaluate the advantages of different design options for further energy retrofit strategies (design optioneering). The information coming from the BIM database have been translated into the BEM simulation model to perform dynamic simulations. It is also possible to go back to enrich the BIM model with BEM calculated values for thermal spaces enabling a bi-directional information flow. In the present research the main scope was map the interoperability process and to test the reliability of energy model in comparison with energy consumption data through a data mining process.

2.3 Data mapping

The interoperability process needs a strong control and detailed data mapping to assure consistency of the model with the real conditions of the building spaces. The importing process through gbXML file is accompanied by an IES VE report showing the encountered problems and the measures taken by the software to fix them. The report also lists the presence of architectural holes in the external envelope, making impossible to carry out the energy analysis. The report is thus a first step to evaluate the process, however, a specific data mapping has been defined through *error sheet* to guide the process for further implementation of the methodology (Figure 3Figure 2).

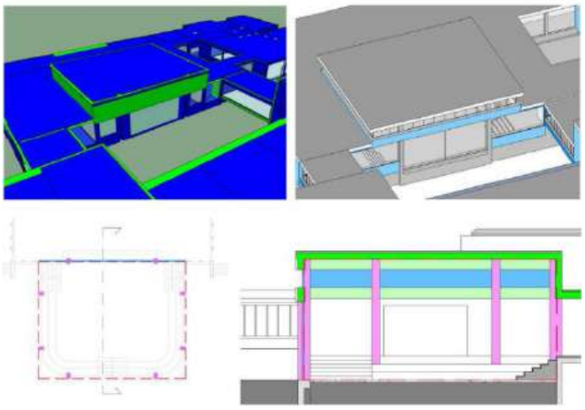


Figure 2. Specific data mapping of the import errors through BIM2BEM and suggestions for the simplification of the energy model.

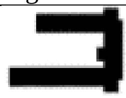
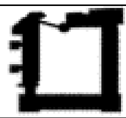
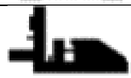
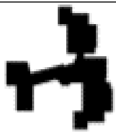
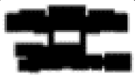
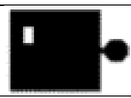
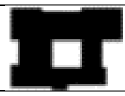
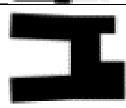
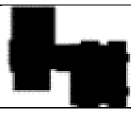
3 Case studies

The research started with the analysis of the educational facilities in the municipality of Seregno, northern Italy where 11 educational facilities dating from 1900 to 1987 are located. The municipality of Seregno is located near to Milan in the province of Monza and Brianza and it is one of biggest cities strongly developed between ’80s and ’90s. the greatest part of the expansion of the city dates in the ’90s and the quality of construction about energy performance cannot be considered high due to the low level of insulation introduced by the national energy laws in 1976 [8] and 1991 [9]. The thermal transmittance that can be assumed for public buildings realized in that period ranges between 0.8 and 0.6 W/m^{2}K for vertical opaque envelope and 3.5 W/m^{2}K for transparent surfaces. Nevertheless, the school buildings have been previously realized as reported in Table 1, this means lower values that can be assumed about 1.1 W/m^{2}K for opaque envelope and 5.7 W/m^{2}K for transparent surface where no retrofit occurred [10]. The school building stock in Seregno is representative of the characteristics of the 62,000 national schools, that have a total annual energy consumption is about 11’630 GWh (i.e. 70% for heating and 30% for electricity). The specific heating and hot water consumption for public schools is about 180 kWh/m^{2}year whereas the requirement for new construction is less than 40 kWh/m^{2}year, according to current standards [11] and EU Directives [12]. The community of Seregno has 44,875 inhabitants. Given the high density of population, a growing number of schools have been developed over the years, both public and private, and currently the following structures are located in the territory:

- n. 9 nurseries;
- n. 3 kindergartens;
- n. 7 primary schools;
- n. 6 secondary schools of first grade;
- n. 7 secondary schools of second grade.

Among these 32 structures, 11 public schools where energy bills were available have been selected.

Table 1 School Facilities in Seregno, Northern Italy.

n.	Year	School Level	Floor configuration
1	1900-1920	Primary (Stoppani)	
2	1920-1940	Primary (Cadorna)	
3	1965	Secondary (Mercalli)	
4	1969	Kindergarten (Nobili)	
5	1970	Secondary (Manzoni)	
6	**1972**	**Primary (A. Moro)**	
7	**1973**	**Kindergarten (H.C. Andersen)**	
8	1974	Multilevel (Gianni Rodari)	
9	1975	Nursery (Aquilone)	
10	1976	Nursery (San Carlo)	
11	1987	Secondary (Don Milani)	

A first analysis has been focused on maintenance costs and BIM-based management strategies while for the present research, 2 case studies among these schools have been chosen to develop a detailed analysis in order to compare the dynamic simulation about thermal behavior with data on the actual consumption. The comparison aims at underlining the level of reliability of energy models and the discrepancy introduced by standard simulation setup compared to actual thermal behavior of the school buildings. The realization of the BIM model with different stages of evolution during time and with different architectural and retrofit development has been useful for the municipality to store information about the historical evolution of the assets. The interoperability path allows also estimating and verifying the energy consumption in the life cycle. Among the 11 schools two case studies has been selected considering the listed criteria:

- area > 1000 m^2;
- construction year;
- morphology;
- interventions occurred over time.

The two case studies are part of the same school complex, the "Aldo Moro" Comprehensive Institute: they are the Primary school “Aldo Moro” (n. 6 in table 1) and the kindergarten “H.C. Andersen” (n. 7 in table 1). It is worthy to note that the 82% of the school is configured in blocks with a distribution corridor, and one or two sides of classrooms. There are only two cases in which a different use and a more complex organization of the space can be guessed. The corridor-classroom distribution is the main traditional configuration that can be found in the national school building stock. A new concept of school related to pedagogic needs is addressed by the two different cases (n.5, n.7 in Table 1). The traditional primary school A. Moro has been simulated in two versions describing the upgrade introduced in the last 2 years regarding envelope retrofit to be compared with energy bills and the complex school kindergarten “H.C. Andersen” has been simulated in the original configuration and with the following extension, (i.e. 1/4 of the space was added during refurbishment).

3.1 Traditional school with a distribution corridor and one side of classrooms

The primary school “A. Moro” presents a traditional distribution of the educational spaces and it has been retrofitted by improving thermal resistance through an insulation layer for the opaque envelope and substituting the windows to increase thermal performance of the transparent envelope. The building has two main blocks in which different uses are hosted. The north side hosts the classrooms section while in the south block the gym, offices, auditorium and canteen are located (Figure 3).

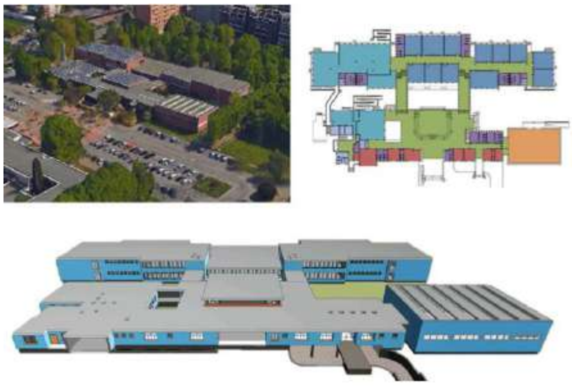


Figure 3. View of the Primary School “A. Moro”, floor area with functional spaces and BIM model.

The modelling process started with a detailed BIM model which included the two stages of implementation of the school: the original envelope configuration and the refurbished one. The refurbishment focused on the envelope increasing the energy performance of transparent and opaque envelope. Specifically the interventions have been: the windows replacement and the increased resistance of the opaque envelope by adding a polystyrene insulation layer.

3.2 Complex school with classrooms around a hall used as informal educational space

The kindergarten “H.C. Andersen” is the most significant complex school in the list of table 1. It has an L shaped ground floor, which has been extended with a fourth squared pavilion giving a final compact squared shape to the whole school. The school has ne floor and as can be seen in Figure 4, the floor plan has the classrooms located in different sides facing a wide common space as connection and distribution. It has also a didactic role for social skills improvement because for children it is very important to exploit informal spaces and learn how to exchange information in a sort of indoor playground. Therefore, the school configuration is a square with a central common space with skylights to bring the daylighting in the central area. A BIM model with the first configuration (L shaped) and the updated configuration (Square shaped) allowed the translation of the information to the energy simulation software. Once all envelope stratifications had been arranged in the BEM model and the correct association of the delimiting building components for each thermal zone has been checked, it is needed also to verify that the envisioned use of the rooms as set out in Autodesk Revit has been maintained. The energy software assigns to the rooms the specific use, which is closer to that defined in the BIM model. The verification of a multiple selection of rooms can be performed through the building manager tool. The database manager is used to set customizable profiles of each thermal (i.e. 7.30 a.m. to 6.30 p.m. for the school spaces and 10.00 a.m. to 1.30 p.m. for the kitchen, Saturday, Sunday and public holidays have been excluded).

Figure 4. Aerial view of the kindergarten “H.C. Andersen”, floor area with functional spaces and BIM model.

3.3 Interoperability process assessment

For both the case studies, problems in the data transfer process have been faced starting with the partial loss of information of the bounding elements of the single thermal zones.

A complete interoperability process should allow the import into IES VE of all the setups defined in the Autodesk Revit model. A partial interoperability is still a good result nevertheless the goal is to develop a workflow that could be easily managed and automatically replicated. Thermal zone delimitation and settings, envelope constructions, use of the spaces, schedule and thermal plants are the fundamental information to be included in the thermal model. Many information are missed if specific modelling strategies are not adopted in the BIM model. As first the internal partitions such as walls, floors and roofs should have active the local delimitation parameter in order to create the correct thermal zone.

In order to overcome specific losses of information about material stratification a fixing downstream procedure can be adopted selecting in detail the element and checking the assigned material and possibly adjusting the stratification directly in the energy simulation software. If the envelope type is transferred from BIM to BEM, a step forward is to check the integrity of the correct layering of the opaque envelope because material layers with no thermal definition in BIM are lost in the translation. This can occur for example for plaster or some substrate.

The problem can be solved by editing the envelope layering adding or replacing the missing layers with existing materials in the libraries or creating new materials. The adjustment and bug-hunting process is a time-consuming hard task. When the model has been completed in all its parts and the correct link between the various elements has been verified the energy simulation can be successfully performed. The results of the energy simulations have been compared to the energy bills in the last three years to confirm the accuracy and measure the uncertainty of the predictive model referred to actual energy use.

4 Results

Energy simulation of the two case studies have been performed in the four configuration (i.e. two for each case study) simulation the existing situation of the schools, before the retrofit and before the extension.

The predicted energy consumption related to the envelope but also to the thermal plants specifications have been compared with the energy bills collected in the archive of the Seregno Municipality.

The main results of the research is thus to emphasize the potential of the optimization process introduced as methodology that uses BIM data to simulate the building energy performance and can be directly compared to existing actual data with a confidence interval to be estimated. The successfully application of the methodology enables and speed up the process providing reliable results and thus potentially consistent economic feasibility evaluations.

4.1 Energy evaluation of the traditional school

In the case of the "A. Moro" school, which has a traditional layout configuration, the energy gave monthly results according with the actual energy bills although a standard setting of the indoor space has been adopted. The standard setting includes data about internal gains, people density, ventilation rates, temperature set points and time schedule that are derived by commonly adopted value for the traditional building use. The more traditional distribution of school with spaces organized as commonly adopted since 1900 has less discrepancy compared to complex and innovative solutions and thus it can be expected that some parameters could not be equally fitting in the traditional and complex schools of the case studies.

Coming back to the "A. Moro" school, in Figure 5 the comparison between the original version and the retrofitted building is shown. The envelope solutions introduced clearly enhance the thermal behavior in the winter period. It is worthy to note that while the most complex "H. C. Andersen" school required to make conscious alterations to the templates changing from the standard data setting to a specific custom definition, for the traditional primary school no additional tuning was needed to obtain a result with an acceptable percentage gap between simulation and energy bill (Figure 6).

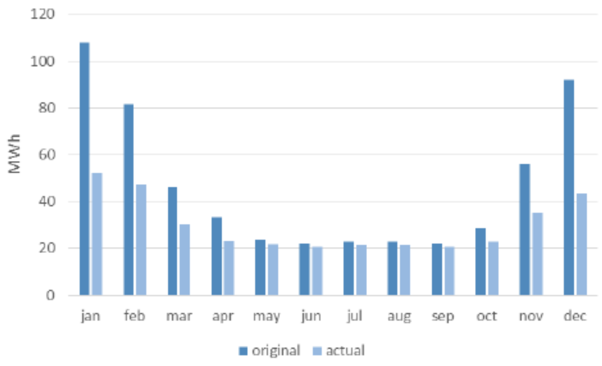


Figure 5. Primary school “A. Moro”: energy consumption simulation of in the original situation and the retrofitted version.

Figure 6. Primary school “A. Moro”: actual energy bills compared to energy consumption simulation and the percentage gap between simulation and real data.

The acceptable uncertainty level is also due to the geometry of the spaces, which inevitably affects their use and also they have been designed with a specific vocation. Actually, the corridor facing the classrooms is not conceived as a place of permanence of the students, it is a simple element of distribution and connection and its size is not exceeding the tolerance of an aggregated energy use and setting. On the contrary, precisely because in the kindergarten "H. C. Andersen" there is neither a need nor an obligation to keep pupils in classes, the school has been designed with a central internal space conceived as a wide circulation space that is also a covered playground suitable for expression of sociality. Consequently the space is constantly used to host the different activities carried out in the school and the children have the possibility to relate with a different space that seem a square or an open space for events with a zenithal daylighting that is far from the traditional enclosed learning space of the classroom. Hence, the configuration of school building should also take into account the specific needs that the different types of pedagogic training require. The school is not indeed a kindergarten however in the setup of simulation and in the assumption the same standards are often supposed.

4.2 Energy evaluation of the complex school

The kindergarten “H.C. Andersen” increased its energy consumption in 2014 when the new section of the school has been realized. In Figure 7 the energy bills and in the original situation (L shaped building) and in the following three years are reported. The average value has been also added as currently adopted procedure to compare energy simulation to actual consumption.

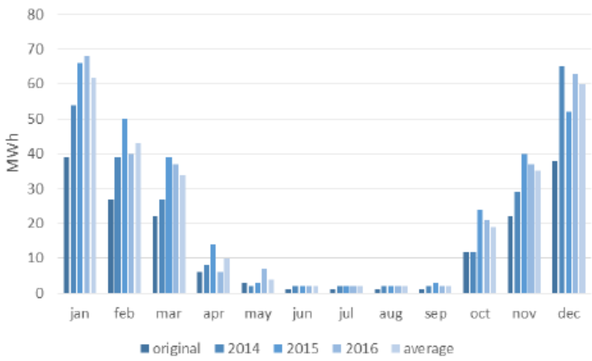
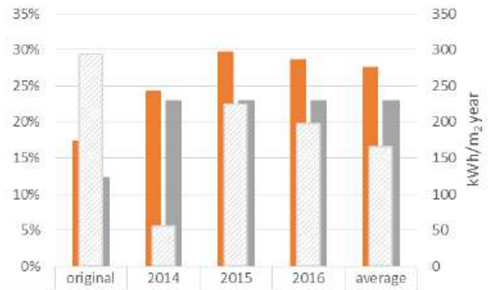


Figure 7. Kindergarten “H.C. Andersen”: energy consumption simulation of in the original situation and during the following three year of operation phase.

The first simulation using the BIM based data has been enriched in the BEM setup with standardized value of people density for the occupancy schedule, nevertheless the particular configuration of the central space defined a different scenario. For that reason the first result diverged from the energy bill of about 40% and therefore a fine tuning of the model have been performed. The standard people density equal to 0.5 people/m^2 adopted for standard school is suitable for classroom spaces however in the complex school case study the central space is used with a lower density that is not comparable to the standard value however educational activities take place. The schedule of use were also re-defined to address this different occupancy rate into the space. Furthermore, a higher temperature compared to the standard value, due to the children presence and the space in which the fan coils are not effective into heating the core part of the school has been established. With this fine tuning procedure and measures the percentage of discrepancy decreased to less than 20% compared to the three years average value of the energy bill (Figure 8). A detailed assessment of users' flow has not been introduced in this stage of the research however could be interesting in future research development. Could be useful to stress that the level of the school and the methods of use are not too flexible, although obviously some uncertainty of the results is linked to the variability of occupant attendance to the classes.



	original	2014	2015	2016	average
energy bill	174.38	243.86	297.19	286.92	275.99
energy consumption	123.07	230.36	230.36	230.36	230.36
percentage gap	29.4%	5.5%	22.5%	19.7%	16.5%

Figure 8. Kindergarten "H.C. Andersen": actual energy bills compared to energy consumption simulation and the percentage gap between simulation and real data.

5 Conclusion

The aim of the research was to explore the possibilities of comparing building consumption directly to predictive models realized through an interoperability BIM2BEM process. The digital twin of the building allows creating an archive of the retrofit interventions and a database for the asset management in the life cycle. The BIM model also permits the transfer of the stored information to other platforms adopted for specific energy assessment and simulations. Through the BIM2BEM interoperability path, an uninterrupted information chain is created generating additional value and ensuring process consistency. By means of predictive models, adjusted and customized during the different phases of the building's life cycle, it is possible to evaluate the design optioneering in an analytical way enabling conscious choices based on results whose accuracy must be verified and double checked.

It is particularly important to give reliability to the process in order to verify the simulation results to critically understand the thermal behavior of buildings. It is very important to ensure the accuracy when approaching existing buildings the need to be upgraded. In fact, the economic feasibility of the retrofit interventions is strictly related to the accuracy of energy savings that can be predicted in the design phase. Too often the energy intervention are not supported by reliable energy calculation and declared NZEB are not NZEB, are not that efficient and the goal is unattended. In the school is also crucial to assure that indoor conditions will be comply with standard comfort level to implement and support learning performance and users' development. Finally, a complete interoperability process needs to be ensured in order to promote reliability and to improve the information management in the BIM2BEM process. The manually implemented part is an adjustment which decreases the level of detail of the BIM in order to reduce the errors in the BEM. This process requires accuracy and simplification not involving crucial elements to assess the thermal behaviour of the building.

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Holonic Management Systems for Resilient Operation of Buildings

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Abstract –

Building management systems monitor and control building performances in real-time. Most control systems, which have been developed in the last decade, achieve the required performances relying on a centralised and hierarchical framework. In the regular operation phase, these systems are usually able to efficiently reach their goals, whereas they often fail to stick to pre-determined targets in the presence of unforeseen disturbances. As a matter of fact, traditional control systems suffer complex unforeseen scenarios that cannot be modelled by the analytics and knowledge integrated in these systems, because hierarchical systems strive to keep full control at any level.

As an alternative, holonic management systems, which have been successfully applied in the manufacturing field, can tackle this type of drawbacks. The flexibility of their elementary units, the holons, makes it possible to avoid the rigid structure of hierarchical systems so as to respond quickly to disturbances and dynamically re-arrange their structure.

In this paper, a first holonic computing structure is developed for indoor comfort management in an office room. The structure developed can drive both the operation management phase and the medium- and long-term measurement of performances. The former is implemented by means of a sequence of specific minimum cost actions which is based on the overall throughput effectiveness (OTE) metrics. The latter exploits the same OTE metrics to suggest corrective and improvement actions. Finally, OTE diagnoses are re-directed to a BIM model to support decision making for long-term improvement actions on the building facility.

Keywords –

Intelligent Buildings, Building Management System, Holonic System.

1 Introduction

Building management is the process of monitoring and controlling the operating systems within building facilities. In the case of indoor comfort control, it includes heating, air conditioning, ventilation and shading units. Most commercial control systems, which have been developed in the last decade, achieve building indoor comfort relying on a centralised and hierarchical framework. Their hierarchical structure is usually made up of the following top-down layers: data acquisition, data transmission, data interpretation, performance evaluation and optimisation [1]. Strict master-slave relationships between layers imply top-down control decision, whereas bottom-up status reporting is implemented [2]. In the operation phase, hierarchical building management systems are usually able to reach their goals in an efficient way and with no faults, whereas they fail to stick to pre-determined targets in the presence of disturbances. In fact, traditional systems cannot pursue the assigned task if any unforeseen events occur. Their rigid structure makes it very difficult to tackle unexpected scenarios. As low-level modules have to consult higher hierarchy levels in case of a disturbance, their reactivity becomes weak. Furthermore, global decision-making is often based on obsolete information [2].

In this paper, a first holonic computing structure based on CPS technology is developed for the indoor comfort management in a room used as an office in a large public building. The operation management is managed by a control based on the measurement of the effectiveness of every device intended as a unit of the system of systems which applies a well-defined sequence of specific minimum cost actions. During simulations, an overall throughput effectiveness (OTE) metrics measures the subsystems' performances and drives corrective actions for their enhancement [3]. Finally, suggestions, history and lessons learnt from the OTE evolutions are re-directed to a BIM model to support decision making for the improvement of the whole building performance and design.

This paper is organised as follows. Section 2 provides a literature review of the holonic approach that was adopted in the present research. Section 3 describes the case research methodology. Section 4 provides a description of the case study. Section 5 shows the simulation results. Section 6 is devoted to conclusions.

2 Literature Review

The holonic concept, which is the basis of holonic management systems, was introduced in 1967 by Koestler [4]to explain the evolution of biological and social systems. Likewise, in the real world, where almost everything is at the same time a part and a whole, each holon can be part of another holon [2]. In fact, the word holon is the combination of "holos", which in Greek means "whole", and the suffix "on", which suggests a part [5], [6], [7]. In the manufacturing field, holons are autonomous and cooperative building blocks, since they can both control the executions of their own strategies and develop mutually acceptable plans [2]. Furthermore, holons consist of an information-processing part and often a physical processing part [2], [5], [6]. The former is responsible for high-level decision making, collaborating and negotiating with humans and other holons, while the latter is a representative of its linked physical component and responsible for transferring decisions and instructions to it [5]. According to Koestler, a holonic system or holarchy is then a hierarchy of self-regulating holons that function (i) as autonomous wholes in supra-ordination to their parts, (ii) as dependent parts in subordination to control at higher levels, and (iii) in coordination with their local environment [2], [4], [7]. Therefore, holonic architecture combines high and predictable performance, which distinguishes hierarchical systems, with the robustness against disturbances and the agility typical of heterarchical systems [6]. In this way, systems' resilience is guaranteed.

The agent, which in latin is "a person who acts", is a software-based decision making unit embedded with internal knowledge. Unlike holons, no such separation of physical and information processing parts exists in agents' structure. Furthermore, whereas holons can themselves be made up of other autonomous holons, agents do not immediately apply the recursive architecture [2], [5]. A multi-agent system is made up of two or more related agents [2], [7].

Cyber-physical systems, in the manufacturing field, are systems of collaborating computational entities which are in intensive connection with the surrounding physical world [8]. The interaction between physical and cyber elements is of key importance to the purpose of this paper. As a matter of fact, cyber-physical systems, similarly to holons, consist of a cyber part and a physical part. This shared feature makes holonic paradigm a suitable approach for constructing and modelling a CPS system in the form of a holarchy. Therefore, on the one hand, a CPS system permits bidirectional coordination of virtual and physical levels and, on the other, the holarchy, with its flexibility, guarantees evolutionary self-organisation or, in other words, resilience [5]. Moreover, CPS systems provide an opportunity for changes in the physical structure to be captured and reflected in the virtual model. Conversely, changes in the virtual model can be communicated to sensors embedded in the physical world [9], [10]. To implement these concepts in real world applications, agents are key enablers, since they act as decision-making and communication entities with agents embedded in other holons and also humans [5], [6]. Holonic management systems, which have been successfully applied in the manufacturing field, can constitute a novel technology to tackle unforeseen scenario variations. Indeed, the autonomy and cooperation of their elementary units, the holons, makes it possible to avoid the rigid structure of hierarchical systems and therefore respond quickly to disturbances [2].

3 Research Methodology

The holonic computing structure developed in this paper involves three development environments, Matlab®/Simulink®, SQL and Revit® (see Figure 1). The Revit® environment concerns the BIM Digital Model (BIM DM, see Section 3.2), as the interface of one of the numerous BIM softwares available on the market, such as Autodesk® Revit®. The Matlab® and SQL environments share the Decision Support Tool (DST, see Section 3.3), which has the function to assess the system of systems' effectiveness and suggest a list of possible corrective actions.

In addition to the DST, the SQL environment involves the BIM Relational Model (BIM RM, see Section 3.2), i.e. a relational database that acts as a bridge between the DST and BIM DM and has a double function. The first function is to update the DST when the BIM DM changes. The second one is to store effectiveness data received from the DST to run building diagnoses. The BIM RM and BIM DM exchange data in both directions, thanks to the Revit® DB-Link plug-in. In this way, the SQL and the Revit® environments are connected.

The Matlab® environment consists of the Supervision Policy (SP, see Section 3.4), the Virtual Simulation Laboratory (VSL, see Section 3.1) and the

DST block.

The measures taken from the VSL provide feedback (delayed by 1 step in order to be realistic) for the decision support tool. The DST evaluates and updates the OEE of each cell by means of SQL queries, then it updates the OTE in all the system's tree and suggests a list of possible actions to the Supervision Policy. Among the actions suggested by the DST, the Supervision Policy selects and applies the one to be carried out in the Virtual Simulation Laboratory based on some internal logic/intelligence.

In Figure 1 all these entities and their relationships are depicted.

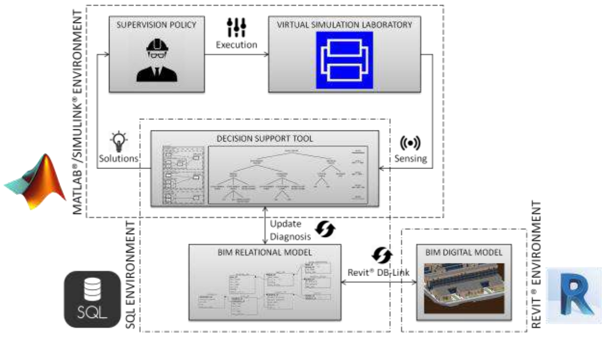


Figure 1. The architecture of the holonic computing structure developed based on CPS technology.

The holonic computing structure developed and implemented by integrating Simulink®, SQL and Revit® environments makes it to carry out any type of desired simulations away from the site.

3.1 Virtual Simulation Laboratory

The Virtual Simulation Laboratory is in charge of replacing and emulating the real building by using a detailed building model. This model was developed in the Dymola® programming environment, which is based on the Modelica® Language. Traditional simulation tools for thermal modelling are usually domain-dependent modelling environments. Whereas, Modelica® brought in relevant innovations allowing for equation-based modelling using program-neutral model description, domain-independent solution methods and the capability of exporting models as Functional Mockup Units (FMU).

The building model used in this work is built upon the open-source Modelica® "Buildings" library [11] and it has the level of detail that is necessary to analyse the behaviour of each device and sub-system belonging to the building. For the purpose of this paper, but without loss of generality, a model of the building restricted to the third floor is considered. However, a preliminary comparison of the comprehensive model with the one restricted to the third floor showed negligible differences. The model was then translated and compiled as a FMU so as to be embedded in the VSL through the Functional Mockup Interface (FMI).

By exploiting the capability of the FMI Kit for Simulink®, provided with Dymola® 2018, the VSL was integrated in the cyber physical system depicted in Figure 1 as an FMI block in co-simulation mode. The selected control inputs for the VSL are three actuator inputs normalised between 0 and 1: the shading level (SL), the fan coil level (FCL) and the window level (WL). The variables measured are both from indoor and outdoor. Indoor measures taken from the controlled room are: air temperature, relative humidity, CO_2 concentration, cooling power, AHU air flow rate, number of people. Outdoor measures are collected by a weather station included in the VSL which provides: air temperature, relative humidity, barometric pressure, wind speed and solar radiation on the horizontal plane.

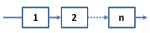
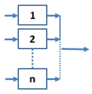
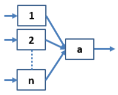
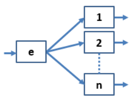
3.2 BIM Relational and Digital Model

In this paper the BIM Relational Model and BIM Digital Model are two sides of the same coin, the practical and the formal side, respectively. The BIM DM of the building under analysis was developed using Autodesk® Revit® and then translated into its congenital relational structure, namely the BIM RM. Hence, the BIM Model works as a repository of any types of data that belong to the building analysed.

The connection BIM RM-DST, as mentioned, provides the opportunity to define and update the scheme of the DST after changes to the building. In addition, the same link provides, in the other direction, the possibility of auto-diagnosis of the holonic management system developed. Actually, the BIM model becomes a repository of the facility history or of the potential actions of improvement concerning the building. Indirectly, a bi-directional communication channel is set up, i.e. a learning phase of the VSL from the BIM repository and the storage of real-time data from VSL into the BIM model.

In order for this to happen, the relational potential of the BIM has to be fully expressed. The underlying BIM representation of the information can be leveraged and further extended to create a mapping between a relational database. Note that the full Relational Model (RM) is intended in the sense described in [12]. In the RM everything is a relational variable (*relvar*). Tables, attributes and database schemas cannot usually be operated relationally. In current SQL-based database management systems (DBMS), these operations are implemented with non-standard host language proprietary extensions for the specific DBMS implementation. By a homomorphic mapping between

Table 1. OTE metrics computing formulas in recursive form adapted from [13].

Interconnection type		OTE of parent holon	R_{th} of parent holon	Q_{eff} of parent holon
Series		$\frac{\min\left\{\min\limits_{i=1,\ldots,n-1}\left\{OTE_i \cdot R_{th,i} \cdot \prod_{j=i+1}^{n} Q_{eff,i}\right\}, OTE_n \cdot R_{th,n}\right\}}{\min_{i=1,\ldots,n}\left\{R_{th,i}\right\}}$	$\min\limits_{i=1,\ldots,n}\left\{R_{th,i}\right\}$	$\prod\limits_{i=1}^{n} Q_{eff,i}$
Parallel		$\left(\sum\limits_{i=1}^{n} OTE_i \cdot R_{th,i}\right) \Big/ \sum\limits_{i=1}^{n} R_{th,i}$	$\sum\limits_{i=1}^{n} R_{th,i}$	$\frac{\sum\limits_{i=1}^{n} Q_{eff,i}}{n}$
Assembly		$\frac{\min\left\{\min\limits_{i=1,\ldots,n}\left\{OTE_i \cdot R_{th,i} \cdot Q_{eff,a} / k_{a,i}\right\}, OTE_a \cdot R_{th,a}\right\}}{\min\left\{\min\limits_{i=1,\ldots,n}\left\{R_{th,i} / k_{a,i}\right\}, R_{th,a}\right\}}$	$\min\left\{\min\limits_{i=1,\ldots,n}\left\{\frac{R_{th,i}}{k_{a,i}}\right\}, R_{th,a}\right\}$	$\frac{\sum\limits_{i=1}^{n} k_{a,i} Q_{eff,i}}{\sum\limits_{i=1}^{n} k_{a,i}} Q_{eff,a}$
Expansion		$\frac{\sum\limits_{i=1}^{n} \min\left\{R_{th,e} \cdot OTE_e \cdot k_{e,i} \cdot Q_{eff,i}, R_{th,i} \cdot OTE_i\right\}}{\sum\limits_{i=1}^{n} \min\left\{R_{th,e} \cdot k_{e,i}, R_{th,i}\right\}}$	$\sum\limits_{i=1}^{n} \min\left\{R_{th,e} \cdot k_{e,i}, R_{th,i}\right\}$	$\frac{\sum\limits_{i=1}^{n} k_{e,i} Q_{eff,i}}{\sum\limits_{i=1}^{n} k_{e,i}}$

the BIM and its relational representation, we obtain the opportunity to develop new structured types that make it possible to record relational information and data. For example, in a BIM entity, it is possible to completely record the real-time history of parts of the building equipment as obtained from sensors. Moreover, it is also possible to record a tracking of the BIM structural changes over time. With data mining, knowledge extraction and representation techniques, some information can be grown upon, enriched, and a reasoning system can be integrated into the relational model of the building. This allows us to make BIM the core of short-term control and medium- and long-term design evolutions and adaptations on the building endowed with intelligence.

As a first experiment, the best available technology on DBMS has been used as a proof of concept. In order to interact bi-directionally with the BIM, the building digital model has been mapped to an SQL Server DBMS using the Revit® DB-Link plug-in. It permits the flow of information between Autodesk® Revit® and the DBMS in both directions. In this way BIM is updated with changes applied from the reasoner or the controller, and receives the real-time data from the virtual or physical models or the sensors. A workaround to the limited relational possibilities has been temporary created by extending some of the basic elementary BIM attributes with a numeric type that creates a primary key to some relations that can store real-time data tables or even a complete (nested) database schema.

3.3 Decision Support Tool

The operation management, as anticipated, is led by a pervasive control of the effectiveness of the system of systems. In other words, during simulations, an overall throughput effectiveness (OTE) metrics measures the subsystems' performances and drives corrective actions towards their improvement [3].

The distributed performance metrics, inherited from the manufacturing field, defines the overall factory effectiveness (OFE), the overall throughput effectiveness (OTE) and the overall equipment effectiveness (OEE). These parameters, whose values are between 0 and 1, are effectiveness indexes referring respectively to the highest level, intermediate levels and the lowest levels of a system's performance. The OEE metrics of one of the lowest production equipment is defined as follows:

$$OEE = A_{eff} \times P_{eff} \times Q_{eff}, \tag{1}$$

where the availability efficiency A_{eff} captures the deleterious effects due to breakdowns, the performance efficiency P_{eff} captures productivity loss due to reduced speed, idling or minor stoppages, and, finally, the quality efficiency Q_{eff} captures loss due to defects [3]. Subsequently, by applying the formulas in Table 1, the effectiveness of every system's cells is determined.

Note that OTE is a recursive function of OEE. This means that OTE is equal to OEE at the leaves of the recursive system's tree. OTE expression depends on four fundamental types of interconnection structures: *series*, *parallel*, *assembly* and *expansion*. In Table 1 we adapt the formulas and the structures from [13] that determine the four kinds of interconnection.

The parent-children relationship affecting elements located at different levels of the system is explained focusing on the assembly that is associated to the active thermal source (see Figure 2 and Figure 3). Once the OEE of the "children" fan coil unit (FCU), shading (SHA) and *assembly* cell (a_{ATS}) are defined, the OTE of the "parent" active thermal source is calculated using the *assembly* formula in Table 1. This is the procedure by which the whole systems tree is compiled with OEE/OTE values. Afterwards, by means of the Event-Condition-Action (ECA) calculation model described in [3], the DST provides, for each iteration, a list of suggested corrective actions.

The development of the structure of the DST follows two necessary and practical steps. The first one consists in defining the system's scheme with semantics. It could be defined as the closest representation to the humans' way of thinking (see Figure 2). Subsequently, the previous scheme is translated into the system's tree, defined, conversely, as the closest representation to the computing structure (see Figure 3). The system's tree shows the reconfigurability, scalability and robustness typical of holarchies, in other words, resilience. Indeed, it can be adapted to environment changes. At any level of it, the tree instance can be changed or dynamically reconfigured on purpose.

Both the system's scheme in Figure 2 and that in Figure 3 are made up of *cells* (the leaves of the tree) whose semantics is described as follows:

- TC: thermal conduction affecting external room's partitions;
- FCU: fan coil as a piece of equipment that is able to provide a cooling power;
- SHA: shading as a device that is able to reduce solar radiation, providing a fraction of it;
- LEA: air leakage through external room's envelope;
- WIN: window as a piece of equipment that is able to provide a moisture content variation and air flow;
- AHU: air handling unit as a piece of equipment that is able to provide a moisture content variation and air flow;
- a_{ATS}: room's mixing capacity of cooling power from thermal sources, function of room's shape and whose specific proportion is defined by k;
- a_{TS}: room's mixing capacity of cooling power from thermal sources, that is a function of the room's volume and whose specific proportion is defined by k;
- a_{HS}: room's mixing capacity of moisture content from humidity sources, function of room's volume and whose specific proportion is defined by k;
- ACR: air change rate defined by the amount of fresh air flowing in the room and its volume.

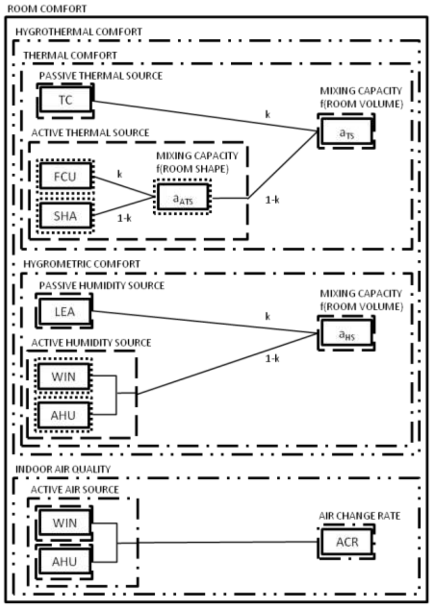


Figure 2. System's scheme developed for the case study.

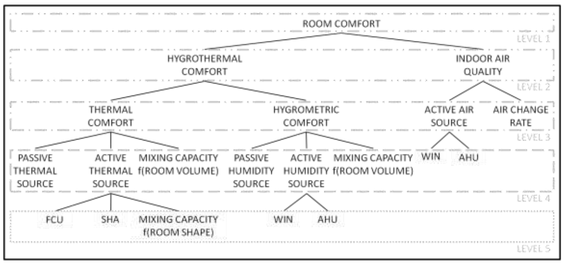


Figure 3. System's tree developed for the case study.

3.4 Supervision Policy

The Supervision Policy (SP) represents an intermediate step between the DST and the VSL (see Section 3.3and Section 3.1) whose function is similar to the one of a manager. Indeed, this entity selects, among the actions suggested by the DST, the action to carry out or leaves the status unchanged (no action). Hence, the SP defines the criterion by which the system acts or does not act. In addition, this "manager" has the ability to learn from the past (i.e. from the BIM, see Section 3.2). The effects obtained during the previous days suggest confirming or changing corrective actions.

In the simulations discussed in Section 5, the policy assumed for short-term operation management sets:

- high priority to thermal comfort (achievable by means of shading closing/opening and fan coil unit power on/off), average priority to indoor air quality (achievable by means of window opening/closing) and low priority to hygrometric comfort (achievable by means of window opening/closing). This means that, if actions are suggested for each sub-system, the first action field is thermal comfort, the second one is hygrometric comfort and the third is indoor air quality. This assumption does not imply that a field action is less important than another one, since the time step of each iteration is short (i.e. 5 minutes);

- higher priority to shading closing than fan coil unit power on and higher priority to fan coil unit power off than shading opening, in order to pursue thermal comfort according to energy saving principles;
- that a lower-priority action will be carried out in the following iteration if the related low performance persists;
- that if a higher-priority action is already running, the selection skips to the lower-priority one;
- that if more than one action for the same sub-system is suggested, the highest gain action is selected.

4 Case Study

Eustachio is the building where the Faculty of Medicine of the Polytechnic University of Marche, Ancona, Italy, is located. This is a large and multi-purpose building composed of two main blocks that create a clear division between the main fronts: the north and the south ones. It is equipped with a traditional building management system (BMS). The heating system is a two-pipe type and the air-handling system serves the north and the south fronts separately. Consequently, the building has some symptomatic discomfort problems like, for example, too high temperatures during winter, too low temperatures during summer, while mid-season temperatures are out of control.

In this paper, the focus is on one office room (i.e. room no. 90), located on the third level of the south front and used as an office (Figure 4). Its net surface is approximately 19 m^2 and the three-module window is about 7 m^2 large, with one module operable. The air handling unit in room no. 90 causes just air recirculation, since the humidifier does not work. The fan coil unit is a FC200 type and, for the purpose of the paper, only its cooling function in the summer season is considered. In addition, a shading system is also included. The actual BMS manages the cooling phase triggering both the fan coil unit and the shading device at the setpoint temperature of 26 °C.

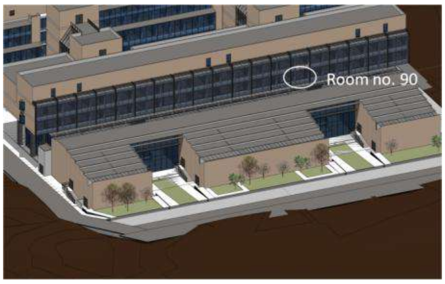


Figure 4. Room no. 90 in a 3D view of the Eustachio building's BIM digital model.

5 Simulations Results

The holonic management system, described in this paper is experienced for the month of June 2016. In this period, weather data define really dynamic boundary conditions able to strongly urge the system. The simulations for this representative scenario aim to prove the system's ability to perform short-term operation management in real time and diagnoses of building with regard to medium- and long-term refurbishment. Such diagnosis ability differentiates the holonic management system at issue from common BMS.

5.1 Operation Management of Building

The holonic management system accounts for building operation, regulating shading level (SL), fan coil level (FCL) and window level (WL) towards indoor comfort. In other words, it can put into practice instructions from the DST, i.e. suggested actions to reach system's improvement, according to the supervision policy (see Section 3.4). Although simulations were carried out for the whole month of June, in this paper only the simulation results of one day are discussed. The following charts show simulation results for the 17th of June. When operating temperature T_{op} exceeds the setpoint T_{set} (see Figure 5.a), the system reacts at first by closing the shading (see Figure 5.b, SL = 0.900) and then switching on the fan coil unit (see Figure 5.e, FCL = 1.000). The shading remains closed longer, giving priority to fan coil unit power off, according to the supervision policy aiming to save energy. When indoor relative humidity RH_i is far from the setpoint RH_{set} and, at the same time, outdoor relative humidity RH_o can help to improve it (see Figure 5.b), the system reacts by opening the window (see Figure 5.f, WL = 0.056). Finally, the system reacts to room overcrowding, which causes too high CO_2 concentration (see Figure 5.c), by opening the window (see Figure 5.f, WL = 0.112).

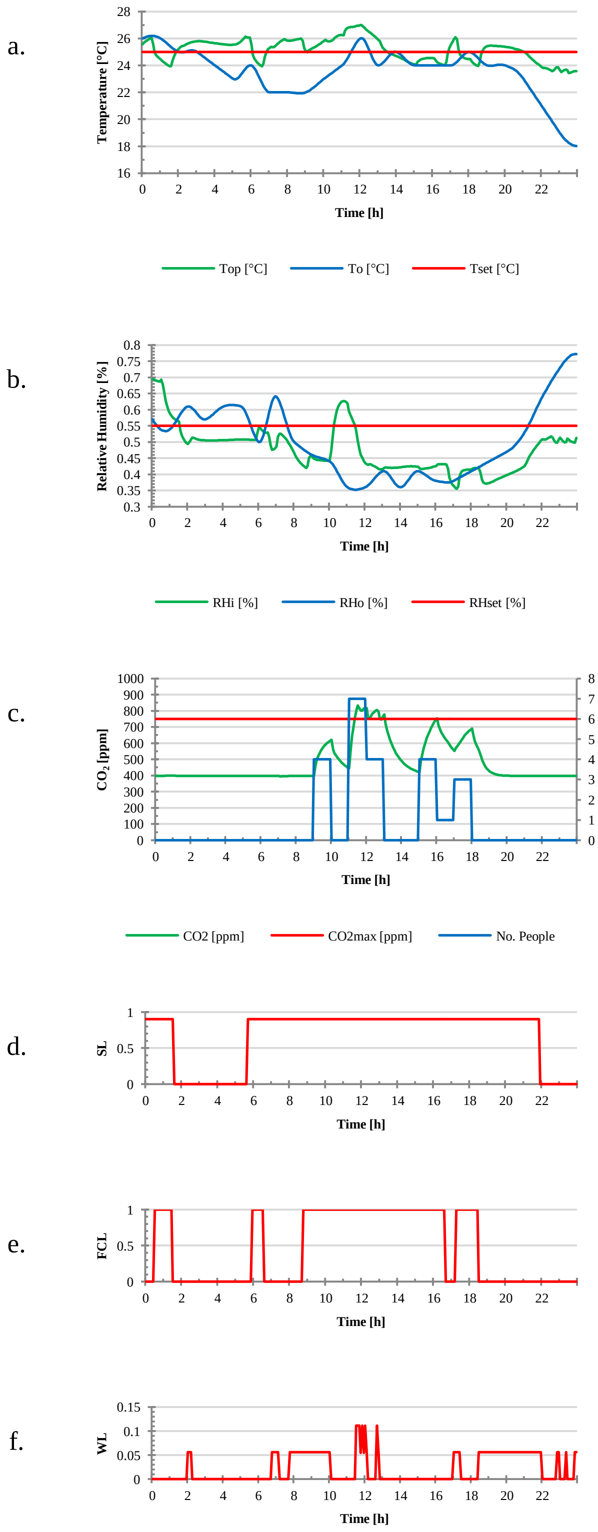


Figure 5. Operation management results for the 17th of June. Trends of a) temperature, b) relative humidity, c) CO_2 concentration vs number of people inside room no. 90, d) shading level (SL), e) fan coil level (FCL) and f) window level (WL).

5.2 Diagnosis of Building

The holonic management system makes it possible to carry out diagnoses on buildings by focusing on the system of systems' and cells' effectiveness mean value. In fact, BIM RM (see Section 3.2) can:

- store system of systems' time data, such as OTE/OEE time values, creating a repository of the facility history;
- store and re-direct their mean values, which are continuously updated according to the last iteration, to the BIM DM (see Section 3.2) in order to visualise them inside Revit® environment (e.g. during refurbishment design of building).

Low mean values of OTE and OEE highlight entities that cannot pursue the assigned target towards room comfort. Figure 6 shows OEE monthly mean values (June 2016) for the system's *cells* (the leaves of the tree) whose semantics is described in Section 3.3. The histograms point out the highest effectiveness of Indoor Air Quality sub-system. In fact, the room assumed as case study has a good air change rate (OEE_{ACR} = 0.90) and window ($OEE_{WIN(IAQ)}$ = 0.76) and air handling unit ($OEE_{AHU(IAQ)}$ = 0.86) ensure a satisfactory ventilation in June. Whereas, the room's external partitions are not effective in terms of thermal conduction (OEE_{TC} = 0.16) for indoor thermal comfort, since they are made of glass and metal. The shading (OEE_{SHA} = 0.19) and fan coil unit (OEE_{FCU} = 0.32) show possibility of improvement, since the former can be extended to the whole glass façade (both the transparent and the glazed part) and the latter can be boosted up. Results about hygrometric comfort point out how the window ($OEE_{WIN(HC)}$ = 0.67) and air handling unit ($OEE_{AHU(HC)}$ = 0.62) ensure a good enough contribution to optimal indoor relative humidity and room's external partitions are not effective, because of air leakage (OEE_{LEA} = 0.34).

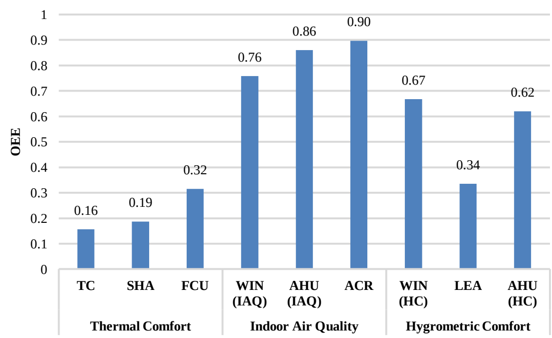


Figure 6. OEE monthly mean values (June 2016).

6 Conclusions

The holonic computing structure, which involves Matlab®/Simulink®, SQL and Revit® development environments, is experienced in a room used as an office. This computing structure works in two directions, the short-term management of building operation and the medium- and long-term diagnoses and refurbishment. In fact, the system shows its ability to reach a target, managing different parameters and devices and following an agreed policy. Besides, the connection of the above mentioned environments ensures diagnoses of buildings based on data history regarding system of systems' effectiveness.

7 References

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Integrated Digital and Model-Based Construction Logistics Management Based on Lean Thinking Approaches

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Abstract –

As an elementary part of building projects, construction logistics encompasses planning, control and monitoring functions to ensure the flow of materials and people on the construction site. Furthermore, it includes the management of storage areas and site facility planning. Despite its importance, the implementation of construction logistics often does not occur systematically. In practice, the project phases in which its planning and implementation take place as well as the considered degrees of detail differ significantly depending on the project conditions, such as the projects' complexity, involved stakeholders or the scope of the construction project.

In this paper an approach is presented that facilitates a systematic and holistic planning of construction logistics over all project phases on basis of lean construction principles. To achieve this, the coordination of all domain-specific stakeholders (e. g. construction logistics planners, site managers, contractors) is essential. As a work basis, construction logistics planners can create a specific digital construction logistics model (CLM) derived from the digital architectural model. This CLM can be used to schedule deliveries and storage areas, as well as logistics related information (e.g., delivery dates, storage areas, escape routes, waste collection points or construction site equipment elements).

Construction logistics has to be generally accepted as an own domain-specific role during and especially in the beginning of construction projects to ensure the regarding of all necessary processes and requirements towards the construction logistics.

Keywords –

BIM; Construction Logistics; Domain-Specific Model; Lean Construction; Lean Logistics;

1 Introduction

A way to optimize processes is to use the methods and tools of the Lean Thinking (LT) approach. Their application allows the optimization of processes aiming at minimizing waste and increasing efficiency. By this approach, an optimally use of resources is facilitated. In order to switch from the conventional to a LT-based working method, an analysis of the processes as well as economic and technological aspects have to be carried out first. The approach of adapting LT methods to the construction industry has been investigated since the early 1990s. For this purpose, the International Group for Lean Construction (IGLC) was founded in 1993 [9]. Although this process of implementing LT in the construction sector has been going on for nearly 30 years, it is only applied in a minority of projects. Recent studies pointed out that the application of the Building Information Modeling (BIM) methodology can facilitate the implementation of Lean Construction (LC). The thereby rising synergies can lead to the generation of a significant additional value [13].

This paper examines the construction logistics as one crucial part of construction projects in the context of the interaction between BIM and LC. It is based on the results of a master thesis [10] written at the Institute of Numerical Methods and Informatics in Civil Engineering (IIB) at Technische Universität Darmstadt. It forms a starting point for further research. The overall goal of this future work is to investigate how the holistic integration and linkage of both approaches over all project phases can improve the projects' results as well as facilitate a more cooperative way of interaction between all stakeholders.

Due to the high demands towards construction logistics, construction projects in densely built-up areas are regarded as a field of application; Resulting constraints are, for example, the limited amount of space available inside and outside of buildings or the tense traffic situation in the surrounding area of the building site. According to [17] "Interruptions caused by breakdowns, clean-up and rearrangement, material search, ways and transports" cause a share on all activities of 33.4%. Optimization of construction logistics can thus contribute to cost reduction, improved adherence to deadlines and, in general, to improving the organization of construction sites.

2 State of the Art

2.1 Building Information Modeling

The Building Information Modeling methodology is applied more and more frequently in construction projects. Furthermore, steps towards the implementation of a legal framework for the public sector in Germany are made. According to [6], BIM should be considered and applied in all public infrastructure projects in Germany from 2020 on. Pilot projects, such as mentioned in [16], have already been planned and implemented according to this methodology. As one main type of output of the BIM methodology building models serve the purpose of digital information management on which, for example, simulations, clash detection checks (between specific domain models) or visualizations can be performed.

On the part of the executing companies, the benefits of this methodology are increasingly recognized (in particular as a data basis for later operation, e.g., Facility Management) and specialized working groups are set up in companies like Strabag, Hochtief or Zechbau. By linking to tendering programs or scheduling software the automation of processes is facilitated and thereby quality can be improved and costs reduced.

2.2 Domain Models and Level of Development

In literature, several concepts to define and classify domain-specific models are outlined. According to [12], a domain-specific partial model is a trades-specific model that contains all information provided and required by a planner. These sub-models can serve, for example, as basis for the coordination of issues regarding different trades like clash detection issues. Depending on the stored information, a distinction is made between the BIM dimensions 3D (geometrical data), 4D (3D + Dates), 5D (4D + Costs), 6D (5D + Life Cycle Data) and 7D (6D + Facility Management Data). In general, these models can be understood as nD-models which can be extended by any kind of information needed within a specific domain or project. [2] states that sub-models differ in their domain (specialist perspective), zones (spacial structure), degree of detail and phases (period of observation). In this paper, a domain-specific model is classified according to the requirements defined in [15]. It distinguishes between Level of Geometry (LoG), Level of Information (LoI), Level of Coordination (LoC) and Level of Logistics (LoL). In the following, the contents of a specialized Construction Logistics Model (CLM) are described in more detail on the basis of the LoL. The LoL reflects the spatial and temporal development level of the logistics processes. All components of the digital building model are put in a temporal and local context with regard to their delivery to the site and their assembly.

2.3 Lean Thinking

One approach to optimize processes and thereby workflows is the adoption of Lean Thinking - including the underlying principles and tools - to the construction industry, known as Lean Construction. LC focuses on the value created from the perspective of the client; by means of continuous optimization and the reduction of waste, the proportion of value-adding activities is to be maximized.

Lean ideas have so far not been applied uniformly to building projects. A major problem with current construction projects is still the waste of various resources and their uneconomical handling. Nonetheless, there are examples from the residential and office construction sector in which the use of lean methods (Takt planning, Takt control, process optimization) led to the minimization of waste and an increase of the cost-effectiveness [7].

2.4 Construction Logistics

Construction logistics as an integral part of the value chain of construction projects must be planned, controlled and managed carefully. In the implementation of large-scale projects, it is already frequently involved in early project phases [16]. In small and medium-scale construction projects, on the other hand, it is often not taken into account until late or even not at all. In contrast to other disciplines, it is not always perceived as an important and independent component of construction projects.

This so far low prioritization of construction logistics, but also its increasing importance, is reflected in the German Official Scale of Fees for Services by Architects and Engineers (Honorarordnung für Architekten und Ingenieure, HOAI), for example. Until 2011, there was no basis for billing the services of construction logistics in Germany, as the HOAI does not include a service profile for the technical planning of construction logistics. This was first made possible by the introduction of [1].

3 Building Information Modeling and Lean Thinking

As recent researches show, overlaps between the two approaches of Building Information Modeling and Lean Thinking can be found on various tiers. Figure 1 illustrates an excerpt of them. Synergies arise which can lead to improvements in a variety of use cases [14].

On an abstract level, both approaches contain principles that complement and can be combined with each other. At the company level, tactical management must already work towards implementing both approaches throughout the company. There are also major overlaps in the objectives of BIM and LT.

At the operational level, project management based on LT and using the BIM methodology must be implemented. Practically, this can be done with different tools. The concept of the Lean Construction Logistics Management, described in the following chapters, covers one part of this topic. Further information and general considerations on the linkage of BIM and LT and the resulting increase in value in construction processes can be found, e. g., in [11], [5], [13] or [3]. Most of recent studies are focusing on the investigation of these synergies on an abstract and theoretical level. The research at IIB has the goal to investigate approaches that promote a holistic implementation of LC and BIM in practice by the example of construction logistics.

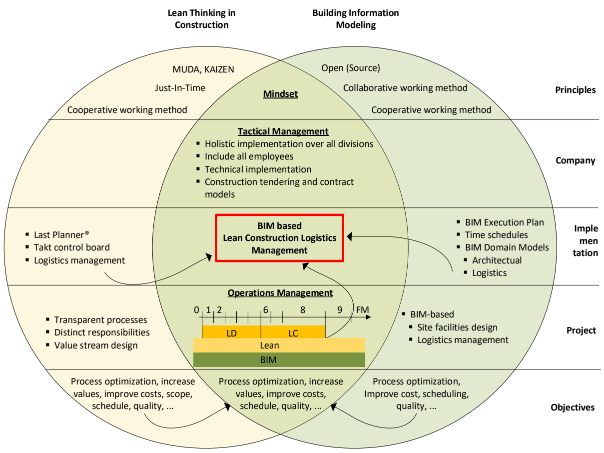

Figure 1. Synergies between Building Information Modeling and Lean Thinking

4 BIM-based Construction Logistics as Part of a Holistic Lean Construction Implementation

For a holistic implementation of the LT approach in construction projects, acceptance by all project participants as well as an implementation in all disciplines and across all project phases is a prerequisite. For this purpose, different tools and methods of LC are suitable.

The types of waste in the construction industry illustrate the importance of construction logistics. For example, the reduction of material stocks, waiting and transit times or the most efficient use of space offer great potential for optimization.

This paper therefore shows an approach for a BIM-based planning and implementation of construction logistics and gives examples for where to increase the value in construction processes in accordance with LC.

4.1 Structural Implementation

Shortly after project initiation, the project management has to consider the role of construction logistics. Only this early integration allows a holistic integration of construction logistics. In addition, all disciplines involved must be taken into account in logistics planning. From the development of the first planning concept and the known constraints, the development of a basic logistics concept can be started. Such a concept must be coordinated with the construction management processes and dependencies as well as with the implementation of LC. It is then worked out and refined over the further project phases.

Construction logistics must also be taken into account in the subsequent project phases. For example, construction logistics services must be subcontracted, which requires a contract specification. In particular, it must define a lean-based implementation. For example, suppliers and contractors need to know that they have to coordinate their production and assembly on site with a clocked schedule and change over to Just-In-Time (JIT) delivery and assembly.

In the execution phase, construction site management must be able to monitor and control the implementation of planning on the construction site. In addition to the implementation of lean methods and tools, a prerequisite for this is the provision of all necessary information.

4.2 Information Management

As in all other spheres of construction projects, comprehensive and well-structured information management is essential for construction logistics. According to the LC approach during all project phases

- the right recipient needs
- the right information
- in the right quality
- at the right time
- in the right scope.

Table 1 gives an overview with examples of information that arise in the context of construction logistics and must be linked to a digital building model. For example, the scope described in [1] can be used as the basis for identifying the relevant information. In section 5, a concept is presented which describes the data storage of all building-related information in a specialized model for construction logistics. Appointments, costs and other types of information (e.g. communication) must be linked to this.

Table 1. Examples of construction logistics specific information according to project phases based on [1]

HOAI phase	Information
1	Available space (property), Transport Connections, Neighbourhood restrictions
3	Building logistics concept: presentation of personnel, machinery, material and waste streams
5	Traffic concept, construction site equipment after construction phases, storage areas for supply and disposal, operating areas

4.3 Logistics Stages and Storage Area Management

Considering construction logistics, it is possible to diversify into the logistics processes up to the construction site (supply logistics), on the construction site (construction site logistics) and away from the construction site (disposal logistics).

The processes up to the construction site include transport, transhipment and storage (TTS). The transport can be optimized, for example, by delivering according to the requirements of the construction site (JIT) and operating interim storage facilities (e.g. logistics hubs).

Logistics away from the construction site consisted mainly of waste disposal processes, since in contrast to stationary industry the distribution of goods is not necessary. Here, new structures are needed on the construction site that enable the waste to be collected and disposed of in an orderly manner. In this way, disposal costs can be reduced, recyclable materials can be reused more efficiently and, in general, the construction site can be kept tidy.

Looking at the logistics processes on the construction site, in addition to receiving and distributing goods, storage area management can be identified as a key competence for a smooth and undisturbed construction progress. Due to limited space on the construction site and in the building itself, these must be planned efficiently and depending on the construction process. For this, detailed phase plans must be worked out, which locate the individual storage areas over the course of the construction process. Additional marking of the storage areas reduces search times and a pre-planned placement of these can reduce travel times. Corresponding requirements for the characteristics of the storage areas must be taken into account in advance. A software concept is presented in section 6.

5 Approach

The approach presented in this paper aims towards the development of an innovative and holistic implementation for planning, controlling and execution of construction logistics over all project phases. Thereby, the early integration of construction logistics in building projects shall be facilitated. As mentioned in chapter 1, in this paper first considerations are presented to serve as a basis for further and more profound research.

The focus lies on a construction logistics model, which is derived from an architectural building model. Besides the geometry and semantics of the underlying model, this CLM encompasses all information concerning construction logistics presented in chapter 5.1. According to the BIM methodology, the CLM must be created in an early project phase and then maintained over all subsequent project phases.

For enabling logistics planners, site managers and suppliers to work with this CLM, a software tool needs to be provided that extends existing software applications. One of its tasks is providing the opportunity to create relations between the building model and the construction logistics schedule. Especially construction site supply and disposal as well as storage and transport operations on the construction site have to be taken into account in this context. This application serves as a central construction logistics information management system and is extended by a digital storage area management.

Figure 2 shows the scope of the concept called Lean Construction Logistics Management (LCLM) introduced in this paper. In the following sections the relations between scheduling, construction logistics and the CLM are presented.

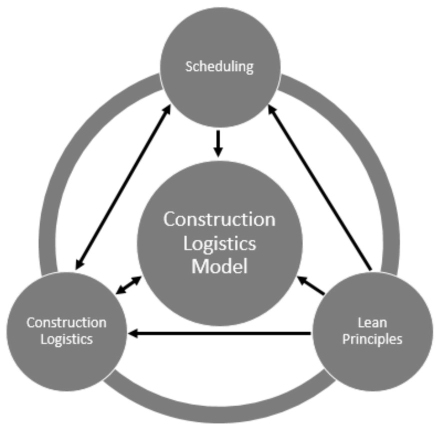

Figure 2. Overview of the LCLM Concept

5.1 Construction Logistics Model

5.1.1 Components

The CLM contains a large amount of geometric and semantic information. Besides the building itself, geometric information include site boundaries, additional floor plan information and object geometries. In addition, the model can have geometric information about the construction site equipment with storage areas, assembly areas and traffic routes. The object geometries include the components to be stored, construction aids and construction equipment.

In addition to these geometric representations and information, various semantic information is necessary for the construction logistics planning. Information about routes, costs and time connections are needed. In addition to construction roads, the routes include pedestrian routes and emergency escape routes. In the inner city environment, the area around the construction project should be included in the logistics planning for delivery. A detailed environment or city model can be used for this purpose. In addition, a logistics hub can be designed in advance if required.

All this information forms the basis for optimizations based on calculations and simulations. For example, the optimization of routes facilitates a reduction of way distances and travel times. Equally, an optimal use of the available space leads to more efficient storage and material distribution and, in general, a tidy construction site.

5.1.2 Requirements

In addition to the geometric and semantic components of the domain-specific model, there are further requirements that are important for construction logistics. For an integral planning of construction logistics, which takes into account the entire progress of the project, it is necessary to link the individual components with the corresponding (logistics) processes from schedule planning. This approach allows the planning to be adapted to the construction process and thus possible conflicts can be avoided.

There are also requirements regarding the information to be stored. These must always be available in the correct level of detail. The most important information includes details on measurements, materials and equipment. The dead weight, transport weight and dimensions are essential. Building geometries and storage areas must also be described in sufficient detail.

Depending on the specialist discipline, other domain-specific models must be included in the planning of construction logistics. For example, geometric framework conditions may exist from the HVAC or carcass construction.

5.1.3 Model Uses

After the comprehensive creation of such a specialized CLM, it can be used in different ways. On the basis of the partial model, collision checks can be carried out with other specialist models in order to detect collision points (paths, areas, dimensions) in planning and to work out countermeasures. Corresponding collision checks on the transport route to the installation site are mandatory.

Furthermore, digital planning methods can be used to carry out a storage area management system that improves the construction process and tidiness on the construction site. Efficient storage space management minimizes travel and search times. The digital planning also enables the control and management of construction logistics. Based on the stored information, a digital construction logistics manual and phase plans can be derived. By linking it to scheduling, simulations can be executed and multiple scenarios evaluated. To examine the flow of goods on the construction site and to control it, the model can be combined with a goods control system, extended by the time component. By using a goods control system, all goods receipts (inbound deliveries) can be checked and logged. This serves for documentation and quality assurance. The use of RFID technology has already proven to be a common practice in (construction) logistics.

5.1.4 Project Context

Information management plays a crucial role in the execution of projects throughout all project phases. In order to ensure a smooth and trouble-free project flow, principles of collaboration and project standards must be agreed upon. As digitalization in the construction industry progresses, contracts must also be adapted and expanded. Common practice is the definition of BIM-related content, such as roles and stakeholders involved, use cases, information exchange, software to be used, etc., in a BIM Execution Plan (BEP). On the part of the client, Employer's Information Requirements (EIRs) are drawn up. These should be laid down as an integral part of the contract between the client and the contractor.

Information generated during the construction process can be classified in accordance with the LoG-I-C-L scheme (see 2.2) [15]. Depending on the scope of the project and the specialist disciplines involved, it is not sufficient to store the construction logistics exclusively by defining a LoL in distributed specialist or domain-specific models. Rather, as explained in the previous sections, a CLM must be created which contains all the information that is directly within the sphere of influence of construction logistics. This domain-specific model must also be unequivocal and completely defined in a BEP, for example, according to the LoG-I-C-L schema. It must be coordinated with all other specialist models.

5.2 Scheduling in the Context of Construction Logistics

Scheduling places the individual work processes in a temporal context and includes the construction logistics processes. The time schedule can be based on the structure as shown in Figure 3.

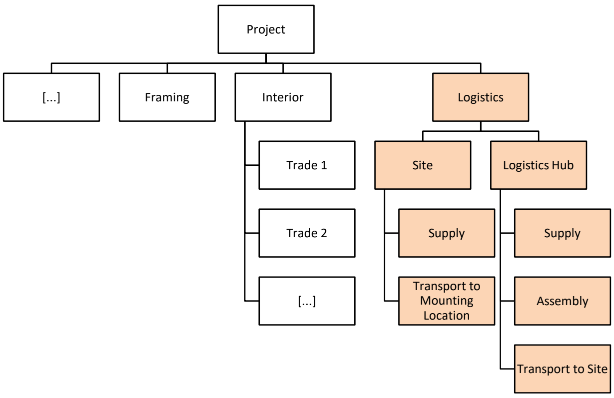

Figure 3. Suggested structure of a construction logistics focused time schedule

One way of classifying the logistics processes is to differentiate them spatially according to construction site and logistics hub, as well as according to their activities in delivery, assembly and transport to the installation location. This structure results from the approach that different stakeholders are responsible for the individual logistics processes. The example structure mentioned above is applicable to all projects with a logistics hub, for example in the inner city area. The structure can be extended to include the provision of construction machinery, taking into account a construction yard. However, the structure can also be reduced by the logistics hub in order to map only the basic logistics processes. It must be adapted to the specific logistical project needs.

5.3 Linkage of Scheduling to the Construction Logistics Model

The connection of scheduling to the CLM can be done, for example, by storing an unique activity identifier on the relevant components. This means that all information is available centrally in the model or is linked to it. The required materials are stored in the schedule as the corresponding resource of the respective operation. By linking the individual processes, interdependencies between building operations are modelled and the execution of construction work is optimized in terms of time. The connection allows a time-dependent observation of construction logistics processes and storage areas in the model.

5.4 Application of Lean Principles

Figure 2 shows that the application of the LC principles influences the scheduling, the CLM and the construction logistics. They are forming the basis for all underlying processes from creation of the first architectural building model to the processes during the execution phase.

The application of lean principles in the construction phase is well known by tools like a Takt Board or principles like Last Planner®. Also in the design phase, the development of a building model can be based on lean ideas. For example, short cyclical design reviews can help to identify issues. Thereby, countermeasures can be taken in an early stage. This approach is called Lean Design (LD) or Lean Design Management.

6 Implementation

6.1 Construction Logistics Model and Time Scheduling

In the following implementation, the specialist model bases on an architectural building model, which contains information on the structural shell and interior finish. The buildings' design follows the LD approach. An architectural model serves as data basis for the developed CLM. Figure 4 shows the floor plan of this model. It consists of four takt sections with the same structure. In addition, the needs of HVAC and other trades must be incorporated into the planning of construction site logistics and, accordingly, into storage area management. This integration will be part of future work.

The shown example building is a reinforced concrete skeleton construction with a steel-glass curtain wall and interior walls made of plasterboard. The elevator and staircase cores are made of in-situ concrete.

Autodesk Revit software was used for modeling. Each object has a comment field within its properties. The connection to a testing schedule is implemented in this module. The comment field is used to include the operation IDs from the testing schedule. In this way, a component can be assigned to several processes. The information of the activities can be accessed via the stored IDs of the processes in the CLM. This enables a time-dependent space management straight from within the CLM.

Furthermore, the model also includes an outsourced logistics hub and the transshipment point on the construction site. The placement of the logistics hub is not geographically correct in the context of site supply, but serves to visualize the TTS processes. The core components of the model are therefore:

- Geometric and semantic representation of
  - Storage areas
  - Ground plans and terrain model
  - Objects to be stored (building materials, components, auxiliary equipment, etc.)
  - Logistics hub
  - Construction site equipment incl. transshipment point
- Linkage of the detailed time schedule for execution and a derived time schedule of the construction logistics
- Different model versions depending on the project phase with the right information content (LoG, LoI, LoC, LoL)

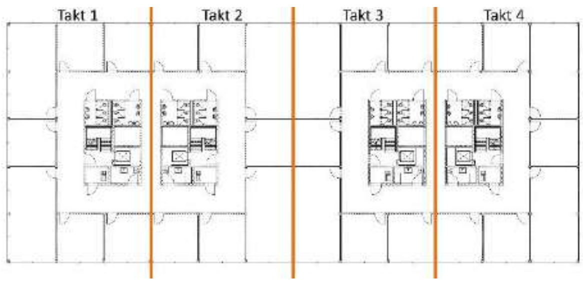

Figure 4. Floor plan showing four takt sections

The time scheduling is structured according to the structure shown in the section 5.2. It is designed in a high level of detail so that it can be used to control the construction progress during the execution phase.

6.2 Lean Construction Logistics Management

Based on Autodesk Revit, an AddIn was created that includes an interface to time scheduling and enables the creation and administration of storage areas. LCLM essentially comprises the following functionalities:

- Linking of tasks from a schedule to components
- Placing storage areas in the floor plan
  - Manually by user
  - Automatically by an algorithm
- Displaying Information about storage areas
- Generate target/actual comparisons with regard to the material delivery
- Display material and components of an operation in the model
- Simulation and visualization of the construction process

6.3 Limitations

There are proprietary software tools available for linking digital building models with time schedules and further information sources (e. g. Autodesk Navisworks, RIB iTWO or ceapoint desite MD). These were not discussed in this paper as well as in the underlying Master's Thesis [10], because the software to use was restricted to Autodesk Revit, Microsoft Project and non-proprietary libraries, like MPJX. Furthermore, a detailed classification in the overall project context becomes part of further research.

7 Conclusion and Outlook

7.1 Conclusion

This paper introduces an approach that puts construction logistics more firmly into the focus of the entire construction process. The role of logistics planning is already taken into account in selected (major) projects. The CLM supports and simplifies logistics planning. Thus, it also promotes the integration of construction logistics for smaller-scale projects.

In contrast to previous approaches, in which only 3D or 4D models are created, the presented construction logistics domain-specific model is integrated into the entire BIM process and not only as a side product, which does not interact with other specialized models and from which no information is returned. By integrating a LoL in all other domain-specific models, the relevant logistics information from these models is also taken into account. The CLM is used for the data storage of building-related logistics information and is linked to schedule planning via software. For this purpose, an AddIn was developed which allows the assignment of processes directly in Autodesk Revit. The basis for this tool is the application of LC, which aims to reduce waste in all processes of planning and execution of the construction project. The presented software supports this by optimizing transport routes and modelling objects of construction logistics, such as storage areas or construction materials.

7.2 Outlook

The approaches and ideas presented in this paper must be further elaborated and examined. The effort required for the creation and maintenance of a construction logistics domain-specific model over all project phases must be determined based on practical examples. In this way, the added value of the described approach can be proven.

On a superordinate level, new ways of thinking must be accepted and applied in the construction industry. In addition new cooperative contract and business models must be promoted, which already build on Lean Thinking and the BIM methodology from the beginning of the project.

Acknowledgement

This work is based on the results of a Master's Thesis at TU Darmstadt's Institute of Numerical Methods and Informatics in Civil Engineering [10].

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Integrating the Use of UAVs and Photogrammetry into a Construction Management Course: Lessons Learned.

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Abstract –

Unmanned aerial vehicles (UAV) have gained tremendous interest in the construction management domain as a platform for progress monitoring, safety supervision, quality inspections, and overall job site logistics. With the continued growth of UAV application within construction domain, it is essential for construction program graduates to develop a general understanding of UAV operations, regulations, and integration with other technologies as a part of their construction curriculum. This document presents an exploratory case study to identify the potential opportunities and challenges of integrating a UAV and photogrammetry module into a building information modeling (BIM) undergraduate-level course. Photogrammetry and BIM integration with UAV have been selected as the use case because of their widely-used applications in construction domain. The module learning objectives as well as the technical components of flight operations, knowledge tests, and photogrammetry workflow integration are discussed in detail. This module provided an opportunity for students to obtain hands-on experience on both software and hardware sides of the UAV, Photogrammetry, and BIM integration. This allowed the students to successfully assess and implement these technologies in a realistic practice exercise. Challenges were found with the time required for student to be sufficiently effective pilots to perform the UAV flight operations under the hardware limitations of the study. Additional blockades were recognized during the integration of federal aviation administration (FAA) UAV regulations within the module. The contribution of this case study is to provide a better understanding of integrating the use of UAV and photogrammetry within an undergraduate construction curriculum.

Keywords –

UAV, Photogrammetry, Education

1 Introduction

The use of Unmanned Aerial Vehicle (UAV) technologies in the construction domain has been continuously growing over the past decade. Academicians and industry professionals have presented tremendous interest in this technology as new technological advancements have decreased the cost, and increased the reliability, flight time, and manoeuvrability of UAVs. Construction professionals seek for safer and more efficient means for conducting their construction management operations and UAVs might be a platform to facilitate them with their tasks [1].

Some recent applications of UAV technology include: building or safety inspection [2,3], progress monitoring [4,5], damage assessment [6], site mapping and surveying [7, 8], building maintenance [9], among others. Most studies consist of two basic steps: UAV data acquisition, and data processing and analysis. UAVs equipped with various sensors have been used to capture visual, thermal or geographical data, then make use of the data to evaluate the condition of target structures or sites. Photo-/video-grammetry has become a widespread technique employed to process and analyze aerial photographs or videos. In such photo-/video-grammetry techniques, the data captured by UAVs has been mainly used to generate point cloud data for applications such three-dimensional modeling [10] or distance measurement [11].

As these applications become more generally employed in practice, a need has arisen for university-level courses that integrate them as part of their curriculum. Efforts have been done in STEM fields to integrate these technologies in their curricula. Mechanical, electrical, and computer engineering, have concentrated on the hardware and software design of the aircraft [12, 13]. In geomatics, the educational aspect of UAVs has focused in geospatial thinking, where the students collect aerial images for remote sensing and image processing purposes [14-16]. Nevertheless, UAV and photogrammetry technology integration in construction management education remains largely unexplored in the construction literature. This paper investigates this integration by using a case study where these technologies are integrated into an undergraduate-level course as a hands-on module.

2 Research Motivation and Scope

The construction management domain is currently undergoing a vast technological and institutional transformation with the adoption of visualization tools such as BIM, and virtual reality (VR) [17, 18]. In the educational context, these innovative technologies have been successfully integrated into several program curriculums using various teaching modules that follow core construction concepts [19]. UAVs offer reductions in work load, risk, and overall cost of some construction operations [3, 20] and over the last few years, this technology has become very popular in the construction domain. Although UAV technologies might have been used by various construction management programs, there are no publications in the construction literature that addresses the pedagogical challenges and opportunities present in the implementation of these technologies in construction management education.

This study discusses a hands-on module aimed to enhance students learning about UAV technology for reality capturing purposes and how it can be used for building information modeling. Without this type of hands-on learning experience, students would have to gain these skills during their internships or after graduation. In this paper, an analysis of the module components (flight evaluations, knowledge tests, and photogrammetry workflow integration) are discussed. Additionally, the pedagogical opportunities and challenges would be explained.

3 Module Design

The module has been designed for the undergraduate-level course BCN4252: Introduction to Building Information Modeling at the University of Florida based on empirical experience of current construction practices in the United States. The course focuses on advance BIM (Clash Detection, Quantity Takeoff, Site Development, Walkthroughs) and related construction technologies (VR, AR, 360-degree photography, UAVs, Photogrammetry). In the course, 7 sessions are dedicated to UAVs and Photogrammetry. These sessions are divided into two major components: knowledge development and hands-on training. During knowledge development sessions, the basic concepts relating to the UAV applications, operations, regulation are introduced. The relationship between UAV and photogrammetry is described by providing practical examples of the integration of these techniques in the BIM methodology (e.g. surveying, mapping, inspection, progress monitoring, and clash detection). Additionally, software and techniques used to generate these point clouds are discussed within the construction domain. In the hands-on training, student perform UAV flight operations using a UAV to generate point clouds through the employment of software workflows. These actives have several learning objectives and expected outcomes that would be discussed in this section.

3.1 Learning Objectives and Expected Outcomes

In the knowledge development sessions of the module, students are expected to understand the definition of UAV, differences between fixed-wing and rotary-wing UAV, key components on a rotary-wing UAV, description and advantages of UAV autonomy features such as waypoint navigation, obstacle avoidance, auto-takeoff and return home. The students are also expected to gain basic understating of UAV regulation in relation to airspace classification, operation requirements and flight restrictions. In addition, students should have been able to define photogrammetry, identify their advantages and shortcomings, and evaluate the incorporation of these techniques into construction-related applications.

In the hands-on training part of the module, students are expected to perform various UAV flight operation tasks and understand the fundamentals of UAV safe flight. Students are also instructed to generate three-dimensional models using recorded photographic data obtained from UAVs, integrating a photogrammetry software workflow.

3.2 Flight Operations

This section of the module evaluates the students' UAV flight skills. The evaluation consists of three different flying tasks, where the students fly the aircrafts above a linear path with three stops – two on each end, one in the middle as shown Figure 1. Stops are marked as numbered circles. A mannequin head is placed in between each of the paths and elevated to a height of four feet by a platform. The students exercise ascend, descend, yaw, roll, and capture pictures or videos using UAV during the flight operation.

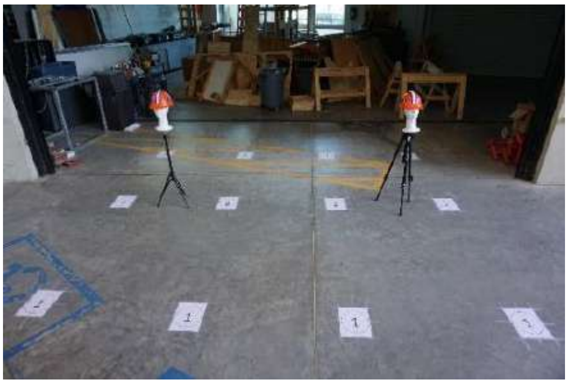

Figure 1. Flight Operation Exercise Area

The difficulty of maneuver in each task increases progressively from beginning to end, which simulates a typical flying session on construction site. Takeoff and landing are included in all tasks as they are critical every time a UAV is flown. To perform the tasks, students use the Syma 5X aircraft, which is equipped with a Full HD camera sensor. The selection of this aircraft was mainly driven by the cost, but other factors such as reliability and maneuverability were considered. Figure 2 displays each task to be performed by the pilots. Initially, task 1 requires the pilot to controls the UAV to take off, ascend, then land on the same location. During task 2, the pilot controls the UAV to take off, ascend, yaw 360 degrees, then land the UAV on the same location. In task 3, the pilot controls the UAV to take off, ascend, yaw 90 degrees then roll to the next stop and land UAS on the circle. Then, the student control the UAV to take off and ascend again, direct the camera to the object, capture a video, roll to circle 3, then land UAV.

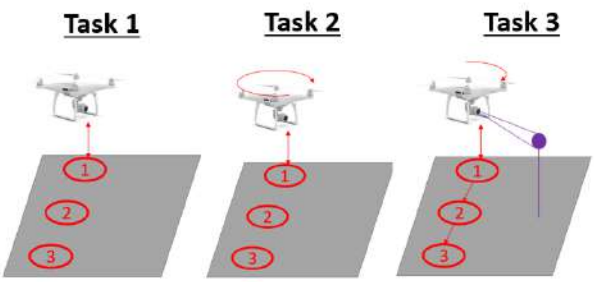

Figure 2. Flight Operation Tasks

Before the test, an ungraded preliminary practice session is provided for the students to familiarize themselves with the operational characteristics of the aircraft selected for the study. Students are divided into four groups, each corresponds to a path within the testing area. Each path is dedicated to two students, who share one UAV and six batteries. Each student at each path has approximately 10 minutes to practice each flight task.

During the test, the students are divided into four groups. Each group is assigned to one path and had one visual observer that evaluates their flight performance. Students pilot the UAV employing the techniques acquired during the preliminary session and are graded by the visual observers based on a Likert scale that measures the performance of each task in a five-point scale, ranging from poor (1) to excellent (5). The students also provide open-ended comments on each task during the evaluation session.

3.3 Knowledge Test

In the United States, the regulatory agency Federal Aviation Administration (FAA) is responsible for setting the standards for commercial aerial operations throughout the country [21]. During 2016, the FAA set in place a standard for commercial operations of UAVs. Commercial pilots must obtain a certification to perform aerial operations, including those performed in the construction industry. The FAA requires for pilots to pass an evaluation regarding UAV regulations, airspace, weather, loading, performance, and operations to get accredited. Analogously, the European Aviation Safety Agency (EASA) have proposed a framework for the operation of UAVs under the A-NPA-2015 [22], classifying the UAV operations as "*Low-risk operation – 'open' category*" which encompasses "*small drones under direct visual line of sight operated within safe distance from persons on the ground and separated from other airspace users*" [22]. Nevertheless, the EASA is still under review and has not presented a final publication with the general ruling as December of 2017. The knowledge section of the module is created to discuss UAVs, these regulations, and their previous applications.

Throughout this part of the module, students are expected to gain a basic understanding of concepts relating UAVs, their applications, safety challenges, and regulations. To evaluate their comprehension of the material, a knowledge test is designed, containing 14 questions in all these topics. The test has five categories as follows:

- The concept of UAV
- UAV technical requirements
- FAA basic regulation and how it might relate to construction domain
- Current applications of UAVs in Architecture, Construction, and Engineering domain
- Safety challenges of using UAVs onsite

3.4 Photogrammetry Integration

For this study, a three-step photogrammetry workflow is used to help the students in their point cloud generation process (Figure 3). The initial step (1) of the workflow requires the extraction of the keyframes for the videographic data captured with the Syma 5X aircrafts that contain the mannequin head. To achieve this, the VLC media player (free and open-source) software is employed to attain screen captures of the keyframes in the video files. On the second step (2), Autodesk Recap® is used to generate the point cloud. The extracted keyframe images are imported into Autodesk ReCap® cloud-based software. An RCS (Point Clouds) file is obtained after processing, containing the mannequin head and the surrounding environment. Using the Autodesk ReCap® desktop software, the point cloud is cleaned with the objective of separating the surrounding environment and targeted object (mannequin head). In the last step (3), the cleaned RCS file is imported into Autodesk Revit ®, where it is scaled relative to the model, and positioned for display in an RVT (Revit Project) file.

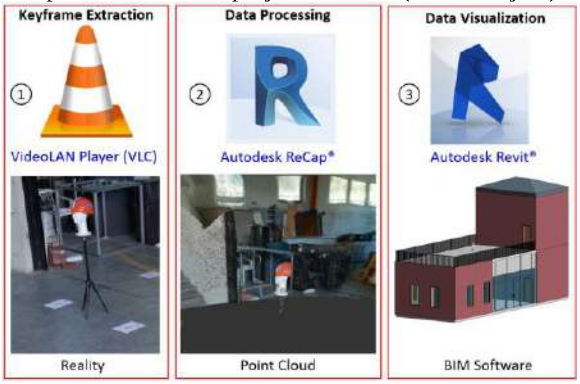

Figure 3. Photogrammetry Workflow

3.5 Data Sampling and Collection

For each section of the module data was collected from the students taking the course. In total, 11 students took part in this part of the module, performing all the tasks corresponding to each section. The data collection was done using the following criteria:

- Flight Operations: The students were evaluated by an observer based on their UAV flight performance using a five-level Likert scale: poor, fair, average, good, excellent. The evaluator graded the students' performance according to the tasks defined on section 3.2.
- Knowledge Test: The number of correct answers were collected from the quiz to evaluate the understanding of the participants regarding UAVs in the construction domain, its usage, and the FAA regulations.
- Photogrammetry Integration: In this section of the module, keyframe images obtained and RCS and RVT files were collected from the students. Each component was evaluated according to its completion and representation accurateness.

4 Results and Discussion

4.1 Participant Demographics

In the sample data collected for the study, it was found that subjects were mostly male (91%), with a minority of female (9%). The average age of the participants was 22 years, with a maximum of 24 years and a minimum of 21 years. All the students (100%) were in the senior year (4th year) of their university education. Generally, the students (82%) reported to have between one and five years of work experience in construction management, and the remainder (18%) informed less than one year of experience. Most of the students stated to have excellent or good eyesight (73%).

Overall, most of the participants did not have any experience with radio controlled (RC) cars, boats, or airplanes (64%) with none of them having any experience. with operating UAVs either in their personal time or at work. Many of the students also had an average knowledge of UAVs in construction (73%) and understanding of FAA regulation (55%).

Figure 4: Students performing flight operations

4.2 Flight Operation

The data collected from the flight operation performed by the students reveal that overall, as the difficulty of the maneuvers increase, the performance decreased (Figure 3). Task #1 - *UAV to take-off, ascend, and land*, was the highest scoring task on average, rating above "*average*" in the Likert scale, but it presented a wide dispersion (Mean: 3.2, Median: 4.0, IQR Low Bound: 1.0, IQR High Bound: 5.0). The evaluators noted that several of the participants experienced issues performing the maneuver as the UAVs "*do not go straight up and down*". Moreover, the evaluators also noticed that if "*the UAV [front] is facing the user, the maneuver difficulty may increase*", which indicates that it was challenging for the participants to identify the front side of the UAS in relation to their positions.

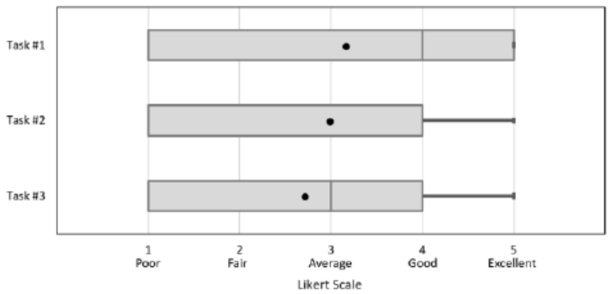

Figure 3. UAS Fly Tasks Grading

Task #2 - *UAV to take-off, ascend, yaw 360 degrees, then land*, was rated "*average*", displaying a wide distribution of scores, and leaned towards the lower end of the scale (3.0, 4.0, 1.0, 4.0). The evaluators commented that most students "*could not perform the 360-degree rotation*", as the UAV was "*hard to control*". Task #3 - *UAV to take-off, ascend, yaw 90 degrees, then* *rolls, captures a video, and land*, presented below "*average*" scores (2.7, 3.0, 1.0, 4.0), with a wide distribution leaning towards the low end of the spectrum. This was the most challenging task in the set of flight manoeuvres. The evaluators commented that the UAVs were "*drifting all over the place*". Additional comments were provided that identified issues with the recording of the video, as the UAV recoding light indicator would "*flash red light [recoding on] and then immediately go back to green light [recoding off]*"

Additional comments were provided by the evaluator immediately after the flight maneuvers were done, reporting hardware issues such as "*had to reset the UAV several times to reestablish the control link*", "*the UAV is very hard to keep steady*", and "*batteries change interrupted the UAV flight*". Additionally, the evaluators observed that "*more time practicing would be beneficial*" and that the participants that did not attended the practices session before the evaluation session had a lower overall performance.

Following the UAV flight operations, the participants reported the total workload required to perform the tasks using the NASA TLX [23] assessment tool (Figure 4). The participants indicated that the mental demand required for the flight tasks was above average (Mean: 11.5, Median: 14, IQR Low Bound: 6, IQR High Bound: 16) with high variability. It was observed during the flight maneuvers, that the participants required their full attention on the task to perform them according to the prescribed requirements. The physical demand reported by the participants was well below average (4.9, 5.0, 2.0, 7.0) with a narrow distribution of responses. The UAV operation required minor physical effort as there are radio controlled aircrafts. The only physical effort required was the manual set-up of the aircraft on the markers. The participants expressed that the temporal demand was below average (8.0, 8.0, 6.0, 11.0) with a narrow distribution. This indicates that the participants did not felt highly pressured in terms of the time or pace required for the tasks.

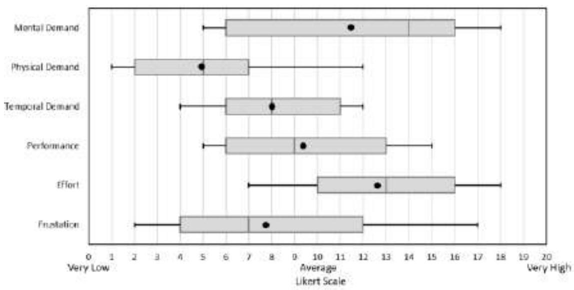

Figure 4. NASA TLX Grading

The participants reported that their overall performance of the task neighbored the average score, but this measurement present a wide distribution of responses (9.4, 9.0, 6.0, 13.0). This indicates that the average participant perceived to be successful in their task performance. Moreover, the participants indicated that the effort required to perform the task was above average (12.6, 13.0, 10.0, 16.0) with a narrow scoring distribution. Finally, the participants indicated a below average level of frustration (7.7, 7.0, 4.0, 12.0) with respect to the tasks. This suggests most of the participants did not felt irritated, stressed, or annoyed during the UAV flight maneuvers.

4.3 Knowledge Test

The knowledge test that the study participants took after the flight maneuvers, revealed that in average participant scored 18.2 out of 20 points with a standard deviation of 1.74. As shown on Figure 5., 45% received the maximum score for the evaluation. Overall, the questions that most participants answered erroneously were related to UAV and its flight height under the FAA regulations. This indicates that the participants had some difficulties understanding basic FAA regulations and their significance in the construction domain. Other questions that were incorrectly answered by the participants were mainly related to the concept of UAV and its application in the construction domain.

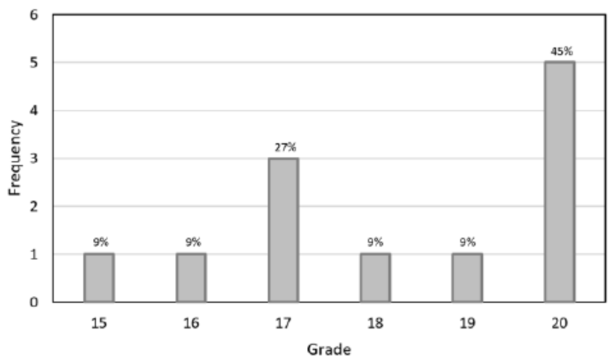

Figure 5. Knowledge Test Results

4.4 Photogrammetry Integration

After the participants concluded the flight operations, the videographic information was extracted from the UAVs, for posterior analysis using the workflow established on section 3.4 The video was successfully split into pictures by the participants using VLC MediaPlayer®, creating an average of 186 keyframe images in JPEG format.

The images were input into Autodesk ReCap® for processing, obtaining RCS format point cloud as a result. Within the same software, the participants cleaned the point cloud as contained the environment surrounding the target object, so that only the desired object remained. The resulting RCS file then was imported into an

Autodesk Revit® architectural model, where the point cloud was scaled to proportional measures to the model. The key issues reported by the participants related to the software the cloud-based software Autodesk ReCap®. Multiple uploading and processing errors of the images were found, mainly caused by the number of input images into the platform.

5 Research Limitations

This research has three major sources of limitations: (1) sample size, (2) participant experience-based limitations, and (3) hardware limitations. (1) The sample size for this study was very limited, containing only 11 participants analysed in the results. This implies that the observations presented in this study cannot be used to generalize beyond the sample population. As this is an exploratory study, the focus aimed to provide general overview of the variables and factors affecting the topic by directly reporting the lessons from the teachers, evaluators, and participants. Consequently, these lessons may not be representative for all instances or conditions in construction management UAV and photogrammetry education.

(2) The participants of the study did not have any experience flying UAVs excepting the preliminary practice session. The flying operation were directly affected by the deficient piloting skills of the participants during the evaluation session. This presented difficulties to obtain usable footage for photogrammetry application. (3) The UAV hardware used for the operation does not provide in-flight stabilization of the aircraft, which requires constant user input to maintain a leveled aircraft. Moreover, the UAV is equipped with a low-end camera without a gimbal, producing photos and videos only up to Full HD resolution. This introduces additional complications for inexperienced pilots to keep a fixed target focused for a reasonable amount of time, and further limits the quality of the 3D models to be produced from the photogrammetry process. With the intention of simplifying the flight operations to control for these variables, the UAV were flown in low altitude without any obstruction, wind or precipitation, (reducing the risk of losing control and crash), which is not representative of real-world fly conditions. With the same intention, the participants monitored the UAS closely in distance, making the tasks less challenging.

6 Opportunities and Challenges

The integration of UAV and photogrammetry in a BIM course module presented insightful pedagogical opportunities and challenges for undergraduate construction management education. The hands-on approach presented on this module enabled students to experience the common hardware and software-related problems professionals might encounter during the application of UAVs for generating point cloud data. The flight operations of the UAV provided a method for the students to experience the problem-solving skills necessary for a pilot to successfully obtain aerial imagery. Establishing a control link, battery life time constraints, and spatial awareness for UAV control were some of the identified factors that affected the students flight operations. Moreover, students understood BIM software interoperability limitations, as they were required to recognize the appropriate file formats for the manipulation of point clouds. Overall, students recognized the necessity for general troubleshooting knowledge in relation to the hardware and software involved in the technical workflow.

The challenges observed in the integration of these technologies into the module related to the UAV (flight, hardware, knowledge) and the photogrammetry software utilized for this study. This module comprised only twelve hours of lecture and lab time, which limited the time needed for the students to practice their flight skills. Only a two-hour session was employed for the students to physically perform the UAV manoeuvres, followed by the evaluation session. Another crucial factor that reduced the efficacy of the students' performance was the UAV hardware. The Syma 5X aircraft used in this study do not possess an automatic hovering feature, increasing the difficulty of any operation that requires steady image capturing. Moreover, constant supervision of the flight operations by the instructors is required, which effectively limits the number of students that can simultaneously fly the UAVs while achieving the learning objectives of the module. This level of supervision could be lowered by providing UAVs with more automated features, simplifying the flight tasks the students are required to learn. Nevertheless, the understanding of the image collection workflow still requires instructor guidance.

The UAV FAA content for the module was also hard to be integrated as this module did not aim to provide an exhaustive overview of regulations and pilot certification. Nevertheless, this module attempted to provide sufficient information to create awareness regarding UAV operations to the students. Only the three major topics that comprised the FAA Part 107 certification were covered at a basic level (regulations, airspace & requirements, and weather), but many other topics were left out. Finally, the software utilized to create the point clouds also generated challenging situations. ReCap® has the advantage of allowing cloud-based processing of the images, reducing the computational power required from the students' computers, but makes difficult the evaluation of errors that might occur during the point cloud creation process due to the limited feedback provided by the platform. Additionally, this software limits the number of images that can be uploaded to the platform, allow a maximum of 250 images.

7 Conclusions and Further Study

The use of UAVs and photogrammetry techniques within the BIM context has become generalized in the construction industry during the recent years. This has generated a necessity for program graduates to have a practical understanding of UAV operations, regulations, and integration with other technologies. This paper describes the opportunities and challenges observed in the implementation of UAVs and photogrammetry module in an undergraduate-level course. During the flight operations, knowledge tests, and photogrammetry workflow integration, data was collected to obtain insight on the design of the module. From the analysis of the data, it was found that the students had an overall "*average*" performance flying the UAVs, while they were highly constrained by the UAV hardware used in the module and the limited amount of piloting experience. Additionally, the photogrammetry workflow presented challenges during the point cloud generation due to limited amount of control and input that students and teachers had on the photogrammetry process.

Further investigation must be done to validate the findings of this study. Data sampling over various semesters is recommended to obtain generalizable results. Moreover, in the subsequent data collections, the hardware of the UAVs should also be improved to remove some of the limiting factors presented on this study. Additional practice sessions are recommended to improve the mastery of the students piloting the UAVs. Future research should explore the effects of the introduction of UAV/Photogrammetry module in program graduate education by assessing how valuable the skills obtained on the course are in relation to industry practice.

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Towards robotic fabrication in joining of steel

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Abstract –
Throughout history, waves of industrial revolutions have disrupted established manufacturing methodologies. Traditional construction processes have been transformed by new means of creating objects and computing information. The manufacturing of steel is no exception to this trend. Past methods for the creation of steel included hot forming (casting, extruding and welding), cold forming (subtractive milling, bending and rolling) and cold connected assemblies (bolts and rivets). All these methods create certain constraints to the application, form and function of steel elements. Developments within fabrication technologies bring a new dimension to the possibility of creating complex geometries in steel manufacturing. This article explores the use of new technologies including additive manufacturing as well as composite joints, and highlights the integration of new robotic programming paradigms for architectural production.

Typical 3D printing technologies create objects by incrementally adding layers of material in order to create a final part. Employing robotics does not only allow for fabrication on a larger architectural scale. The flexible configurations of the robotic arm, with its six degrees of freedom, allows for the additive manufacturing of elements on top of existing structures or surfaces.

Within this article we create an overview of fabrication technologies for joining steel, as well as their influence on architectural design. We explore how new technologies enable the creation of new design possibilities, through the increased flexibility of robotic fabrication.

Keywords –
Additive Manufacturing; Robotics; Fabrication; 3d Printing; Steel; Welding;

1 Introduction

Construction technology has a significant impact on the design and performance of architectural projects. The evolution of materials and methods of production has enabled the Architecture, Engineering and Construction (AEC) industry to design and build projects of increasing complexity, form and function. As new techniques develop, the industry integrates these innovations in order to push the boundaries of construction capabilities. This trend can be seen in the history of architecture as low rise buildings evolved into the skyscrapers that define modern skylines. The impact of manufacturing technology has a determinant role in shaping architecture. Many examples can be identified that attest to this connection whereby shifts in capabilities transform the AEC industry at large.

Advances in construction technology shape the design of architecture, from new digital information workflows to innovative fabrication processes. The current wave of fourth industrial revolution is now taking shape and architecture is again evolving. New levels of intelligent automation, and the increasing connectivity of information networks are creating more ambitious and efficient structures than ever before. The power of designers to computationally optimize designs is matched by new means of manufacturing complex components. This trend is amplified by new methods of collaboration, from algorithmic design to Building Information Models.

The development of new processes for using machines and materials is an important aspect of realizing innovative architectural ideas, from robotic fabrication to new methods of working in steel and composites. These advancing capabilities are combined with increasing ambitions for architecture that are cost competitive and efficient to assemble while still achieving high levels of performance, sustainability and geometric complexity. With this evolution in mind it is helpful to consider examples of architectural forms which encompass these transitions in process.

We can observe the evolution in architectural process by juxtaposing projects from the past with those from the present in order to see the impact of new means of construction. It is important to keep in mind that while technology may change there are many constants that remain. These constant conditions run throughout the course of architectural history to add a shared context to construction efforts. Each building for instance must negotiate a balance between form, function and structure in order to find a means of creating space which efficiently meets its design requirements and can be built within its constraints of technology, time and budget.

The Eiffel tower demonstrates this balance in a truly iconic way. By utilizing the height of the times existing technology and manufacturing methods this structure embodied the benefits of steel construction. From its structural definition of form to its rapid construction schedule, this tower became synonymous with the city of Paris and an age of advancing architecture. The form takes advantage of repetition as its symmetry allowed for the preparation of parts to have repeatability and structural integrity that could be calculated by hand.

In contrast to the Eiffel towers symmetry we can consider the ArcelorMittal Orbit, an observation tower designed for the London Olympic Games. This tower is a complex creation of non-symmetrical geometry in which each part is uniquely created according to a digital model. The asymmetric form was made possible through the utilization of computational design tools and advanced structural analysis software. The principles of structure, construction considerations, and the desire to create an iconic experience to represent a city are common to each project while the impact of digital design and fabrication processes can be seen to considerably increase the complexity of the built form.

A further example of the impact that advancements in technology has on architectural projects can be found in the evolution of thin shell structures. Engineers such as Richard Bradshaw were key figures in designing thin shell structures that utilized the strength of form to optimize structures. These designers required a deep understanding of structural analysis, hand calculations and the geometries required to create such impressive forms. New digital design tools, methods for iterative structural analysis and file to factory workflows that design for mass customization have empowered designers such as Marc Fornes to reimagine the shell structure as a highly complex geometry comprised of thin sheets of material that derive great structural integrity from the form of the construction.

Works produced by Marc Fornes, such as Minima | Maxima, create shell structures through continuous surfaces which draw their structural integrity from both the geometry of the construction and the aluminum laminate weave it is constructed from. This increase in design complexity continues the tradition of creating impressive structures that consider construction methods early in the conceptual process in order to integrate design and fabrication. These workflows seek to optimize a project and increase its ability to be constructed efficiently in light of bespoke geometry.

The integration between design and fabrication tools continues to grow. In the future of construction, digitalization will be the central interface in the supply chain. The integration of robots and automation technology can improve the competitiveness of the construction industry, which lags behind other industries in regards to increases in efficiency and productivity. The integration of digital processes has significantly advanced the tools of architecture in a short amount of time.

A concept for furthering this trend was commissioned by the BMVi in 2015. To guide the integration of modern digital processes and technologies in the planning, construction and operation of buildings envisages a step-by-step plan for the introduction of BIM [1] was developed. Building Information Modeling or Management (BIM) is ideally used to digitally create and manage information regarding the physical and functional properties of a building over the course of its entire lifecycle, from design, to construction, to occupancy and operation, to its eventual decommission. BIM serves as an information source and database for interdisciplinary collaboration between all parties involved. Currently, BIM is utilized mainly during the design stages of an architectural project and does not yet sufficiently integrate machine production. In many cases a BIM model must be rebuilt in a shop level tool or set of drawings before physical production of parts and assemblies can proceed.

These developments also affect the steel construction industries. New flexibilities within the digital tool chain of design to production also require new flexibilities in the fabrication processes. While casting of metal is a relatively cheap process especially for mass production, the fabrication constraints exclude a number of parts. Even though 3D printed sand molds already extended this process and allow for the creation of undercuts and can be created without draft, this is still a relatively time consuming process, which requires a high lot size to be efficient.

On the other hand, subtractive milling, generally limited to 3 axis of freedom, creates a high waste factor. Other limitations are inherent in this process including the creation of undercuts or parts that require tooling from all sides. While five axis CNC machines are able to create undercuts and CNC technology overall is distinguished by very high accuracies, they do not achieve the same flexibility as a robotic milling solutions both in workspace as well as reachability.

Within the field of forming through bending or pressing often times stencils need to be used. The high forces within the process require stiff machinery and therefore prevent the use of more flexible robotic solutions. However, the field of single point incremental forming has shown that robots are able to create a wider range of parts but only with materials up to a certain thickness.

Within this paper we take a closer look at direct additive manufacturing technologies such as welding for joinery, as well as incremental welding for part creation and hybrid processes which allow the use of composite materials for joining of steel parts. While flexibility can be achieved in every part, this often leads to higher fabrication times. We therefore focus on flexible joints for prefabricated parts.

2 Robotics in Steel Construction

Currently the construction industry utilizes automated production systems almost exclusively for prefabrication. Specialized systems for the production of standardized components are limited in flexibility and costly to obtain and operate. These systems often require specialists to program and are designed to repetitively execute movements without mass customization or variation. Feedback from these processes is generally not communicated to the design process. Sensors and intelligent dynamic adaptivity are also not the normal method for correcting errors in tool paths or part placement. While these methods are used in other industries, it is only recently that research aimed at bringing these processes into the architectural workflow. By considering these initiatives, we can observe a variety of further-reaching approaches that stand on the borderline between research and real-world use.

Over the last ten years, robotics has made its way into architecture schools all over the world. Conventional industrial robots serve as universally applicable machines. The possibility of combining abstract movements with various tools opens up a wide range of possibilities for individualized production.

Early projects incorporating robots into the architectural process explore the changing design to fabrication workflow and the exploration of possible tooling strategies [2]. Through cooperation with the construction industry, these efforts resulted in highly individualized objects as demonstrations of this new file to factory robotic strategy. Pioneering projects such as the exhibition hall of the Landesgartenschau of the University of Stuttgart [3], [4], the roof of the experimental hall for digital production at ETH Zurich [5] or the work of the Institute for Timber Construction of EPFL Lausanne [6] can be seen as demonstrator for the creation of complex high performance geometries particularly in timber construction.

Beyond digital prefabrication, there are various efforts to bring robotics to the construction site. Advances in drone and machine vision technology have fueled the use of these systems in stocktaking and inspection, as well as in construction documentation and analysis [7]. With these approaches, there are still far-reaching questions regarding the level of detail and sensible interfaces for rectifying deficiencies.

While manually controlled construction machines have long been at work on construction sites the future will find a greater integration of semi - autonomous or even fully autonomous machines involved in construction site logistics for civil engineering [8]. Lessons learned from other industries, such as agriculture, mining, automotive and aerospace will help to adapt technologically advanced manufacturing methods for use in the construction industry.

In the field of steel construction, semi-automated systems for welding were developed at an early stage, or systems for sheet metal forming were adapted from prefabrication to be used on construction sites [9]. Systems for in-situ production have different approaches to operation when compared to use of robotics in prefabrication. One example of the conversion of conventional construction machinery from prefabrication to on site application, is the Hadrian X brick building robot [10].

In research projects industrial robots are brought to the construction site as prototypical systems [11], [12]. However, such robots are not yet suitable for use beyond proof of concept development due to programming difficulties, safety issues, lack of contextual awareness and the low payload handling capabilities of robots used in research compared to those that may be used in production. For similar reasons, different directions of development are emerging for lightweight steel and metal construction. While the focus of robotic applications in steel construction will probably remain in the factory, development options for assembly will open up the field of robotics in lightweight metal construction.

Steel construction is one of the most common trades at work in the architectural enterprise. The steel industry is characterized by a high degree of prefabrication. This construction method has influenced the planning and execution process and led the industry towards an approach more traditionally seen in mass manufacturing as efficiencies of scale are utilized in order to bring down production time and costs while still increasing quality. To achieve this objective, the steel construction industry uses digital tools at every stage from design to production. This integrated, process-related planning already leads to BIM-based construction planning [13], which is highly demanded but rarely comprehensively implemented.

Automation has not only found its way into the planning process, but also into production. Not only serial or small series of steel components and modules are processed in specialized saw-drilling or welding systems, partly with industrial robots, but also individual productions. The robot has been used for a long time in industries where "exactly repeating" activities are characteristics of manufacturing. However, a robot-oriented further development of the steel construction production has to deal with facts such as very different component weights and sizes, a large number of primary materials, batch size 1 series and relatively large tolerances [14].

Despite the high level of automation, there are further potentials for the use of robotics in prefabrication. Where previously specialized stand-alone machines and associated software have been in use, more flexible systems and a higher-level view of the working structures can offer considerable advantages.

In construction steel production, the material flow, the recording of pre-material (tolerances), welding, cutting and drilling, the assembly sequence etc. are required for robot development and programming. Clearly, these things must be geared to the special requirements of steel construction and lightweight metal construction.

3 Prefabrication

In addition to subtractive manufacturing, assembly and joining, construction research also shows approaches to additive processes. The 3D printing of concrete is propagated by different companies for the printing of entire walls or even houses [15]. Others use 3D printing, partly with robots, to produce formwork and reinforcement [16]. The first experiments on the vertical application of mineral substances with robots are carried out at the RWTH [17]. In steel production, additive processes such as deposition welding or coating with robots could also gain in importance, since they enable complex geometries that are difficult or impossible to produce by subtraction [18].

Conventional prefabrication processes can be made more flexible, cheaper or even possible in the first place by using robots. For example, collaborating robots can bend a hot wire and guide it through polystyrene blocks to create moulds for free-formed concrete parts [19]. In cooperation with the Institute of Welding and Joining Technology, the Chair of Individualized Production in Architecture at the RWTH Aachen University is concerned in particular with further-reaching automation potentials and parametric factors of classical welding technology.

Arc welding processes are of particular interest for the production of large metallic structures [20], [21] due to their significantly higher melting capacity and comparatively lower plant and operating costs. As early as in the 1980s, generator shafts with a component mass of up to 225 tons were produced additive using the submerged powder (SAW) process. gas metal arc welding (GMAW) is much more mobile and flexible than the submerged arc welding process. In particular, the use of energy reduced short arc processes makes it possible to manufacture complex to highly complex metallic components in an additive manner. The LASIMM project relies on the collaboration of robots for fully automated additive and subtractive component production. In this case, the arc-based additive manufacturing is carried out by industrial robots in combination with machining, whereby a parallel kinematic structure is used here due to its increased stiffness [22].

Highly complex structures can be produced by incremental spot welding. A robot-guided GMAW torch places spot welds in any orientation on top of each other, thus creating structures of almost any size and complexity. Parametric models allow for the development of systematic approaches to design of robotic tool paths. In this way the robotic path, welding strategy: speed, angle, duration, weld height and resulting executable code can be programmatically updated to adapt to the mass customization of bespoke architectural elements. The parametric nature of the process empowers the robot with the ability to dynamically adapt to input provided by sensors. Figure 1 details experimentation in robotic wire arc additive manufacturing (WAAM) at the at the Welding and Joining Institute (ISF) of the RWTH Aachen. Figure 2 illustrates some of the results.

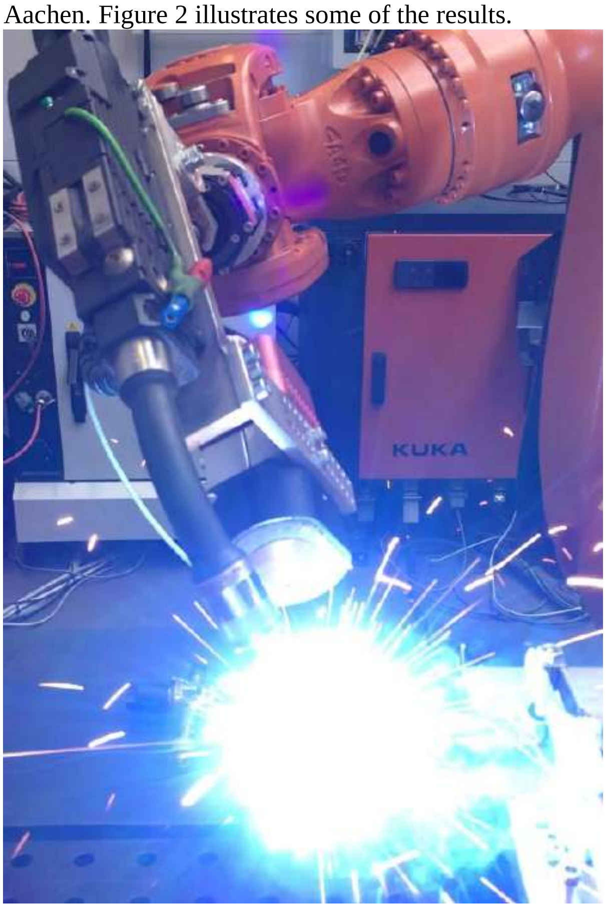

Figure 1 Robotic Incremental Point Welding

The development of additive manufacturing through the robotic fabrication of incremental point welding in steel can lead to advancements in construction technology and new ways of mass customization of bespoke geometries.

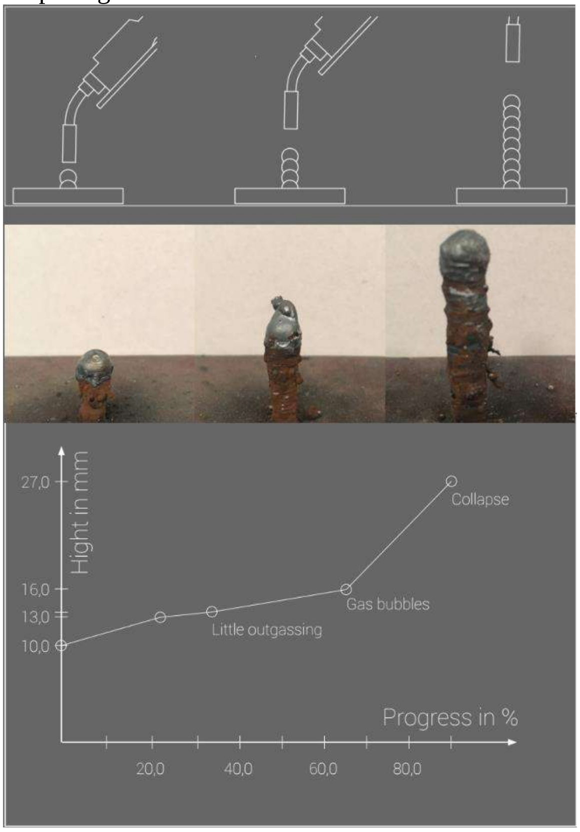

Figure 2: Incremental welding results

Another application area for flexible robot applications is the application of pin structures by means of CMT pin welding on complex shaped surfaces as illustrated in Figure 3. By a combination of targeted current conduction and the dynamic movement of the welding wire, it is possible to reproducibly create pin structures on metallic surfaces. This process opens up a multitude of possibilities for the production of composite components made of different materials.

Possible fields of application are metal-concrete composites for bridge construction or metal-CFRP composites for high-strength lightweight construction applications [23], [24].

The advantage of the high flexibility of GMAW welding can only be fully exploited if a suitable concept for implementing a complex adaptive path planning is available at the same time. In addition to a comprehensive analysis of the factors for an optimal development of the pin through the welding process, potential applications have been identified. A direct on-site production of composite materials is of particular interest, as this opens up new possibilities for the renovation of existing steel structures.

In order to provide the necessary flexibility, the process was transferred from a 3-axis positioning machine to an industrial robot with six degrees of freedom. A KUKA KR3 with a particularly high speed of movement was used. This makes it possible to flexibly design the distance of the pins in order to reduce the heat dissipation in between two weldments.

Figure 3: CMT pin welding with KUKA KR3

By increasing the degree of freedom, it is also possible to work on individually shaped metal surfaces. In order to enable the measurement and installation of the robot on site quickly and flexibly, a new robotics-based process for measuring surfaces was developed. Due to a direct communication between the planning tool and the robot controller, surface parameters at important points can be measured directly with the robot. Using these points, the surface description is used directly for the further path and process planning of the robot. In particular, the measurement can be carried out directly with the robot and reduced from a complete spatial positioning to an adaptation of individual parameters based on the working direction.

In the long term, innovative manufacturing processes will lead to a far reaching change in industrial prefabrication in the construction sector. This will not only lead to the development of new production facilities, but will also lead to a new planning and construction process. Due to the large dimensions of a building, modular components will continue to be in the foreground. Up to now, quite complex plant technology has been used which represents closed systems in terms of both hardware and software. The possible flexibility of the robot is limited here. As a universal tool carrier, it should be able to carry out various work steps, e. g. post-processing of the seams as required or combine more flexible process steps such as plasma cutting, notching and welding.

The demand for more flexible machine and software platforms will increase in the near future. The desire for individualized construction and increasing demands in terms of recyclability and reusability necessitate a rethinking of the concept of integral and differential construction. Prefabrication will have to be more agile. The aim of developing adaptive and flexible machines must extend the capabilities of people in the form of intelligent assistants. A transfer of experience from man to the digital machine is a sustainability strategy that allows companies to keep their manufacturing knowledge safe and free up resources for new developments.

4 In-Situ Fabrication

The main challenge for the work on the construction site is to support people in their work with machines. In addition to occupational safety, health protection and a shortage of skilled workers caused by various factors, the closing of the digital gap in the construction process is the driving force for innovation in this area. Since the construction site is currently dominated by machines without intelligence, there is great potential for improvement. However, this is also associated with high technical challenges.

Factory settings allow for a conclusive prior planning of fabrication. The construction site requires a new level of intelligence within the programming, that takes into account all possible and often unpredictable events and is therefore beyond the scope of current technologies. Simultaneously the construction environment does not constitute a completely unknown fabrication environment as is assumed in the field of service robotics. Over the course of multiple planning phases and experts integrate a high amount of basic information into digital tools. However, changing environmental influences and constant structural changes in the working area of the machines do not occur in the industrial factory environment.

This requires an intelligent use of planning knowledge in combination with easy configuration and adaptability on-site. Most sensors used in production are still not suitable or in most cases not as reliable in construction environments. Within the field of CMT Pin welding we implemented a new paradigm for in process surface measurements, which tries to combine the capabilities of robotics with human planning knowledge. Instead of measuring on a point by point basis a group of control parameters is combined with a parametric geometric surface model as illustrated in figure 4. Within a configuration program the robot movement approaches a number of sample positions.

Manually the distance and angle to these positions is adapted, which in turn inform a parametric surface model used for the welding process. Figure 5 shows the process in detail. After measurement of the surface within the planned constraints and parametric model the placement of each pin is then executed automatically. Depending on the complexity of the surface and therefore the used parametric model the configuration phase requires a much lower number of adaptation steps then an adaptation of each weld position.

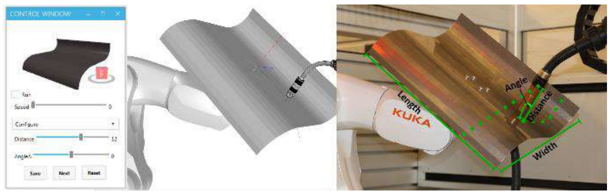

Figure 4 Link between parametric model & physical objects through robotics, with measurements through visual inspection

This allows the in-situ configuration based on parametric geometric models inside the parameter space instead of requiring and adaptation of the robot trajectory space. While in turn also informing the design and reducing sensor based adaptation to a local level.

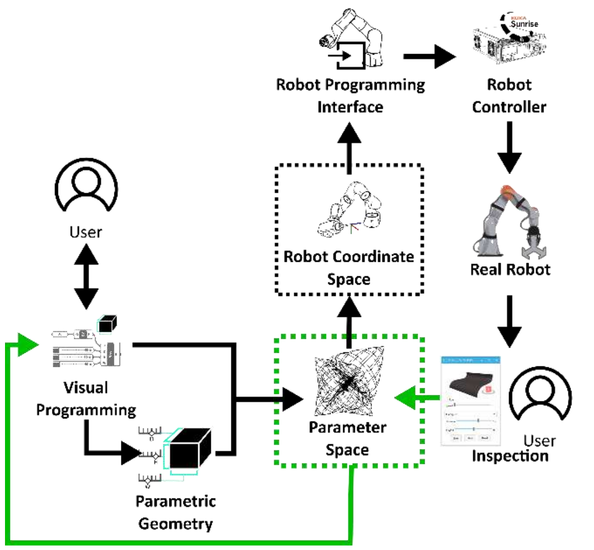

Figure 5 In-Situ parameter space adaptation in pin welding

While alternative approaches require a full scan of every part, the process can be optimized just by a distance measurement to ensure optimal fabrication while overall part position and dimensions are informed by interconnecting parameters within the robot coordinate space. Figure 6 shows the quality difference in aligned and unaligned pin welding.

Within other projects [25] for the assembly of timber structures the chair for individualized production in architecture used similar means of employing planning knowledge in combination with force torque sensors for localized measurements.

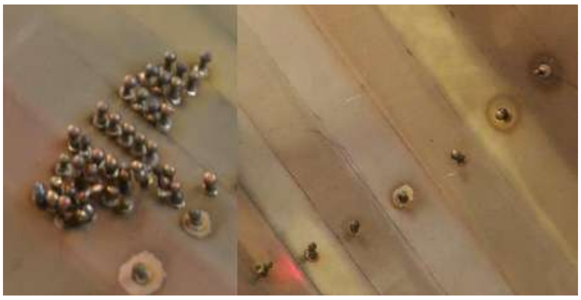

Figure 6 Pin welding with & without surface alignment

5 Approach for Planning and Scheduling

Due to the extensive changes both in prefabrication and in-situ production, it is necessary to adapt digital planning, working methods and organizational structures to changing circumstances. An important aspect here is the area of tension between the possibilities of industrial prefabrication of modular components in the factory for customized individualized application on the one hand and a targeted exploitation of site factors at the construction site, such as shortened transport routes, the use of local resources, assembly without devices and local production methods on the other hand.

This requires further development of agile planning methods and an uncertainty management for the building sector, which encompasses the entire construction process of a building from the beginning of the planning to the final acceptance of the finished building. Possible changes need to be evaluated at any time in a comprehensible way with regards to their effects (construction time, costs, etc.) according to the criteria of Lean Construction. Utilization can be increased due to the ever-increasing networking and the resulting improved possibilities of production planning and monitoring. In the event of planning or construction changes, both points provide the possibility of forecasting and initiating the costs and times of a necessary just-in-time production. The rigid structure of the production facilities in steel construction and the enormous specialization of workstations has so far prevented a high degree of individualization and the efficient production of small batch sizes and individual parts. However, the demand for this from architects and users of buildings is steadily increasing.

Here, the use of robots can achieve significant added value. If one understands the industrial robot as a machine for the assumption of stressful or highly precise motion sequences, a multitude of universal, adaptive tasks can be carried out with it, which only requires the development of adaptation to on-site factors and material- or product-specific process sequences. The same robot can take over a wide variety of sub-processes and minimize the organization and transport costs. The juxtaposition of bulky, locally tied special machines can be replaced by a flexible, multifunctional workspace. In order to further increase the degree of flexibility of such a highly adaptable workspace, mobile and stationary robots can be connected by means of intelligent, modular process flows. In addition, the wide range of movements of robots compared to conventional linear or gantry mounted machines enables simple and fast adaptation of standard mass production processes to the manufacture of highly individual components with complex geometries within the scope of mass customization. In addition to increasing the efficiency of the process and the cost-effectiveness and sustainability of buildings, further areas of application for steel construction are thus opened up and can lead to a general increase in production in the sector.

6 Usability and Adaptation

In order to guarantee a fast and continuously adapted development of new process sequences for individual, unique components, the handling of machines and machine programming must improve considerably with the help of adaptive software and intuitive operations. Up to now, the development of production processes and adapted machines has been in the hands of machine builders and computer scientists, leading to the accumulation of various special software. The adaptation of complete or individual process flows cannot usually be carried out by the steel constructors themselves, but only in consultation with specialists. This not only leads to unnecessarily long conversion and adjustment times for existing factories. It also prevents the seamless, direct integration of the existing material and process know-how of the steel constructors and other parties involved in planning into the production process. Uniform, intuitive software can lead to planners, employees and technicians of the steel construction companies being able to develop and map their production processes themselves in ever faster cycles. Stronger, interdisciplinary interaction between different disciplines for effective integral planning and BIM should be urgently implemented.

The software plug-in KUKA|prc (parametric robot control) [26] is a model for intuitive robot programming in the creative industry. The universally usable basic structure of the software enables a simple, geometry-dependent path planning of the robot as well as the smooth integration of further design and material parameters up to the optimization of the arrangement of work pieces in the working space of the robot to improve the production time. This is also what inspired the described process adaptation used within the described pin welding process.

The proliferation of such an open, intuitively operated system could, in turn, not only increase the efficiency of a single trade union, such as steelwork within the construction industry, but could also bring about the linking and simplified monitoring of the entire construction and planning process of a building. This offers advantages above all in the cross-facility production of highly complex, multifunctional components and building modules and saves the time-consuming assembly of individual parts on the construction site.

7 Conclusion

Even though theoretically there is already a high degree of automation in steel construction, high investment costs and extensive factories make it affordable only for large companies. Scalability of workspace through the flexible use of robots and intuitive, open software systems can be solutions here. The challenge for industrial scale applications will be to combine individualization, which is important for the construction industry, with process reliability. It is already becoming apparent that in the field of robot-assisted manufacturing, topics such as the standardization of interfaces can only be solved jointly and pre-competitively.

Innovative researchers such as MX3D [27] and the RAMLAB (Rotterdam Additive Manufacturing LAB [28] are developing the incremental welding of additive manufacturing. This approach lays down lines of welds to build up a three dimensional object. This method creates challenges for determination of structural integrity as the heating and cooling phases of each additive layer varies in terms of distance and durations. Fundamental research into the robotic fabrication of 3d printed steel is being undertaken. This research has the goal of analyzing the material characteristics and structural qualities of 3d printed metal deposition in order to optimize and speed up the process including the integration of adaptive methods informed by sensor data and predictive models.

The development of additive manufacturing through the robotic fabrication of 3d printing in steel can lead to advancements in construction technology and new ways of mass customizing bespoke geometries both on-site and in factory settings. This paper provided a first foundation for future architectural developments to build upon. Through a consideration of this technological innovation, both present and future potential applications, considerations, constraints and benefits of this new methodology were analyzed. This included a discussion on future challenges and opportunities, ranging from fundamental questions in need of analysis, as well as the possible applied opportunities that suit the unique capabilities inherent in the robotic 3d printing of steel.

The intersection of automation and material innovation can lead to new paradigms of architectural construction. Future industrial revolutions will continue to disrupt existing standards of practice. This paper brings to light the potential of steel's future in order to provide a milestone by which to measure our progress to date and plot a path into the future with respect to new methodologies for creating steel structures.

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Building an Integrated Mobile Robotic System for Real-Time Applications in Construction

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Abstract -

One of the major challenges of a real-time autonomous robotic system for construction monitoring is to simultaneously localize, map, and navigate over the lifetime of the robot, with little or no human intervention. Past research on Simultaneous Localization and Mapping (SLAM) and context-awareness are two active research areas in the computer vision and robotics communities. The studies that integrate both in real-time into a single modular framework for construction monitoring still need further investigation. A monocular vision system and real-time scene understanding are computationally heavy and the major state-of-the-art algorithms are tested on high-end desktops and/or servers with a high CPU- and/or GPU- computing capabilities, which affect their mobility and deployment for real-world applications. To address these challenges and achieve automation, this paper proposes an integrated robotic computer vision system, which generates a real-world spatial map of the obstacles and traversable space present in the environment in near real-time. This is done by integrating contextual Awareness and visual SLAM into a ground robotics agent. This paper presents the hardware utilization and performance of the aforementioned system for three different outdoor environments, which represent the applicability of this pipeline to diverse outdoor scenes in near real-time. The entire system is also self-contained and does not require user input, which demonstrates the potential of this computer vision system for autonomous navigation.

Keywords -

SLAM; Context awareness; Real-time integrated system; Robotic computer vision system; Construction monitoring

1 Introduction

A mobile robot operating in the physical world must be aware of its environment. A large part of this awareness is about estimating spaces (i.e., of mapping) and the robot's location (i.e., localization) [1]. In the absence of external localization aids, the robot must be able to build a map and, at the same time, localize itself in the same partially built imperfect map [2]. The robot must be "contextually aware" of its surroundings, meaning that the robot must be capable of sensing different objects and making situation-specific decisions based on them. This is achieved through object recognition via semantic segmentation, which enables the generation of a spatial map of the obstacles and the traversable space of the environment. This work can also boost autonomous robotic applications to achieve a higher degree of automation in construction monitoring and personalized safety, which have high rate of interest among researchers in this area [3–8].

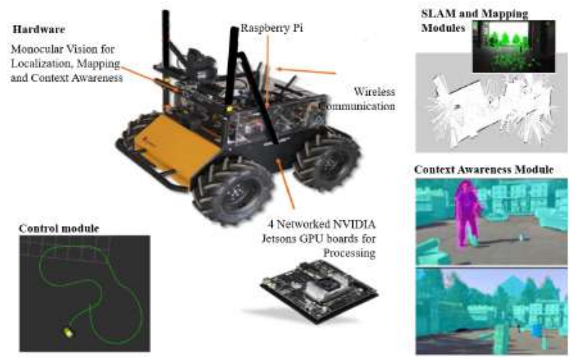

Figure 1. Overview of system components- hardware, control, SLAM, context awareness and mapping

The recent advance in powerful and portable processing units have enabled analysis of complex data streams in real-time. These small processing units with high-computing capabilities are well-suited for environmental monitoring using a combination of cameras, microphones, and sensors for temperature, air-quality, and pressure [9–11]. Still, there are a few well-set platforms that combine the state-of-the-art hardware with accessible software and opensources. This paper proposes an integrated mobile robotics agent that is capable of processing localization, mapping, scene understanding, and control and planning. The proposed integrated system uses multiple NVIDIA Jetson TX1 boards [12], each handling a specific task. The low-power consumption and integrated GPU make the Jetson TX1 an ideal candidate for running the aforementioned processes in real-time. As illustrated in Figure 1, the sub-tasks are control, simultaneous localization and tracking (SLAM), image segmentation (denoted as Context Awareness), mapping. For validation, three case studies that captures three different outdoor scenes are performed to evaluate the system's robustness, performance, its integration, and, therefore, its feasibility of the future development of an autonomous ground robot.

This paper is organized as follows: Section 2 presents a literature review on SLAM and scene understanding which are the primary sub-tasks in this approach. Sections 3 describes the system overview and hardware modules of the proposed system. Section 4 describes the approaches taken to perform the above-mentioned pipeline. Section 5 presents the system evaluation and results. Section 6 ends this paper with the conclusions and future works.

2 Background

2.1 Monocular SLAM

In a dynamic environment, human eyes can quickly and accurately provide visual information that our brain uses to map and understand the environment. A robot must also know with a high degree of certainty, where it is located in the environment. Only if this occurs, can it localize itself with respect to the map, which is essential for tasks such as navigation and motion planning. Likewise, using cameras, robots get visual information and they can generate maps of their environment. For building a good map, accurate localization is needed and for accurate localization, a good map is necessary. This chicken and egg problem is what SLAM aims to solve [13].

Initial approaches focused on 2D maps using a laser scanner or LIDAR [14]. The advantage of such approaches was the speed of mapping and the lower computational cost. However, LIDAR-based approaches suffer when there is a lot of heat and reflective surfaces that affect the laser [15]. Also, 2D approaches are unable to capture the scale of the obstacles. With an increase in processing power and development of better algorithms, the use of cameras for SLAM became more feasible.

When it comes to monocular vision-based SLAM, ORB-SLAM [16], Direct Sparse Odometry (DSO) [17] and LSD-SLAM [18] are the widely used algorithms. ORB-SLAM is a feature-based method, while LSD-SLAM is a direct method based on color intensities in the image. Relying on feature extraction, feature matching, and visual odometry, maps are built, but the drawback is that the map is accurate only up to a scale. There are several methods available in the literature which can achieve this task in real-time [16, 18–21]. The approach discussed in [16] is the most appropriate for the current task due to its speed and ability to run in real-time on the TX1. The point cloud and odometry of ORB-SLAM is not directly usable as their units are not in real-world scale. Hence, one of the tasks is to transform the unscaled odometry to real-world units. In this work, the SLAM Module provides the odometry and tracking state to the Context-Awareness and Control Modules.

2.2 Scene Understanding

The literature in object recognition is very rich, and yet growing. The goal of making the robot contextually aware can be achieved through recognition of the objects and taking decisions based on such insights. Either object classification or scene segmentation can be used for scene understanding purposes. Scene segmentation, while being more computationally intensive, provides more precise results, especially near the boundaries of objects.

Even though, convolutional neural networks (CNNs) had been utilized for a long time [22], they seemed to be hard to use for bounding-box object classification up until 2014. This was when an image region proposal scheme was combined with CNN's as classifiers and was able to outperform other object detection frameworks [23]. Later versions of R-CNN object detection were introduced to resolve some of the R-CNN's limitation, such as training pipeline complexity and slow test-time [24, 25]. Fast R-CNN [25] sped up the inference time by a factor of 25. In this method, computation of convolutional layers was shared between region proposals of an image. Faster R-CNN [24] inserted a region proposal network (RPN) after the last convolutional layer. By this change, the method required no external region proposal which improved computational speed up to 250x.

High computational load is one of the main limitations for (CNN)-based frameworks for semantic segmentation. [26] proposed a semantic segmentation framework using fully convolutional networks and utilizing existing classification networks, such as GoogLeNet [27] and AlexNet [28]. This method transfers learning approaches via fine-tuning of pre-trained models. [29] is also based on a very large encoder-decoder model performing pixel-wise labeling which suffers from a tralarge number of computations.

MobileNets [30] and Enet [31] are computationally lighter convolutional networks. ENet is designed to run on embedded boards with a focus on distinguishing roads from the rest of the scene. These capabilities make it suitable for autonomous robot navigation in outdoor (and particularly construction) sites.

3 System Overview

The monocular vision-based approach in the current study is described in this section. Figure 2, shows the

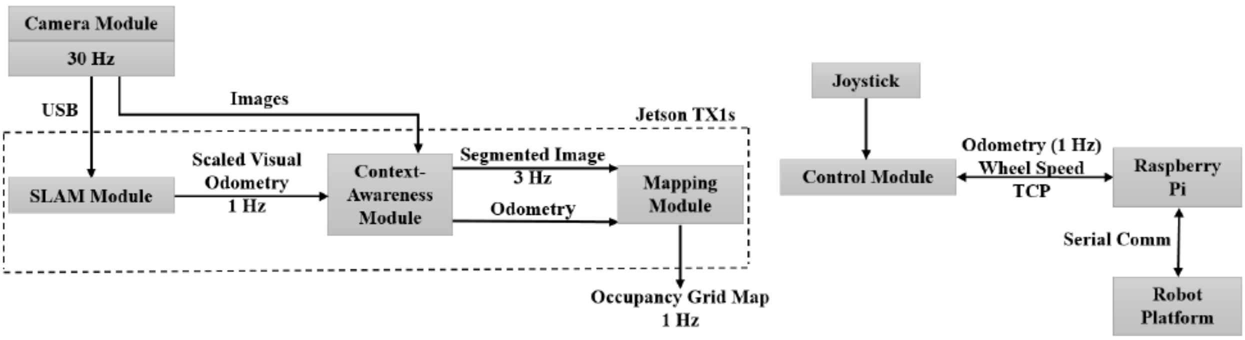

Figure 2. Monocular vision-based general pipeline

integration of aforementioned modules. The SLAM Module sends the scaled odometry to the Context-Awareness Module. The Context-Awareness Module processes the images using a scene segmentation scheme and generates a 1-D array. This array indicates the obstacle boundary which are inputs to the Mapping Module. The Control Module receives the control commands from a joystick and passes them to the Raspberry Pi. Robot Operating System (ROS) [32] is used in this research to simplify the data exchange process between multiple modules.

Figure 3, illustrates the hardware used in the proposed system which are; A Clearpath Husky A200 [33], NVIDIA Jetson TX1 [12], Raspberry Pi, Wi-fi enabled router, and a Microsoft Xbox controller. The controller is connected to the Control Module and is responsible for manually controlling the robot for initial mapping of the scene. This happens by sending this information to the Raspberry Pi through a TCP socket and the Raspberry Pi sends back the wheel encoder information. The Raspberry Pi can also operate a kill switch to stop the motors in case of an emergency. In Figure 3, There are four NVIDIA Jetson TX1 boards. Each module runs on one board to minimize logistics and integration time. A network via router on the robot connects all the Jetson boards.

4 System Description

The main goal of this research is the integration between SLAM Monocular Module, Context-Awareness Module, Mapping Module, and Control Module. This integration leads to the generation of an occupancy grid map of the environment which forms a spatial map of obstacles and traversable space of the scene. In this section, other capabilities of these modules are explained in detail.

4.1 Real-time visual SLAM with scaled odometry

The provided odometry to the Context-Awareness Module cannot be used directly. To solve this issue, the proposed approach in [34] is implemented to get the scaled information between visual odometry and wheel odometry. Both odometry are calculated for the entire path and then a closed-form solution is generated. Finally, The scaling matrix between wheel odometry and visual odometry is found and updates every second. The final odometry output that other modules can use is published as a ROS topic at a frequency of 1 Hz, as shown in Figure 1. Figure 4, shows scaled ORB-SLAM in red compared to unmodified SLAM in blue which shows that the scaled ORB-SLAM improves the trajectory. The unmodified SLAM is not able to detect the simple turn or even moving in the straight line.

4.2 SLAM and Context-Awareness Modules contribution to provide segmented images

The next step is to provide images and synchronize scaled odometry to the Context-Awareness Module for the segmentation of ground plane and obstacles. Contextual Awareness Module provides the intelligence and aids in decision-making while in motion. It strives to improve a general awareness of the environment by enhancing the visual information from the monocular camera.

Creating the segmented images and preparing them to be used by Mapping Module consists of three steps; pixel-wise semantic segmentation, filtering the segmentation vector, and perspective transformation. The segmentation model Enet [31], is used to produce a pixel-wise semantic segmentation map per image. The segmentation vector is a 1-D vector along the horizontal axis that represents the distance to the closest object at each point. Finally, a perspective transformation is implemented to convert from image to the world coordinate system. This information is used by Mapping Module to create the occupancy grid map of the environment.

4.2.1 Pixel wise semantic segmentation

The pixel-wise labeling task assigns a label to every pixel of the image. This typically requires models that are computationally heavy, with a lot of parameters. Due to

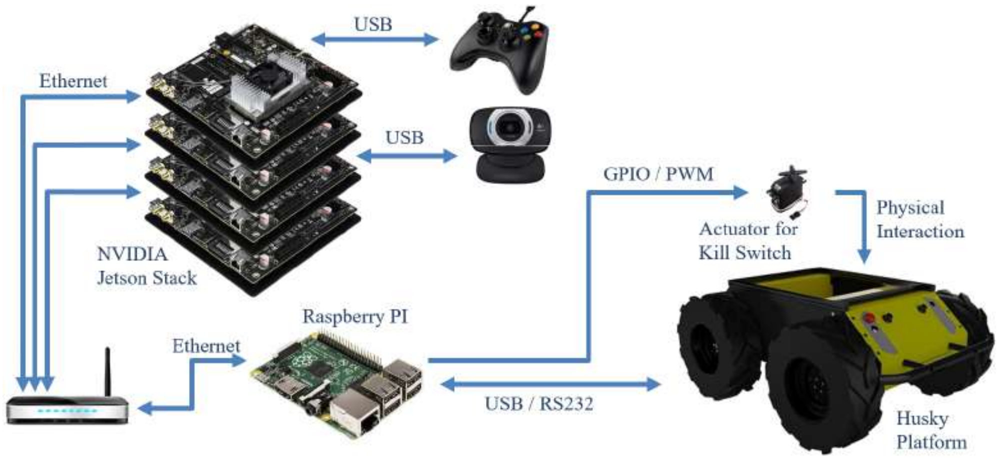

Figure 3. Physical diagram of components in the platform. The channels used for interactions between the different physical modules are labeled in blue.

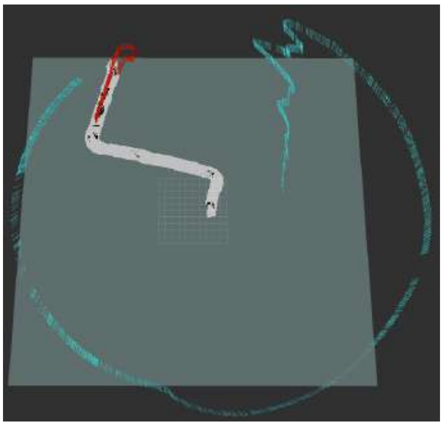

Figure 4. Scaled ORB SLAM odometry (red) vs. unscaled ORB SLAM odometry (blue)

the limited computing capability of the Jetson, a smaller model (ENet) is chosen with a slightly lower accuracy, but fast enough for near real-time performance. ENet method for semantic segmentation [31] is designed to work on embedded boards and in the current research this method is implemented on the Jetson TX1 with image input size of 512×256, at speed of 10 fps (much faster than other models such as Segnet and FCN [26, 29]).

The labeled pixel-wise data are input to ENet during the training phase. In this research, a scripting file is implemented to easily label images with freehand drawing. 1000 images, captured from multiple videos, are sampled and labeled manually. Grey-scale images with pixel information being the class label and size similar to input image size are used for training the network. Five labels are used for labeling as shown in Figure 5: object, road, person, sky, and unlabeled.

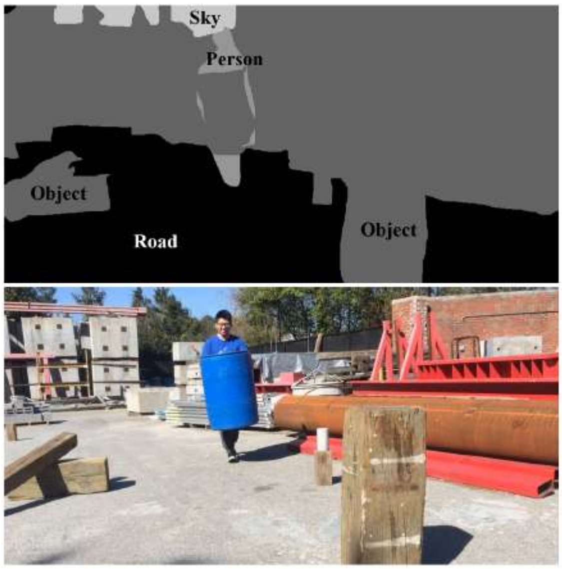

Figure 5. Different labeled classes

The training process includes 2 steps. First, training the encoder part. The input images for encoder training has a size of 512×256 and the size of output labeled map is 64×32. The model is trained for 300 epochs with a batch size of 10. Second, training the decoder part on top of the encoder to convert the intermediate map into the same dimensions as the full image.

4.2.2 Filtering the segmentation vector

The robot can move safe in the places that are known as road in the image. First of all, a 1-D vector is computed which provides the first instance of the obstacle when going through the bottom (the blue line in Figure 6). The filter is tuned to only include objects that are within 2.5 meters of the camera. Also when the vector is vertical it probably means that it is not actually the base of the object so it should not be included in the occupancy grid. To this end, points with the high gradient (more than one) in the x-direction are filtered out. The red segments in Figure 6, indicate filtered segments which are plotted as obstacles.

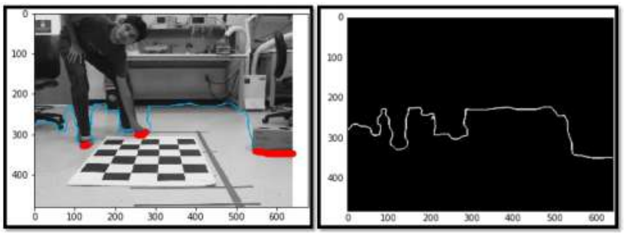

Figure 6. Red dots indicated filtered points to be considered obstacles

4.2.3 Perspective transform

The 2D image coordinates are transferred into physical distance values from the base of the robot using perspective transform. In the proposed system, the location and orientation of the camera are fixed related to the robot. Hence, a fixed perspective transform from specific focal length and camera position can be used for the whole process of mapping the pixel locations to its real-world locations (see Figure 7).

In reality, the perspective transform matrix is little different with the transformation matrix in Figure 7. The reason is, the origin starts from the top of the image, not the camera itself. Also, it is necessary for the pixel mapping to be symmetric on the left and the right sides of the robot, but the camera is not exactly in the center of the rectangle.

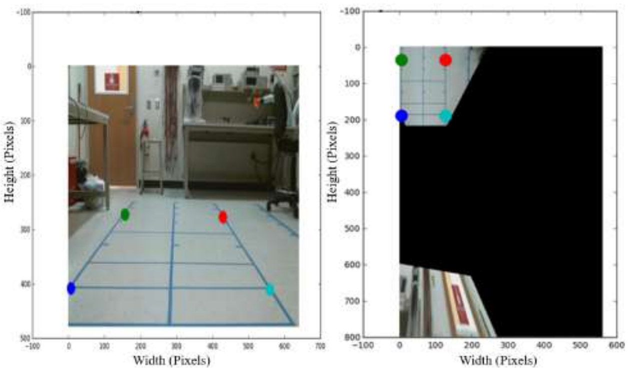

Figure 7. Left: Original image, Right: Perspective transform

4.3 Occupancy grid map creation

The Mapping Module uses the segmentation results to provide an occupancy grid map. The aforementioned obstacle position vector from Context-Awareness Module is processed to find the lower boundary of close obstacles. Next, the perspective transformation matrix helps to find the real world obstacle locations. Finally, the position of obstacles is plotted on a local rectangular map with 1.1m wide and 2.5m long and the global map incrementally updates by using the local map (see Figure 8).

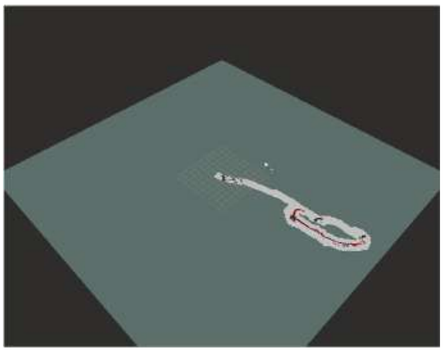

Figure 8. Global map

4.4 Publishing tracking state of ORB-SLAM for SLAM and Control Modules integration

It is necessary for the SLAM Module to know whether or not ORB-SLAM has initialized tracking. The Context-Awareness Module is not able to segment the images if the SLAM Module loses track. Also, the Mapping Module needs the images from SLAM Module to update the global map and the SLAM Module can only send the images in the tracking state. SLAM Module publishes following states: waiting for images, not initialized, tracking, and tracking lost. Providing this information for Control Module enables the robot to retrace its path in case tracking was lost. [35] shows the tracking state in the ORB-SLAM Module.

5 System Evaluation and Results

The proposed system is tested in three different outdoor environments with various object and weather conditions as shown in Table 1. The Figure 9 shows a representative image of the environment and a screenshot of the occupancy grid map during its generation. The RVIZ tool of ROS is used to visualize the occupancy grid map. The red line in the image is the trajectory of the robot and the grey rectangles represent the mapped areas.

The focus of the validation in this research is on the integrated robotic system which brings multiple components together and runs in real-time. The videos of the

Table 1. Environment description

Evironment Type	Object Type	Weather Condition	Video Length (minutes)	Number of processed frames (pipeline rate of 1 Hz)
Parking space 1	Car, curb	Cloudy	12.7	762
Construction site	Wooden planks, trash bin, cement slab	Cloudy	15.15	909
Parking scene 2	Trash bins, utility cart	Sunny	9.5	570

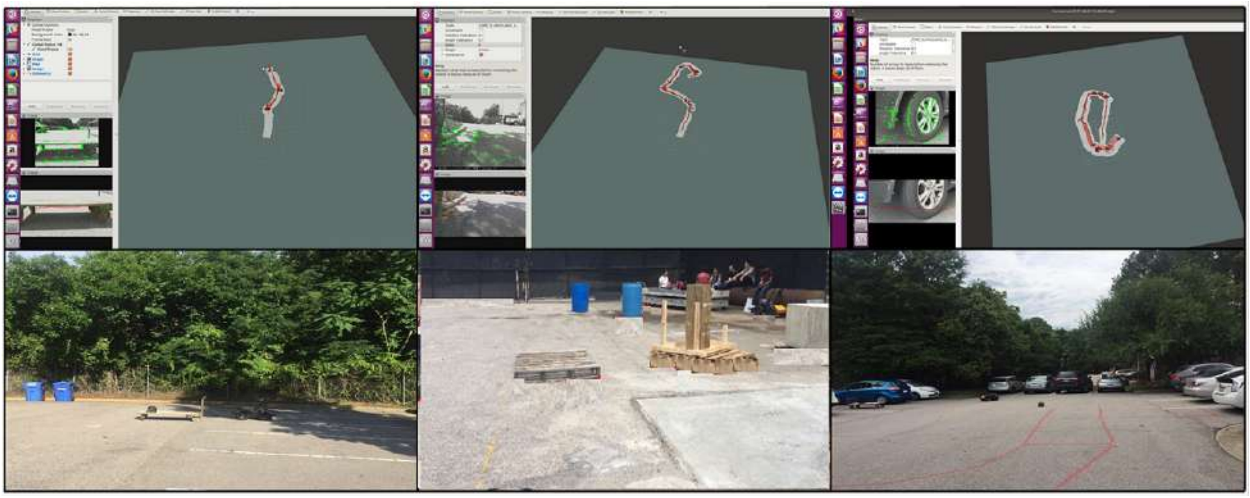

Figure 9. Image of the environment (bottom) and its corresponding occupancy map (top).

whole pipeline demonstrate the capabilities of this integrated system in near real-time [36–38].

The computational load on the Jetson boards is also presented for future systems and pipelines (see Table 2). Since the Jetson board has a quad-core processor, the percentages for the CPU are within a range of zero to 400. The CPU usage of ORB-SLAM is very high, but the scaling process in SLAM Module requires light computing. Figure 10, shows that the Context-Awareness Module runs heavily on the GPU. When an image is passed over to the ENet network, a segmented image is produced and is shown as a spike in the GPU usage in Figure 10. This process publishes the boundary-position vector at the end of processing. The hardware usage for Mapping Module is not significant and it shows the potential of implementing more than one module on one Jetson.

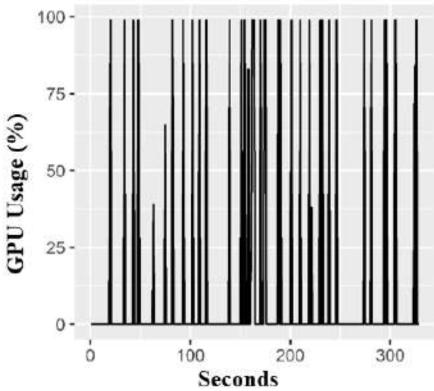

Figure 10. Context-Awareness Module GPU usage graph (%)

Table 2. CPU usage statistics. (100 corresponds to full usage of one core)

Code/CPU Usage	Average CPU Usage
ORB SLAM	186
odometry scaler	5
segmentation process	101
store_images	33
global Map	54
local Map	18

6 Conclusion

This paper presents an integrated mobile robotic system that runs multiple vision-based components in real-time. The proposed system implements monocular SLAM and contextual understanding of a scene, which creates a 2D spatial map with detected obstacles. This system showcases the importance of a modular framework which can include latest SLAM and Context-Awareness algorithms in a plug and play format. This system is effective and can be run in real-time on multiple embedded platforms that are integrated as a system. The proposed system is a step forward in making intelligent and contextually aware robots ubiquitous. The results also demonstrate the potential for enabling a computer vision system for autonomous navigation.

Some of the possible extensions and improvements to this projects are documented as follows. For instance, the proposed system does not have an effective way to deal with a large area to be mapped in real-time. A potential solution is to remove older parts of the global map and will be investigated in the authors' future work.

The use of higher resolution input images with more features will result in better tracking and mapping. To ensure that the algorithm still runs in real-time, the feature extraction and matching parts can be moved to the GPU. This will allow us to get better results in a dynamic environment.

The computational load put on each Jetson board shows that the module corresponding to the segmentation task runs heavily on the GPU. The size of the model and high memory usage along with the need for real-time performance restricts the speed of the Husky [39]. Improving the segmentation model in order to reduce the computational load in the Context Awareness Module will address this issue.

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A 4D visualization tool for TBM worksites using CAP: integration of 3D models and real-time modeling thanks to database connections

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Abstract –

The Building Information Modeling (BIM) is getting more and more common into building construction, but it hasn't been developed into underground work so far, although it would be very useful. Indeed, underground works strongly interact with their environment, and with many different stakeholders, whose data are partitioned into their own field. In this paper, a study dedicated to the development of a new decision support system is presented: it is a 3D visualization interface dedicated to worksite's technical management.

This tool is focused on tunnel boring machine (TBM) projects. Its main assets are:

-To have a 4D (3D + time) model, built in real time thanks to the connection to different databases of the worksite.

-To integrate data that comes from different fields such as: TBM excavation parameters, geological data (3D block model describing the lithology and rock alteration), buildings, tunnel as-built, stations, geotechnical and structural monitoring (settlement for example).

Until now, there has been no integration of these data into one single tool, making analyses of their mutual impact on each other quite complicated and tedious.

Keywords –

TBM; 3D modeling; 4D modeling; Visualization; Monitoring; Decision support system; Information management

1 Introduction

CAP is a system for tunnel boring machine (TBM), navigation, guidance, and data acquisition and survey. It is also a subsidiary company whose clients are TBM projects (Vinci and other general contractors).

The navigation module is based on automatic and periodic measurement of the real-time position relative to the tunnel alignment (using a total station).

The guidance module is composed of the steering console controlled by the pilot and the automaton leading to the action of the pushing rams and other actuators.

All the sensors data are stored into a database which can be used for surveying; including real-time analysis and monitoring.

This core system of the TBM is central to the worksite activity. However, it is not the only one needed. Indeed, the geology and geotechnics studies are not included; as well as the structural monitoring (such as the vertical settlement induced by the passage of the TBM).

These other systems are based on their own software solutions, with separate data representation. It means that a TBM worksite is driven by partitioned systems: there is not a global tool to integrate the crucial data throughout the project.

In addition, there is for now a lack in 3D representation for the linear infrastructures, and especially for linear underground works (geometric design tools, and data structures). The creation of Industry Foundation Classes (IFC) dedicated to underground works is at its early stage [1].

These are the reasons why we decided to carry out a study with the aim of developing a new software for CAP system which would integrate data not only related to the TBM, but also to the other systems and available 3D models (for visualization purpose, not for navigation).

The research conducted herein has led to the creation of a 4D (3D + time) interface for data visualization and automatic tunnel modeling. However, it should not be considered as a BIM tool.

It has been developed in Unity3D and is in the prototype and demonstration stage. It has not yet been deployed/marketed on TBM's projects: which is what we aim to do (from one root software, making different projects for each worksite/client).

The data used in this case study is a real project: Rennes (France) metro line B (under excavation between

2015 and February 2018).

The rest of the paper is structured as follow. Section 2 presents the inputs that we wanted to integrate and how we worked on to do so. Section 3 describes the integration processes driven by a maximum of automation. Section 4 describes the implemented tools. Section 5 presents the feedbacks of the operators who would be the users of this system.

2 Inputs

2.1 TBM digital model

For the TBM modeling, 3ds Max has been used for its convenience for computer graphics design. Indeed, the head (cutting wheel, shield, tail, articulation jacks, pushing rams, erector segment) is geometrically conform to the blueprint, but the rest of it is only computer graphics representing an earth pressure TBM. It has then been textured, and rigged to enable its animation.

The Figure 1 represents its head, and shows the cutting wheel, the shield (separated in two by the 14 articulation jacks), and the 14 pushing rams (the jacks pushing on the concrete rings).

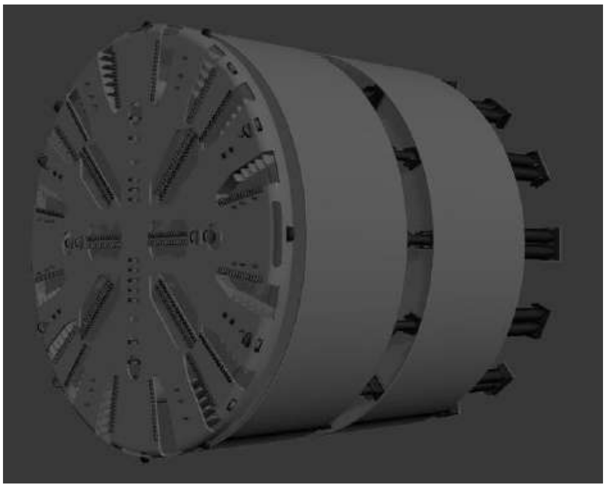


Figure 1 : Model of the TBM head

2.2 TBM parameters

CAP stores all its sensors data (it usually represents around 1000 parameters, including computed ones) in a relational database with a one second timestep. For this study, only around 60 seemed relevant to use.

The data needed for spatial representation of the various parts of the TBM are the articulation jacks and pushing rams extensions; and most important, is the curvilinear abscissa of the cutting wheel on the alignment of the tunnel (chainage).

The other data are the main excavation parameters: energy, speed, torque, speed, jacks pressure, etc.

2.3 Geological block model

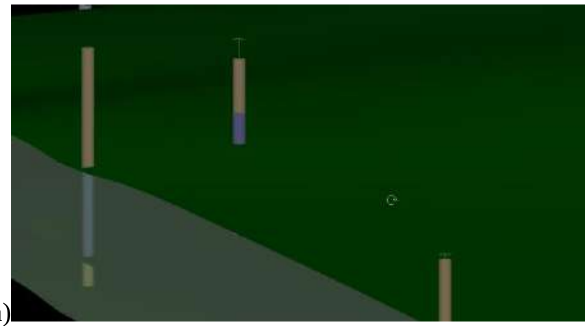
The geology of the project has been modelled by interpolation of rocks interface identified into the drilling logs. The limits in between two given layers are considered as 3D points. The process consists in computing an interpolated surface passing through that points: giving a 3D model of the border of that two layers.

This is performed over all the drilling logs description, for each lithological rock interface. Additionally, the rock alteration profile can be modelled.

This leads to the generation of multiple 3D surfaces [2], constrained by the modeler, to its geological and/or geotechnical interpretation: the common constraint is to give a preferential orientation and dip of the layers. This 3D geological output has been generated using Eureka software (Maptek).

For automatic integration of the 3D geological data, it has been chosen not to use these 3D surfaces directly as inputs. Indeed, the objective was to map a mesh (ground) with geological information extracted from the 3D model; the most automatic process is to use a 3D block model composed of voxels (volumetric data). This geological block model has been computed from the 3D surfaces (Eureka software output) using Vulcan software (Maptek). The size of the cells has been set to 0,5m x 10m x 0,5m to fit the orientation and dip of the layers (E-W 70° S).

The Figure 2 shows the alteration profile of: a) two 3D surface meshes interpolated from the drilling logs information b) a cut in the block model obtained in Vulcan.

a) 

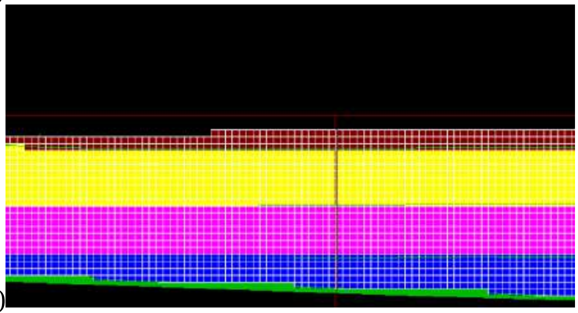
b) 

Figure 2 : a) 3D surfaces and drilling log in Eureka b) cut in the 3D block model in Vulcan

2.4 Structural monitoring

The structural and deformation monitoring is crucial for ensuring the stability on top, at the passage of the TBM. It is mainly automated, thanks to the setup of many different sensors (extensometers, inclinometers, total station / prism target etc.). On the ground, vertical settlement and differential vertical settlement is monitored.

Specific companies ensure this monitoring, centralizing in real-time into a database all the sensors data; analyzing them and computing rules and threshold for trigger alerts. They also provide software solutions for communicating to the worksite these monitoring results with GIS maps showing sensors and their values. Arising from this tool, the operators are facing many different maps and graphs, corresponding to different infrastructures, orientation, levels, etc.

We chose to represent only the vertical settlement; in the area where the settlement induced by the passage of the TBM can occur: 30m before the cutting wheel, as far as 100m after the cutting wheel (after the passage).

2.5 Tunnel alignment

A tunnel alignment does not have a 3D geometric description, because it is defined in projection plans. In the horizontal plan (x, y), it is composed of straight segments, clothoid, and circle arc. In the vertical plan, along the tunnel alignment – that is the 2D alignment previously defined – it is composed of straight segments and parabola. This geometric data is what is used to compute the position of the TBM relative to the tunnel alignment (thanks to the topographic polygonation and automatic total station tracking of the TBM).

The first extension for the IFC5 (dedicated to infrastructures) – the IFC Alignment [3] – has not been so recently released, but, to our knowledge, has not been deployed on linear infrastructures projects so far. It is connecting to GIS-like modeling, and will be the base for IFC bridge, IFC rail, IFC road and IFC tunnel [4]. While IFC Bridge is on progress for many years [5], the work on the IFC Tunnel has just started (in 2017 in France, via MINnD national project [1]).

We did not used IFC Alignment format; but simply the geometrical information of the tunnel alignment to compute a series of 3D points. A one-meter resolution of the chainage has been chosen; which is a greatly satisfactory precision: the 300-meter minimum radius resulting in 0,4mm maximum distance between circle arc and one meter segments.

The Figure 3 displays the tunnel alignment made of 3D points, in horizontal plan.

Figure 3 : tunnel alignment in horizontal plan

2.6 Stations BIM models

We had to our disposal the BIM models of the stations in IFC 2x3 format. These are LOD 300 BIM models (level of detail), and are segmented in subtrades which enables the integration of civil works only. These models have been exported via Revit in FBX format, keeping only the geometry and not the metadata. The Figure 4 displays one digital model of the project.

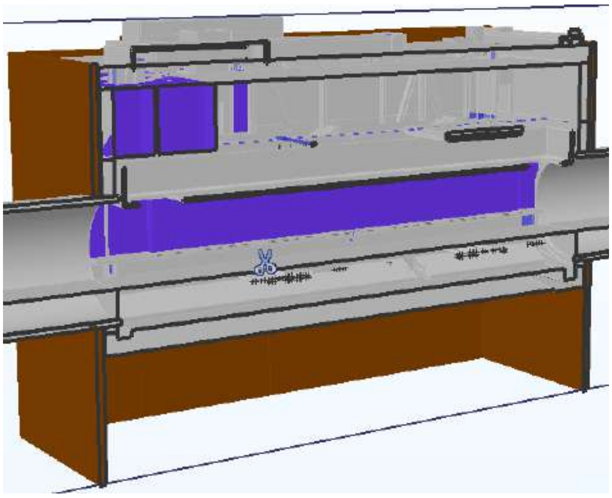


Figure 4 : BIM model of one station

2.7 City buildings model

Virtual 3D city models can be obtained from multiple techniques: photogrammetry (satellite, aerial or close range) and laser scanning (aerial or terrestrial laser scanning) [6].

After acquisition, the modeling can end up on different data: raw meshes, segmented post-processed models (like as-built buildings models with a certain level of detail). The standard file format for geographic information system (GIS) applied to cities is CityGML.

CityGML open-source data, including 3D models, are available for many big cities (for example Lyon metropolis, France [7]). These data are very relevant to integrate in a 3D application since they are segmented in sub elements, which can be used for interaction.

However, for the city of Rennes this data is not available. We decided to use satellite photogrammetry data composed of a unique mesh, including some artifacts, and vegetation (which is not the desired focus).

The Figure 5 shows a part of that mesh.

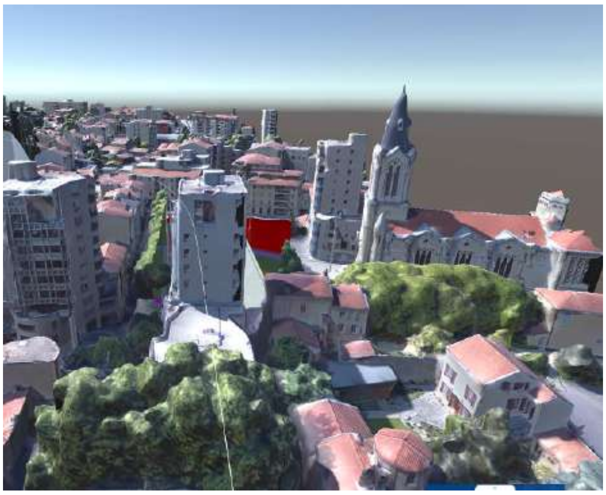


Figure 5 : City mesh

For further development, we would consider using CityGML models for the reasons mentioned above (which, if not provided in open source by cities, can be bought from dedicated companies).

2.8 Ring (tunnel lining segment) digital model

For tunnel modeling, the elementary object is the concrete ring. It has been designed on Inventor, based on the blueprints of the project. Its geometric features are detailed in section 3.3 p.4.

3 Integration into a Unity3D software

3.1 Integration overview

The inputs are integrated into a Unity3D software with maximum automation (for further projects to be created most efficiently). The TBM model is positioned and animated thanks to the TBM parameters, accessed via a http query on CAP database.

The digital models (static) were integrated into Unity3D using FBX format.

The geological block model is at the frontier between static and dynamic data: an update in the model is automatically integrated into the software (part of the Streaming Assets, with no need to get back to the Unity Editor). The methodology for its integration is developed in Section 3.4.

The Figure 6 illustrates the overall integration in the software. The verification is quite basic: the problems we encountered were due to bad georeferenced data (the worksites often use multiple coordinate systems); which are easily detected (visual check).

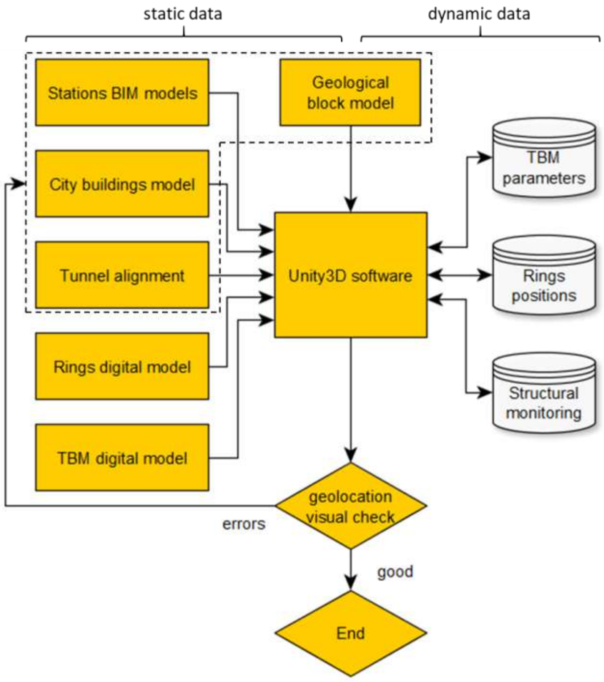


Figure 6: Inputs integration and verification overview

3.2 The choice of Unity3D

Unity3D is a game engine and an integrated development environment used to develop video games and simulations for computers and other devices. It is increasingly used in many industries applications.

Developing plug-ins onto BIM software would have been more complicated than using Unity3D (if not impossible); and it seems more likely to become obsolete with development on a specific software.

There are also convenience reasons that naturally led to choose Unity3D: drag-and-drop functionality, C# scripting. Unity3D being multi-platform is something valuable too: our software is only built on a computer application, but AR or VR may have a use for this tool.

Additionally, its widespread use in the field of 3D industrial application makes it an appropriate solution to plug in with other similar tools.

3.3 Automatic tunnel modeling

The real-time storage of rings position enables the automation of tunnel modeling. The json answer to the http query on the database is structured as follows: ring number, ring type (there are two types of rings: 1,3m thick and 2m thick), and angular position of the key segment. Besides, the chainage of the first ring is given.

A ring is composed of different segments (seven in our studied project). They form a cylinder cut at its borders by planes which are not orthogonal to the axis of the cylinder (forming a trapezium if looked at in the right projected plan, cf. Figure 7).

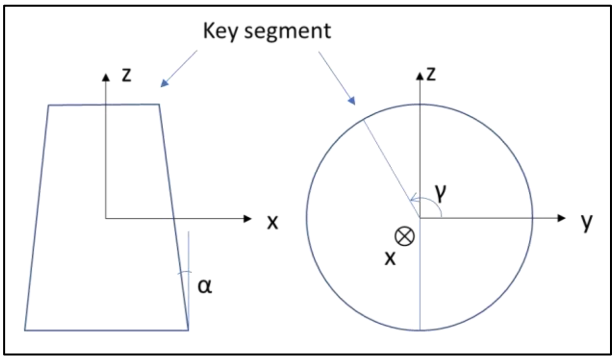


Figure 7: Drawing of a concrete ring

From the chainage of the ring, we can compute five degrees of freedom (DoF) thanks to the tunnel alignment data. The sixth one is given by the angular key segment position (γ) which is incremental.

This information is satisfactory to instantiate the sequence of ring models centred on the as-designed tunnel alignment, and with the true key segment positioning. Since the segment positioning is not defined by the construction survey, we can consider that as being a semi as-built modeling of the tunnel. The scripting of this part, and the frequent database connection (0,1Hz), makes it an automatic and real-time modeling tool.

Moreover, as time information for the pose of rings is stored in the database, we gave the possibility to watch its evolution over time (making it a 4D model). In addition, a metadata has been added on the segment models to link it to the document management system (DMS) of the project relative to the quality survey of the rings and to the traceability of their manufacturing.

The Figure 8 represents a part of a ring sequence seen from inside, and in which we can navigate. The ring number is displayed, as well as the segment numbers (the key segment is displayed with darker color).

Figure 8: Semi-as-built tunnel model

To obtain a full geometrical as-built of the tunnel, the real (as-built) tunnel alignment should be integrated.

M. Lu et al. computed an as-built of the tunnel from the position and orientation of the TBM [8]. However, the tunnel is moving a bit after the TBM passage (it is usually going up at a centimeter order of magnitude, due to the subtraction of the TBM weight). That's why topographic surveys are necessary to precisely measure the as-built tunnel alignment (the deformation of the rings is also measured). These data were unavailable at that time, therefore we tested another technique to obtain the as-built tunnel alignment. It has been computed using only the first ring position (for which the 6 DoFs are known), and the sequence of angular key segment position.

Based on the drawing of Figure 7, we can write the angular differences between ring N and ring N+1 (spherical coordinates) as follow in Equation 1-3.

$$\theta_{N+1} - \theta_N = \alpha(\cos\gamma_N + \cos\gamma_{N+1}) \quad (1)$$
$$\varphi_{N+1} - \varphi_N = -\alpha(\sin\gamma_N + \sin\gamma_{N+1}) \quad (2)$$
$$\alpha = arctan(l/2D) \quad (3)$$

γ being the angular key position; θ being the angle from x in the (x,y) plan of the ring frame; φ being the angle from z; l being the tapering of the ring; and D being the diameter of the ring.

We computed it on a dataset – in the cartesian coordinates system of the tunnel alignment – and compared it with the as-designed tunnel alignment. The Figure 9 shows the difference between these two alignments, along with their distance to the first ring.

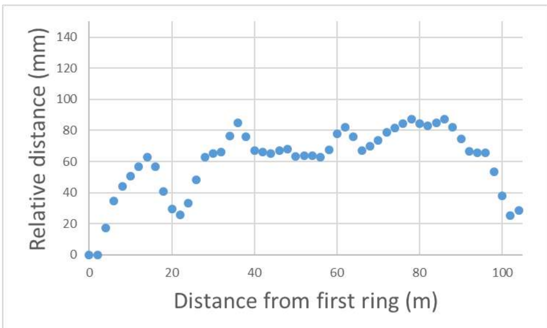


Figure 9: difference between tunnel alignment and computation from ring sequence

These values (around 7cm) are too big to be the true distance between as-built versus as-designed alignment. We suppose that the difference is due to the elasticity at the interface of the rings (rubber sealing).

For as-built alignment computation, we should either use the technique developed by M. Lu et al [8], or wait for the topographic survey to be done. The presented technique is of no use on its own, but could be used in complement with a topographic survey (for computation between the measured rings).

3.4 Creation of a ground mesh with display of geological information

For representing the geological block model data, we choose to create a ground mesh. This method is lighter for rendering computation than a volumetric rendering of the topological data.

The process of the mesh generation is based on “naïve surface nets”, a simplified version of “marching cubes” process [9]. It consists in meshing an implicit surface in a discrete distance field defined in each point of a 3D uniform grid. The size of the grid has been set to the smallest size of the block model cell.

The geometry of the model to mesh is defined by Constructive Solid Geometry (CSG) operator. This simple and fast process consists in combining closed surfaces thanks to Boolean operators (union, intersection, subtraction) [10].

For creating the ground mesh, we combine:

- A cube representing the edges of the ground.
- The surface of the tunnel defined by its polyline dilated to the radius.
- The simplified envelops of the stations by convex decomposition.
- The level at the surface of the ground. The implicit surface of the ground is defined by the distance of a point to the weighted neighbors projected on the weighted normal of the neighbors [11]. The neighbors search is optimized thanks to a KDTree (knnflann).

The surface mesh is then generated by surface nets method; which guaranty one quad per cell, rendering a color information for each cell without the need for creating textures, and wrapping/unwrapping them on the mesh. The drawback is the number of triangle to display, but it is still lighter than a volumetric rendering.

The color information (corresponding to a geological information) is rendered by “vertex color”. We define a color on each vertex of the mesh, thanks to the geological block model, and the color of the triangle is interpolated.

The Figure 10 displays the result of that process on the project dataset, including TBM and tunnel model.

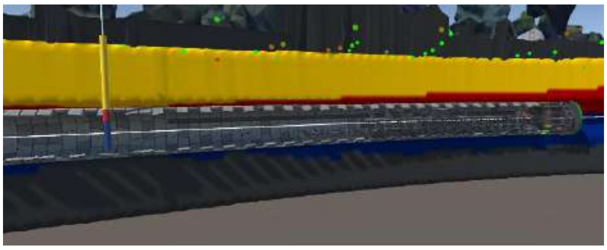


Figure 10: Ground mesh with geological colour information

3.5 Other integrated inputs

The Figure 11 shows the vertical settlement: each monitored target being represented as a sphere colored by its settlement value: green (0mm) to red (-3mm). The big white sphere represents the position of the TBM’s cutting wheel. This is a straight forward integration, relying on a database query.

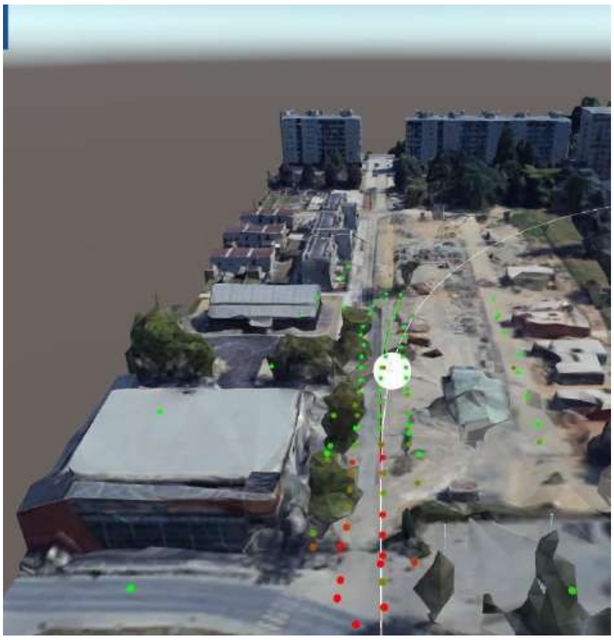


Figure 11: Vertical settlement monitoring

The Figure 12 displays the positioning of the TBM (head and rear cars) thanks to the chainage information, articulation jack extensions, and tunnel alignment. The rings are also represented.

Figure 12: TBM positioning on the tunnel alignment

All this information being stored in databases, it is possible to visualize it over time such as for the tunnel modeling. However, in this prototype software, it has not been fully integrated with data over time. It will need some optimization not to overload the internet bandwidth of worksites with high frequency queries.

3.6 Resource-efficiency compared to data weight.

We worked on optimizing the size of the meshes. The original versions were much heavier than the final ones presented in Table 1.

Table 1. Mesh vertices number classification

Element	Vertices	Triangles
City	1 166 626	2 060 814
Ground	286 167	558 185
Station 1	12 646	51 104
Station 2	78 116	245 079
Station 3	49 293	105 205
Station 4	34 377	94 639
Station 5	27 397	96 300

When testing the run of the built application, it has been noticed that we are far from overloading the processor (Intel Core i7-7500U). Around 40% of its resources are used (cf. Figure 13).

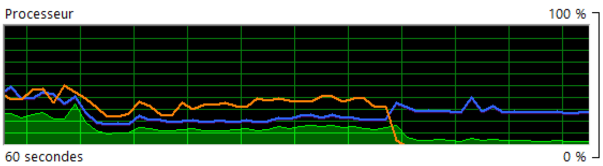


Figure 13: Processor resource (orange curve)

However, a full worksite can be much bigger than this scene (this represents only 1,4km of the 9km of Rennes project). Without optimization on data visualization (such as GIS rendering optimized with the distance of the camera), it will be overloaded. This subject will be addressed on further studies.

These performances do not guarantee every possible project with the same mesh volume: it relies also a lot on other parameters, like the textures. Additionally, a changeover on WebGL could be asked (which would need to do some compromises).

The geological block model represents 87 728 935 points. Instantiating a cube GameObject for each point would have led to over than 2 billion vertices.

4 Implemented tools

4.1 An interpolation of the surface vertical settlement

To give a better representation of the vertical settlement local data, we decided to compute 2D map over the surface of the project, inspired by the interpolations usually employed for level interpolation [12]. The result presented on Figure 14 has been done using an inverse distance weighting interpolation (IWD). We should consider studying also other interpolations to analyze what fits best, because we did not find articles on that specific topic.

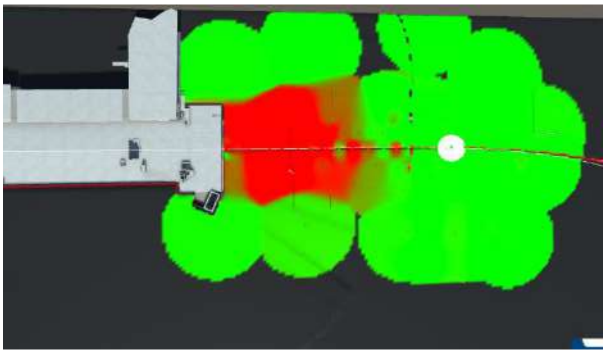


Figure 14: Interpolated vertical settlement map

4.2 A cutting functionality crosswise of the tunnel alignment

Usually, the geological (and potentially geotechnical) drilling logs interpretation does not end up with the computation of a 3D model for underground worksites. In most cases, it is manually interpolated over the longitudinal vertical cut of the tunnel alignment. That's why the only visualization of the geological data along the longitudinal cut does not have a strong value added.

The crosswise cuts, on the contrary, are not usually produced, except for specific areas where it is required. To differentiate from what already exists, we implemented a cut functionality crosswise of the tunnel, positioned by the user. It is a 2D raster geolocated that gets the data from the 3D block model.

Additionally, it represents the interpolated vertical settlement along its cut segment (the settlement value has been multiplied by 1000 so that it is visible). The Figure 15 displays an example of a cut.

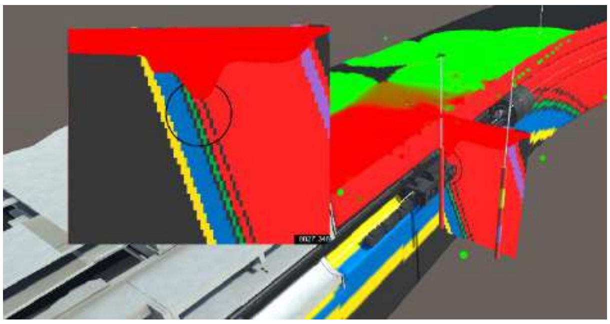


Figure 15: Crosswise cut

5 Feedbacks from the worksite operators

This prototype software has been presented to many worksite operators (technical management) to have their feedbacks. From their point of view, having global information represented in 3D is very valuable. They consider this potential tool as a decision support system that would ease representation of a big amount of data that can't be naturally seen in the real world (because underground). Indeed, the environment, the geology, and the TBM behavior (amongst others) are impacting for the decision making (such as the confinement pressure). Furthermore, the overall visualization can help understand/interpret soil behaviors (e. g. structural monitoring behavior explained by a geological analyze), leading to a better response. It would be particularly helpful when they are facing an incident, and needing to take a quick and efficient decision.

Opinions are diverging when it comes to discuss who the user would be. Everyone agreed that it would be used by technical management, in the office; but some say that it could also be used in the TBM, by the pilot.

Something specific has been noticed, and is important to highlight. From what we know, 3D geological block model is not used in the construction industry (unlike in the oil and gas or mining industries). Operational teams are not used to its scientific representation, and can find it inaccurate since it leads to knurled edges on the cuts, whereas they usually analyze cuts with smoothed interpolation in between drillings logs data. That's why it is necessary to well explain this representation before deploying such data.

The interviewed people also agreed on its limitations: it will not substitute from the other data representations, and software solutions. This new tool aims to ease the overall comprehension of the worksite and better its representation for the operators. It will not enable high end analysis of specific data, for which the existing tools are satisfactory.

6 Conclusion

This study resulted in the development of a functional prototype software of a 4D visualization tool dedicated to underground projects including a TBM: merging data that are usually partitioned into their own field.

We consider that it is a successful proof of concept of what can be done using the data to our disposal from worksites (3D models, and database information) for global 3D integration thanks to Unity3D. The main limitation to broadly deploy this software on worksites equipped with CAP system is the need for manual integration of the data; despite the efforts for maximum automation (such as station texturing, and database connections). This will be further investigated for creation of new projects quickly and efficiently.

One of the problem we faced during that study is the lack of clean, structured data; in addition to the multiple coordinate systems used. For further work – development or deployment – we would ensure that the exchanged data with the worksite are well specified, until BIM become widespread in the underground projects.

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Predictive Analytics for Close Calls in Construction Safety

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Abstract –

Extracting knowledge from data on near hits (aka. close calls) might warrant better understanding on the root causes that lead to such incidents and eliminate them early in the risk mitigation process. While a close call is a subtle event where workers are in close proximity to a hazard, its frequency depends–amongst other factors–on poor site layout, a worker's willingness to take risks, limited safety education, and pure coincidence. While existing predictive analytics research targets change at strategic levels in the hierarchy of organizations, personalized feedback to strengthen an individual worker's hazard recognition and avoidance skill set is yet missing. This study tackles the bottom of Heinrich's safety pyramid by providing an in-depth quantitative analysis of close calls. Modern positioning technology records trajectory data, whereas computational algorithms automatically generate previously unavailable details to close call events. The derived information is embedded in simplified geometric information models that users on a construction site can retrieve, easily understand, and adapt in existing preventative hazard recognition and control processes. Results from scientific and field experiments demonstrate that the developed system works successfully under the constraints of currently available positioning technology.

Keywords –

accident investigation; building information modeling; close call; construction safety; data mining; education and training; hazard identification; location tracking; near miss; predictive analytics.

1 Introduction

Better understanding the root causes that lead to an accident is important to protect construction personnel from similar mishaps in the future. Unfortunately, most of the current accident investigation methods focus on supplying valuable information after the fact, once a person has been injured or killed. Accident investigation reports, as explained in [1], are often (purposely) brief and only a few pages long [2]. Fatality assessment and control evaluation (FACE) reports are one example of a practiced method of an investigation [3]. They typically contain factual information, for example: a description of what happened, the actual results of the event, the persons involved, the equipment or material involved, the activities preceding and during the event, the date, time and place of the event, any emergency actions taken, some pictures of the event situation, and the immediate remedial actions taken.

While the contributions of this study do not substitute any of the existing investigation approaches that are in place, it tackles the topic more pro-actively. In the ideal case, the proposed method will support existing processes with new information to close calls that has not been available before. As [4] has previously outlined, construction safety has to happen at the right-time. Thanks to emerging technology, detailed information on close calls can be recorded and analyzed near real-time. The generated information then can be used for predictive analysis and even immediate mitigation.

This paper first reviews the existing research body on close calls in construction. It explains the proposed algorithm for quantitative analysis of close call events in construction safety. Scientific verification through simulation and validation using real field experiments follow. The results demonstrate the functionality of the developed algorithm and software user interfaces. A discussion and an outlook for future research conclude the paper.

2 Background

2.1 Definition of close calls

Several researches in construction describe a close call as an event that almost resulted in an accident. Too close proximity between a pedestrian worker and a known hazard is one of such events. However, there is no research that provides a scientific definition of the exact characteristics of a close call [5]. According to [6], a close call can be part of a sequence of events that result in anywhere from minor to major accidents. Therefore, close calls should be recorded and followed-up with a close call reporting program. Such programs, in an ideal case, measure safety performance and reduce the probability of accidents. However, the success of close call reporting crucially depends on the participation of persons to report near-misses, which can lead to inconsistent or false results [7]. Due to the often complex contractual organization of projects, construction companies often face difficulties in implementing effective close call reporting and analysis programs.

2.2 Reporting and analyzing close calls

Heinrich's safety pyramid (aka. the accident triangle) provides an early example for separating close calls (called therein near misses) from actual accidents [8]. Fast forward and decades later, the results from a survey by [9] suggest that employees from companies with high health and safety ratings perceive their own safety, zero harm, and continuous improvement in health and safety as very important. In the same study, construction hazard identification, including close call reporting, ranked 10th out of 38 topics which shows the general acceptance of such a system. [10-11] then discussed the strengths and weaknesses for a qualitative (matrix) and quantitative (index) near-miss management system. They focused on how close call reporting and filtering could be implemented to minimize both missed near-miss reports and unnecessary reports. Their design consists of four separate phases: Event identification and reporting, event assessment, prevention measure application and follow-up actions. Among other noteworthy research that followed, [12], for example, established a database consisting of feature vectors (values that represent information on an incident) for close calls, filled with data from common written incident-reports, viewing close calls as events which lead to an accident.

Today, under often self-motivated initiatives for establishing leading indicators for safety, pioneering owner and contractor organizations highly encourage the (voluntary) reporting and analysis of close calls by everyone involved in a project. Databases with restricted access exist where close calls are entered manually or via guided user interfaces (GUI) on mobile devices. Such recent examples from modern construction sites demonstrate the advancements that have been made for reporting and investigating incidents. In brief, the reasons for this change can be summarized twofold: (a) driving organizational change in safety culture by rethinking existing and establishing new processes and (b) taking advantage of sophisticated technologies to record and analyze real data. Our work therefore focuses on low-severity, high frequency injuries. It does not necessarily translate to high-impact, low-frequency events.

Among other research studies, the most closely related previous study was performed by [13]. It describes a method called Proximity Hazard Indicator (PHI). PHI successfully detects spatial-temporal (proximity) conflicts between workers and construction equipment using real-time location sensing (RTLS).

2.3 Summary

Practiced close call reporting and analysis rely on manual data gathering efforts. Using only manual reports as a source of information has several disadvantages. Some of the issues presented in the following help explain the problem:

1. *Size of the problem:* The number of reported close calls is probably smaller than the true number (i.e., personnel may not report close calls fearing retaliation or a drop in productivity).
2. *Standardization:* Accident investigation reports vary by country and are kept general to inform the entire organization and sometimes even the industry. An open-access benchmark which is based on high quality (anonymized), near real-time data and available to every construction site or personnel is missing presently.
3. *Data availability and processing:* Processes depending on manual data lack the necessary level of detail (i.e., unlike the airline industry for the past decades or unmanned autonomous vehicles just recently, trajectories of construction equipment are often neither recorded nor analyzed).
4. *Collaborative planning:* Though BIM offers the construction industry a method to plan, build, and operate infrastructure or buildings, standardized tools for construction safety (and health), site layout or work station planning are missing (i.e., most projects perform modeling efforts with BIM manually at low or moderate detail and only on an as-needed basis).
5. *Safety culture change for labor and management:* Since close call reports may include sensitive information to an incident [14], person(s) reporting them might impact labor-management (i.e., workforce vs. supervisor, management) relations and organizational fairness.

3 Proposed method

The proposed method intends to change the close call reporting and feedback process. As introduced earlier, close calls are typically reported when a human witnesses or participates in an event which compromises or threatens to compromise the health or safety of a person or the environment. If necessary, a person may conduct first efforts to prevent an accident or a further incident. The person notifies their supervisor or safety coordinator on site directly or using a close call reporting application on a mobile device (i.e., if permitted on site: smartphones or tablets) (see Figure 1).

Figure 1: Close call reporting, analysis, and personalized feedback process

Some general information about the event is shared once the case reaches the corresponding safety professional within an organization (a knowledgeable person). Afterwards, a problem-solving peer-review team consisting of workforce (who are trained in operational skills), safety professionals (who are trained in root-cause analysis), and management (who are trained in continuous-process improvement) will heighten the awareness for the seriousness of the case within their own organization. Various means exist to learn more about the risks and how to mitigate them, for example, calling for dedicated close call review meetings, department safety meetings, one-on-ones with workforce or supervisors, or involving a neutral third party. The team, while protecting employees from blame [15], finally recommends corrective actions. At this point, well-working close call reporting processes in practice (should) ensure timely feedback to the person(s) who reported the incident in the first place.

The proposed close call reporting and analysis, and personalized feedback process takes advantage of remote sensing and information modeling to automatically record the circumstances that lead to close calls. By attaching a RTLS device on every resource (pedestrian workers, equipment, and material that was a-priori declared hazardous), their then available trajectory data will be analyzed in BIM to locate close calls.

The proposed methods used in the new workflow are explained next in more detail. It is followed by a detailed investigation into the theoretical verification of the proposed methods using first a simulated data set in a fictional construction setting and thereafter (after ensuring the methods work successfully) several realistic data sets for experimental validation on live construction sites. As a note, the initial selection of simulated over realistic data permitted the verification of the proposed method under ideal (repeatable) conditions. In the simulated setting, a fictional building information model and trajectory information was assumed for the artificial pedestrian workers' and equipment travel paths.

3.1 Trajectory data to construction resources

Construction resources are physical objects and spaces that are required to finish a construction process. In this research, the term construction resource refers to (a) the pedestrian workforce, (b) construction equipment, and (c) objects or structures of temporal or final state. The number of any of these resources in the scene under investigation can be one or many. They can also be static or dynamic in nature. Pedestrian workers as well as equipment are moving frequently, while temporary objects, such as scaffolds or hazardous materials like gas bottles, are mostly static and stay in one position. Other examples of static or as-built structures which can be hazardous are unprotected edges in elevator shafts or leading edges in high-rises.

Construction resource data is defined as a term to summarize boundary data from building information modeling and trajectory data from trajectory logging files. Trajectory or position logging devices frequently store a resource's relative position and the current time, namely timestamps, inside a log-file [16-17]. The logging frequency and additional logging information like battery status both depend on the type of device. In this research, a frequency of one event per second (1 Hz) is assumed to simplify the following calculations.

3.2 Protective envelopes

To automatically detect and analyze close call events between *resources*, additional descriptive information for each individual resource involved in a close call event is necessary. For example, its precise position and *boundary* information define a *protective envelope*. For the reason of simplicity, all data presented in this study is kept to two-dimensions (2D, plan view). As a result, the protective envelopes come in shapes of circles or polygons. The number of the involved resources as well as their parameters, i.e. the size of the protective envelope called the *safety distance*, are set in advance based on the previous research findings by [18]. Trajectory information and building information model complement this chosen approach. The size of its safety distance and its shape are based on the following assumptions:

- *Pedestrian workforce:* A circle with a radius of 1.5 m is selected. This value is based on the average distance a human walks in one second, reacts, and comes to a complete stop [18].
- *Construction equipment:* A protective envelope for equipment must be wisely chosen considering several of its operating parameters. These include, but are not limited to: operating speed, angle of operation, and articulation. Even external factors, such as ground conditions, might be included into calculating a machine's breaking distance. While [19] has shown that multiple hazard zones for equipment are advisable to avoid a hit, generally a fixed value decided by a user is added around the equipment's known bounding box.
- *Temporary object:* The size of a protective envelope for temporary objects (e.g., safe storage of gas bottle) is determined according to rules and regulations set

by governments and local authorities [20]. The resulting shape is a resized version of the existing boundary.

- *As-built structure:* Many structures, once they are erected and remain on site, might also require protection. Guardrails, for example, preventing workforce or equipment from falling to lower levels typically have protective envelopes associated to them. Their safe installation is also regulated by official regulations or company best practices [20].

3.3 Close call event and analysis

Currently, there exists no common definition for close calls [5-6]. A close call, as defined in this research, is a proximity event between one or several pedestrian workers and a hazard, leading to an endangerment of the workers. Also, a close call as it relates to a too close proximity event between two resources A and B is defined as an overlap of their protective envelopes at positions $P(A,t)$ and $P(B,t)$. When using trajectory data, there are two possible approaches towards categorizing close call events: (a) to categorize every proximity event as a separate close call or (b) to combine consecutive occurring proximity events to a single close call. The latter is the more sensible choice for this study.

For each proximity event, a proximity event buffer is created to store information for later processing. This information includes timestamp a [yy:dd:hh:mm:ss], position [m], velocity [m/s], and orientation [°]. Information on the distance [m] and facing direction [°] towards the other resource is also stored. In the example shown in Figure 2, a piece of equipment has been traversing too close to a gas bottle.

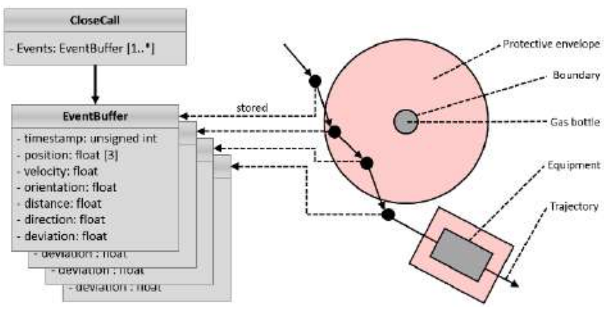


Figure 2: Close call EventBuffer class diagram

For two resources A and B, a close call detection algorithm (1) analyses their trajectories and (2) checks for each *timestamp* $t \in T(A),T(B)$ if their protective envelopes overlap. If an overlap is found, a new close call gets created and a proximity event buffer is assigned to it. Every consecutive proximity creates a new event buffer which is added to the same close call. If no further overlap is detected, the close call is completed and the next proximity will create a new close call. As the trajectory data only consists of coordinates and timestamps, *velocity, facing direction, distance, and orientation* must be calculated separately.

For each close call a radar plot is computed showing the weight values for velocity, duration, deviation, distance, and orientation. Values to these weights visualize the severity of the different aspects that contributed to the close call event. The higher the value points in the radar plot, the more the aspect contributed to the endangerment of the resource. Velocity and length during the close call event (see Figure 3) give a user a brief overview of a resource's safety performance. As suggested by [16] personalized feedback or other change (i.e., selection of other equipment or type, modification to site layout plans) can be issued and future performance monitored until the issue is resolved.

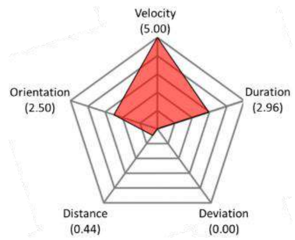


Figure 3: Factors leading to a close call

3.4 Close call visualization

The computational analysis of the gathered data starts with the examination of all single event buffers. From there, it abstracts and combines these information into more general statistics. As the level of detail drops with this generalization, a Guided User Interface (GUI) displays the construction site layout on a map, general construction site statistics and an overview to all construction resources, separated by type. A heatmap, if selected by the user, shows the location of close calls (see Figure 4). It covers statistical data as well as a brief overview on all resources being present at the construction site and involved in close calls. This GUI might be used by management to derive a quick performance overview on close calls for one construction site.

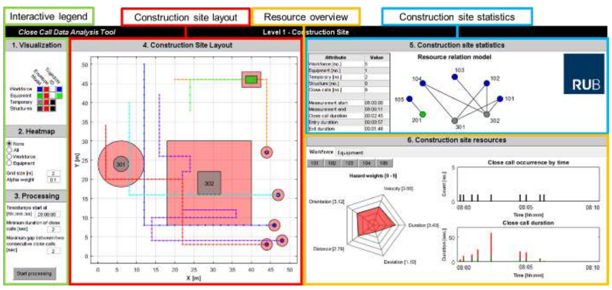


Figure 4: Guided user interface for close calls

4 Verification of method

To verify the method, close calls among few resources were artificially generated. Details were discovered, for example: the course of close calls, individual resource- and hazard-statistics, a heatmap as well as comprehensive construction site safety statistics.

Industry expert input asked to find intuitive answers to typical safety-performance-related questions:

- Which are the areas where close calls occur frequently?
- Which workers or pieces of equipment are involved in a close call and are there any particular differences in the safety performance among them?
- How does a worker react on entering a hazard zone, when might the worker recognize to be at risk, and how will the worker react upon detecting it?
- Which ways exist to leverage the newly generated information for continuous safety performance improvement, e.g. in safety education and training?

The artificially generated data set (called scenario) is based on known trajectories (straight lines) where the ground truth is known and evidence available is used to verify the close call analysis algorithm. This scenario included five workers that traverse a construction site in a continuous manner, facing two temporary static hazards and one dynamic vehicle. Each worker simulates a behavior which addresses one of the different hazard weights. To raise the orientation weight value for a worker, for example, the vehicle creates a close call in a workers' blind space. All trajectories are straight lines. This permits simplicity in the verifying process of the algorithm. A heatmap displayed in the GUI further allows the evaluator to spot the close calls.

Some more specifics to the scenario: one pedestrian worker (A) traversed the site at a speed of 2 m/s (at a maximum allowable speed limit of 1 m/s). A second pedestrian worker (B) was a too short distance towards the hazards (301 and 302). A third pedestrian worker (C) simulated a behavior which should result in a high deviation weight. The duration weight was tested by pedestrian worker (D). Pedestrian worker (E) was confronted with a traversing vehicle (F) to verify the orientation weight function. The heatmap functionality was verified by comparing the trajectories with the hazard locations on the map (see Figure 5).

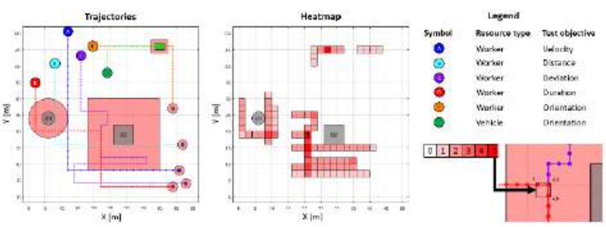
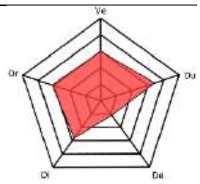


Figure 5: Guided user interface for close calls

The weight radar plots for all resources (team) are displayed in Table 1. The data can be explained as: velocity (high), duration (long), and orientation (vehicle approached from the rear) of the observed close calls in the artificially generated data set were high. The other criteria played a lesser role.

Table 1. Results to close calls from artificial data set

Criteria	Performance
Radar Plot	
Velocity (Ve)	3,00
Duration (Du)	3,43
Deviation (De)	1,10
Distance (Di)	2,79
Orientation (Or)	3,12

5 Experiments and results

To validate the close call data analysis algorithm, datasets from a construction sites were analyzed. The following sections cover the pedestrian workers' individual performances and the overall construction site safety performance. Discussions including future work follow.

5.1 Data from building construction site

A dataset was gathered on a real building construction site where several pedestrian workers were present at an elevated work level. A restricted workspace was located inside the work area. Although the protective guardrails around the leading edges met the required safety standards, the present supervisor estimated it as insufficient (asking his and subcontracted personnel "to stay away from the edges"). The close call analysis algorithm aimed at analyzing the trajectories of 4 workers for potential close calls near the leading edge and/or unauthorized entry into the restricted work space.

As shown in Figure 6 (see the grey areas in plan view) the restricted space and the leading edges were modelled as individual objects using BIM. UWB served as the sensing technology for recording the trajectories of the personnel. UWB allowed to allocate a specific ID to every worker. The information in Figure 6 displays the individual trajectories (in blue color) and, by applying the developed close call algorithm, the resulting heatmap (in a range of red colors) for every worker. The images indicate several close calls, mostly towards the southern and eastern sides of the work environment.

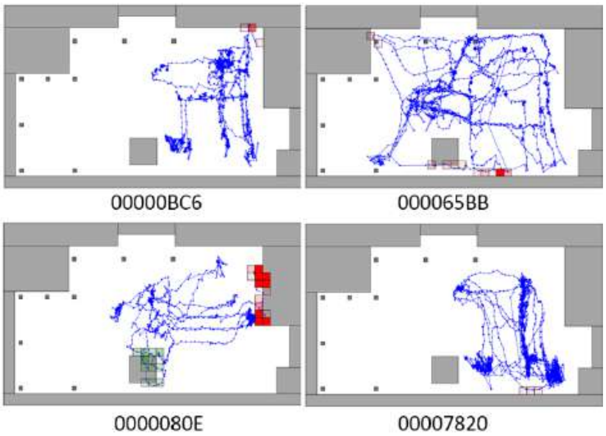
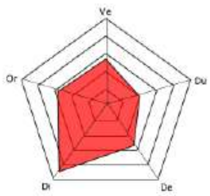


Figure 6: Individual close call performance

The analysis the generated hazard weight radar plot for the pedestrian workers' team performance gives further insights into the observed close calls (Table 2). Many of them were related to very close distances to the leading edges.

Table 2. Results to experimental validation

Criteria	Performance
Radar Plot	
Velocity (Ve)	2.69
Duration (Du)	2.00
Deviation (De)	2.64
Distance (Di)	**4.46**
Orientation (Or)	2.83

5.2 Personalized feedback

The data generated in this research might be used to give safety professionals the required facts to take corrective actions that protect the human workforce. While multi-lingual manual reporting cards for close calls may still exist in the future, they have–as outlined before–shortcomings in practice (e.g., incentives, collection, and feedback cycle). A successful transformation to digital recording and feedback is possible and yet has to be investigated in the future in much more detail. A conceptual digital feedback card would, for example, need to be tested for simplicity and acceptance by the workforce (Figure 7). While intrinsically safe mobile devices are required for industrial construction applications, recording and analysis via Internet-of-Things solutions like [21] exist to reduce the time needed in the feedback cycle. The foreman would then have new information in toolbox meetings available for use in safety awareness training.

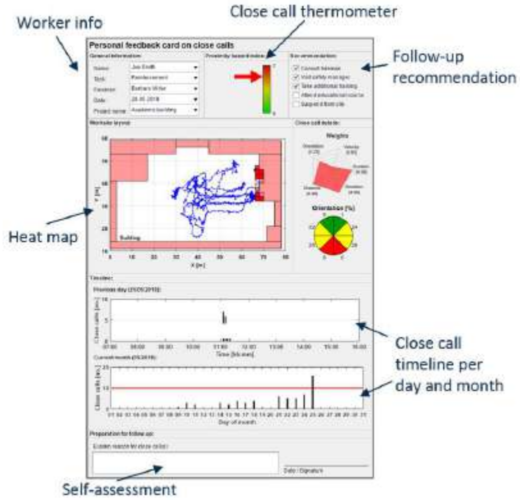


Figure 7: Conceptual display of digital close call reporting and feedback card

6 Conclusions

This study presented an algorithm for the quantitative analysis of close call events in construction. A process of collecting trajectory data as a valuable construction resource was introduced and a graphical user interface was presented that provides safety personnel with automatically generated safety information on close calls. The proposed algorithm was successfully verified first in a simulated and later in a field realistic work environment.

Although the developed method provides useful information on both artificial and real trajectories that cause close calls, the performed calculations are based on several assumptions. They rely in particular on the performance of RTLS. While many type of sensors provide RTLS data (i.e. computer vision, wireless), existing measurement errors may not qualify these (yet) for commercial application in the harsh construction environment. Though [18] demonstrated that errors with UWB can be below 1 m for each positional data log, RTLS technology must also withstand ethical concerns of tracking workforce and be effective in acquisition, use, and maintenance. The latter issue could be solved by targeting worthwhile business applications at the same time, e.g. logistics for indoor work environments. However, most of the existing RTLS still faces major hurdles and demand new sophisticated solutions to operate successfully in such complex work environments.

On a similar note, the developed algorithm considers trajectory-related information only. Although it tackles a complex question, when are workers safe/unsafe based upon their location and the situation, it uses fixed safety distances. Their current size relies on empiric findings.

Though all of these assumptions made still add new functionality to existing close call management processes, additional research is necessary. For example, the presented hazard weight calculations are based on simplified values. Field-based observations are likely necessary to complement the definition of terms and calibrate the weights accordingly. This then may solve whether a close call was a true close call. Options to expand the dataset for such purpose exist. For example, data fusion including new data points from proximity alert sensors that are able to automatically record close calls between pedestrian workers and heavy construction equipment [22-25] could serve future research agendas well. To enhance personal awareness of every worker, a port to safe test bed environments within mixed reality environments would enhance more realistic education and training scenarios, providing users with much needed personalized feedback [26].

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Cup-of-Water theory: A review on the interaction of BIM, IoT and blockchain during the whole building lifecycle

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Abstract

The Architecture Engineering and Construction/ Facility Management (AEC/FM) industry plays a significant role in the development of economy. In recent years, the wide application and development of Building Information Modelling (BIM) promote the development of informatization and digitalization of AEC/FM industry. However, due to the limitation of a one single tool and lack of understanding of single source of truth, the problems of the industry cannot be solved completely. Therefore, the revolution and innovation of industry can be stagnated. Internet of Thing (IoT) and blockchain can be considered as two technologies that can be integrated with BIM for AEC/FM industry. The aim of this paper is to understand and analyse the basic principles and the applications of these three technologies in AEC/FM industry through literature review. With the integration of these three technologies, the virtual and realistic object and data during the whole building lifecycle can be managed and stored in a security, transparency and convenient decentralized common data environment (DCDE). Finally, a theory named, Cup-of-Water theory is presented.

Keywords –

BIM IoT blockchain AEC/FM industry whole building lifecycle

1 Introduction

In recent decades, the development of global AEC/FM industry is slow compared with other industries, such as manufacture industry, aerospace industry or financial industry. This phenomenon results from low digitalization, loose collaboration and ineffective management methods in most building projects. Hence, it is of significant importance to use new technologies to improve the productivity and efficiency in all phases of a building project, including design, construction and operation and maintenance stages.

BIM, which represents one of the key technologies in revolutionizing the AEC/FM industry, is expected to stimulate a major change to this conventional industry with lots of waste, low productivity and low efficiency. BIM not only provides advanced visualization tools and real-time information synchronization, but also realizes multi-disciplinary collaboration and comprehensive management for a building project lifecycle. Increasing number of AEC/FM firms are having transition from CAD to BIM [1]. It can be estimated that more and more innovations will occur in the future as the building information can be easily recorded, queried and transmitted in a common data environment (CDE).

IoT is a network which allows the data collection and exchange of real objects supported by Internet or traditional telecommunication network. It is possible to use IoT to make building components to be on the network in a unified form [2]. Construction management can then be optimized since materials, equipment and other objects can be traced.

Blockchain technology is a decentralized ledger database, which is initially adopted as a bottom structure of Bitcoin system. It has a well performance on data updating, storage and protection [3].

The objective of this paper is to investigate how these technologies can interact with each other and produce new applications that can benefit AEC/FM industry. Through review and case studies, the principle, technical advantages and applications of each technology are reviewed. Based on those information, the author makes classification with regard to interaction forms, and discuss the advantages and limitations of different ways of interaction. At last, a new theory is came up with to demonstrate the integration of these technologies and how they affect a building project.

2 BIM based Building lifecycle

The lifecycle of a building, mainly contains several processes including the programming, conceptual design, detailed design, analysis, documentation, procurement, fabrication, construction, construction logistics operation and maintenance, renovation or demolition [4]. Due to the characteristics of a construction project, rich technical content, long construction period, high risk and many stakeholders, the project requires systems of good management over the lifecycle of a building. Life-Cycle Management (LCM) has been developed as a business approach for managing the total life-cycle of products and services [5].

With the integration of BIM, some problems of the traditional LCM such as lack of effective information sharing, and the efficiency of the LCM indeed increased significantly [6]. The BIM models contain actual information of the building including the geometric information and non-geometric information such as material for building components, weight, price, procedures, scale and size [7]. Information management aim to provide the right information, in the right format and quantity, at the right time, to the right person, and at reasonable cost [8]. BIM can provide semantically rich digital building models at each process of the project in the whole building lifecycle and the object-oriented concept is utilized to improve the efficiency of the information management in the building lifecycle [9].

A construction project has many stakeholders. With the development of BIM, many questions and problems of BIM application are put forward during the collaborative work. Thomas [10] indicated some legal issues including the ownership of the building model, the modification rights, the distribution rights and the liability for changes or errors. Meanwhile, how to manage copyright protection and how to protect digital intellectual property are also the questions that should be of concerned for relevant stakeholders. Due to the data and information exchange between each stakeholder, the trust and networking costs are also two problems of BIM application currently [11].

3 IoT

IoT is a network of internet-connected objects that able to collect and exchange data using embedded sensors [12]. It mainly includes three key technologies. The first one is sensor technology. It can be used to convert the analog signals to digital signal. The sensors include the infrared sensor, global positioning system and other information sensing devices. The second is RFID tag. It is a kind of sensor technology combining wireless RF technology and embedded technology. Third is Network Embedded System Technology. It is a complex integration technology integrated with computer software and hardware, sensor technology, integrated circuit technology and electronic application technology [13].

4 Blockchain

4.1 Definition and principle

Blockchain technology is most commonly known as a technical base of Bitcoin system. It allows the transfer of ownership of valuable things by binding the digital currency with rights to an asset [3]. The success of bitcoin trading attracts people to explore the theory of blockchain and relate it to other fields, such as IOT, supply chain, smart contracts. In substance, blockchain is a decentralized distributed ledger database using peer-to-peer network. The data on blockchain is maintained by every node on the network, and every user preserve total history of all transactions. This mechanism eliminates the existence of central administrator. In other words, no third party would participate in the network to supervise and manage user data [14].

When user performs a transaction on their computer, which is recognized as a node in the network, the node should identify whether this transaction is valid based on rules of protocol. If this transaction deemed valid, it would be relayed on a new block. Some nodes with strong computation power would put a number of transactions together and encrypt them into a block. Due to the nodes which made encryption requires a lot of energy, money and time to operate machine to calculate hash number [15]. It resulted in the difficulty for anyone who wants to attack the network for they need to expend more to decrypt the block [16]. After transactions are assembled and new block is enclosed with a header called timestamp, the new block is added to the end of the longest chain and referenced to the preceding block. This made the time sequence of the chain clear so that less resource would be wasted due to the delay of P2P network [17]. Once the chain is updated, the new chain would be announced to all nodes on the network and every user had the same copy of ledger of transactions.

4.2 Categories of blockchain

There is always misunderstanding that all the blockchains are opened to any parties in the world so that information storing on blockchain might have privacy problems. Actually, this case refers to the most commonly seen category of blockchain, which is named public blockchains. Besides, blockchain includes two more categories: Consortium blockchains and private blockchains.

4.2.1 Public blockchains

On public blockchains, any individual or organization all around the world can send transactions and the transaction can be verified to be valid. Everyone involved in this peer-to-peer network can take participation in the consensus process. Public blockchains enable users to handle their transactions in a simple manipulation. However, the network might be slow sometimes due to too much load on it.

4.2.2 Private blockchains

On private blockchains, the network demands an invitation and must be validated by either network builder or certain rules assigned by network starter. Each transaction is recorded by the approved parties or entities, instead of all participants in the network. The blockchain creator would normally set up a permissioned network, which defined authority of participants in the network [18].

4.2.3 Consortium blockchains

Consortium blockchains are also called simply hybrid blockchains, which combines the public and private blockchains. The transaction recorders are preselected in an internal group, and the production of block is determined by all these preselected nodes [19]. The rest of access nodes just participate in the transaction, they do not interfere with the Bookkeeping process, and anyone could query the limited information on the blockchain by accessing the specified API provided by the blockchain network.

4.3 Technical advantages of blockchain

4.3.1 Decentralization

Blockchain network uses distributed storage instead of a central storage system. There is no central governor on the network, which implies the consensus could be reached without centralized control. The right and responsibility of any nodes are equal, and the data in the system should be preserved by all the nodes with maintenance function. Decentralization make the transaction on the blockchain complete without extra third parties. Consequently, it provides a reliable ledger platform which eliminate the credit risk of involvement of intermediate parties [20]. At the same time, decentralization has spared the burden whenever database administrator should make decisions on protocol rules. The participants on blockchain could make specified protocols according to property of business.

4.3.2 Peer-to-peer network

Peer-to-peer network is a network system without central server and exchanging information by user groups. It realized the information transfer between each two nodes on the blockchain [21]. Unlike central network systems with central servers, each user terminal of a peer-to-peer network is both a node and a server function. In the blockchain, each node has a complete set of historical transaction books. The peer-to-peer network of blockchain solves the problem of data correctness caused by a single data source. Each user node has a history record so that the overall database could remain static even one node is attacked.

4.3.3 Immutability

Blockchain always maintains a growing chain, once the information is verified and added to the blockchain, it will be permanently stored. The transaction on blockchain can only be added and cannot be modified. Therefore, the data stability and reliability of the blockchain are much higher.

4.3.4 Consensus mechanism

The consensus mechanism solves the problem of data block being encrypted by any node in the network, so as to prevent the blockchain from being bifurcated, and there always exists the unique longest chain. Because most blockchains are open, the anti-attack and stability of the consensus protocol is critical. Current workload proof (PoW) and equity Certificate (PoS) are two of the most common consensus mechanisms.

4.3.5 Secure encryption system

Taking advantages of asymmetric encryption and hashing, blockchain ensures that transactions cannot be denied and destroyed, and the privacy of user information and records is protected as far as possible.

5 Interaction of BIM, blockchain and IoT

Overall, BIM, blockchain and IoT are advanced technologies in three various categories. BIM digitalizes the building information while IoT connects realistic objects with Internet, and blockchain transmits data on a decentralized network. When considering how these technologies can contribute to a building project, it is difficult to analyse benefits of a single technology. In other words, it is interaction of different technologies that breeds new applications, and therefore improves the way the AEC industry generates single source of truth for digital information. In this paper, the enhancement from interactions of these three technologies can be concluded below.

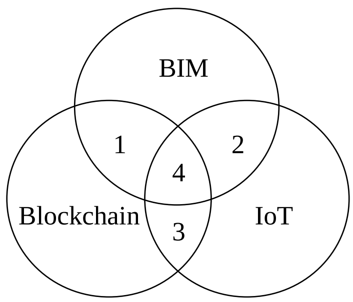

Figure 1. Interaction of BIM, IoT and blockchain
Note:

1. BIM and blockchain: contract, supply chain, modification record.
2. BIM and IoT: green and smart building, construction site safety, e-Commerce
3. IOT and blockchain: Decentralized IOT database, privacy, external collaboration
4. Integration of BIM, IOT and blockchain

As shown above, the interaction of BIM, blockchain and IOT could bring about technical and management innovation throughout the life cycle of construction project. It is necessary to analyse the potential benefits and restriction of these applications following the order as listed above. After that the value of interaction of BIM, blockchain and IoT can be realised.

5.1 BIM and blockchain

5.1.1 Smart contract

In construction project management, there existed many issues relevant to transaction and documentation. First, payment delay or not paid on time have been stressed out as one of the main factors causing conflicts and disputes between each party [1]. Secondly, the traditional contract signing in a construction project required a complex procedure with confirmation of different parties. And the documentation of a contract is a time-consuming process considering various forms of contracts and different properties of transactions. However, smart contract, which is an important innovation enabled by blockchain technology, might be helpful in construction.

Szabo, the proposer of smart contract, described that "smart contract is a computerized transaction protocol that executes the terms of a contract" [22]. It should have several functions that meet fundamental contractual conditions, such as payment and liens. At the same time, smart contract can reduce or eliminate the influence of third party and can improve the efficiency of signing. At that time, digital technology is not mature so that smart contract was only at conceptual level. Today smart contract can be computer program coding based on blockchain system that executes the predefined terms without intermediate. Digital currency like bitcoin or ether are used to achieve payment or exchange with realistic asset.

Compared with traditional contractual ledger, smart contract has several advantages on built environment.

a) As mentioned above, payment not being completed on time is a serious problem causing loosen collaboration and decreased working efficiency. Smart contract can effectively prevent such cases by binding the payment together with contract. Once the work has been done, the fund stored on the contract would be released and sent to a contractor.

b) Smart contract can be executed automatically following its code. It saves a lot of time which people should spend executing or supervising the contract manually.

c) Due to the decentralization property of blockchain, the data of smart contract is of high security and immutability. Further, decentralization eliminates the trust risk from the involvement of intermediate party [23].

d) If the logic and content of contract could be written properly in the program, the software would accurately execute the items step by step. It reduces the possibility of some manual errors.

In BIM workflow, it is a perfect state provided that every contract can be written as a smart contract. However, the workload and technical requirement might exceed the capability of project team to achieve it. At the beginning when project team start using smart contract, it is suggested that smart contract should be applied on some specific transactions, which can raise the efficiency, security and collaboration of a project at most.

a) BIM model management

One of the main obstacles to replace traditional document-based construction process by BIM-based construction process is that information is distributed on more than one version of a BIM model, model reviews and digital documents [24]. It results from fragmented management of model usage, their associated right and ownership of a BIM model. The Using smart contract, each party in a project team can only access BIM model under the permission of such intelligent contract, and their operation can be recorded on the blockchain. By this way, the responsibility and right can be effectively allocated, and information can be integrated on blockchain database.

b) Property and land ownership transfer

In a construction project, there are amounts of property transfer transactions, like equipment purchase or prefabrication procurement. Otherwise, there also exists land ownership transfer events when the building area is modified. It is significant to use smart contract to transfer the property and land ownership since smart contract provides an authentic platform without redundant cost.

5.1.2 Modification record

Due to the immutability of blockchain, the record is permanent [23]. As many people and teams working in one project, the modification of one BIM model at same time is unavoidable. The tamper proof and time-stamped data can be record by using blockchain not only for internal member but also for external collaborators [23,25]. Immutable public record of all model modifications can be stored [22]. With the application of this record the efficiency of the data sharing can be significant increased, the efficiency of management can be improved [26], the collaboration and trust between each participant can be enhanced [23].

5.1.3 Supply chain and logistics

In the traditional construction supply chain, the collaboration between each partner is temporary, the cooperation period is short, and the number of participants is huge. Therefore, the unstable relationship can cause the lack of transparency and traceability [27]. The problem of trust between each participant in supply chain leads to a low efficiency and low level of productivity [28]. The blockchain can be considered to solve these problems through an immutable digital ledger system [29]. This system is authenticated and the information on this system is more reliable than the conventional [26]. Based on the reliable information and without the participation of third party, more companies can be considered to hire as contractors or subcontractors. A reliable, open and competitive market is a positive motivation for the companies and people in the industry [30]. The efficiency of the procurement can be increased [31]. Moreover, blockchain can provide consistent report for each participant in supply chain including owners, contractors and subcontractor. It helps managers to track the progress of the project and the logistics timely.

5.2 IoT and BIM

IoT can be applied in different processes in the building lifecycle based on BIM. In terms of the green and smart building design, some sensors can be used to measure the temperature, air quality, humidity; monitor the location and movement or control the system respectively to provide safety and thermal comfort with limited energy consumption intelligently and automatically [30, 32]. With respect to the application of IoT in construction site, the wearable sensor can be used to monitor the acting of workers to make the workplace safer and more efficient [33]. In terms of the construction supply chains and logistics, the RFID sensor can be used to monitor various aspects of product and their environments [34]. Meanwhile, the IoT have potential to promote the application of e-commerce in procurement process [35]. In terms of the facility and asset management, the IoT can improve the efficiency of O &M; reduce the track cost and process in real time through the RFID technology [36].

5.3 IoT and blockchain

With the development of IoT, the limitations of it is gradually exposed. Firstly, due to the centralized of the currently IoT system, the central database is vulnerable to attack. With the exponential growth of data, the cost for operation and maintenance of database is increased rapidly. Secondly, credit mechanism is hard to build without the third party. The cost of the collaboration work between external partners is high. Meanwhile, the privacy of participants could be leaked via the third party. Based on the characteristics and advantages of the blockchain, the limitations can be solved.

5.4 Integration of BIM, IoT and blockchain

The applications of integration between two of these three technologies are came up gradually. However, the application of integrating BIM, blockchain and IoT is rarely mentioned. One of building maintenance systems based on "Decentralized Autonomous Organizations" (DAO) can be considered as a meaningful approach that adopts BIM, IoT and blockchain technologies in the construction industry. This example shows the feasibility and the value of integration between these three technologies.

5.4.1 Building Maintenance System （BMS） based on DAO

An efficient operation and maintenance system of a building can save labour and management cost as well as reducing health and safe issues. A new building maintenance system based on DAO is expected to perform well rather than existed systems in the future [37]. DAO is the abbreviation of " Decentralized Autonomous Organizations", which is an organization that runs through rules encoded as computer programs [38]. This organization does not have any human governor. It follows completely the rules of a smart contract. On the other side, BMS takes advantages of IoT technology to retrieve the operation information of every building component. Once BMS could monitor the performance of building and get prepared to react to any abnormal conditions based on a fixed contract, a set of troubles on operation and maintenance stage can be solved in an abbreviated time [39].

Supposed an elevator in a large office building breaks down, the sensor from BMS could quickly find the problem and detect which part of the lift got damaged. Then transaction would be uploaded onto blockchain network. DAO could make responses to this event according to the scheme of the smart contract, such as writing facility damage report, connecting with service provider, or purchasing new component with supplier. As a consequence, the broken elevator could soon get repaired and return to operation. It prevents hundreds of staff in the building from having to walk on fire passage, which leads to safety concerns [40].

From this example, it is of great significance to apply blockchain along with IoT during operation & maintenance of a BIM life-cycle. IoT provides the opportunity to access the dynamic data of building while DAO make automatic reaction to any situations based on predetermined programs. The absence of any of BIM, blockchain and IoT technologies could make BMS unable to work.

6 Discussions

In the UK, the Digital Built Britain national strategy describes the plan to create a mature digital economy for built environment and lead to a smart cities, services and grids [41]. It requires a large amount of digital information, new commercial model, interoperable and safety working environment. This strategy indicated that the informatization and digitization are the tendency of the development of the future AEC/FM industry in the UK. As one of most advanced countries in the development of construction and BIM standards, the HM Government's strategy can be used for reference in the global construction industry. Meanwhile, the development of informatization and digitization of AEC/FM industry are also mention in the 13th Five-Year Plan of China. The advance technologies are required for the development of economic and social [42]. Both national strategies can indicate a digitized and informationalized world in the future. Those mass of data and information need to be well managed without wastage, excessive transfer and unnecessary cost burdens [43].

BIM, IoT and blockchain are three advanced technologies that are explored to achieve the informatization and digitization of AEC/FM industry. These three technologies can be considered to be complementary.

Without linking to IoT, the correctness of project data is poor. Considering that a smart contract was made to manage the equipment lease, it is essential to collect the dynamic data of equipment in order to ensure the performance and safety of a machine. The virtual 4D BIM data could only provide some static data such as manufacturer or provider information of the equipment. Manual recording and uploading of these dynamic data of equipment generate problems. For instance, the updating is not real-time, and the data accuracy cannot stay on a prominent level, which could lead to execution error of a contract. Therefore, it can be realised that blockchain technology can improve the trustfulness of virtual BIM data, but the independent interaction of these two technologies still lacks support from real world data. Meanwhile, IoT can improve the level of intelligentization and automation of the supply chain and logistics through sensors and RFID. It ultimately increases the efficiency of these applications with the participation of IoT.

Without blockchain, the integration system of BIM and IoT is lack of security and correctness due to the single source of truth. Due to the various data format between each technology, the information exchange is complex. With the regular format data in blockchain, the collaboration can be more efficient in an integrated system. Overall, with the construction industry, the generation rate of data is exponential from a number of stakeholders along the life cycle of the building. These data and information need to be transferred, stored and shared by an efficient and safe method. Blockchain is a reliable technology to process data. With the blockchain, the data and information can be managed well.

Without BIM, all the information in the whole building lifecycle is hard to be digitized. Paper-based document cannot be used in IoT and blockchain directly. BIM is the first step and the basement for AEC/FM industry to convert and manage digital information through-life.

In conclusions, BIM, IoT and blockchain are complementary. With the integration of these three technologies, the traditional AEC/FM industry can become a digital and informationized industry in a high efficiency and secure environment.

In order to clearly illustrate the interaction of these three technologies and how they rely on each other in a building project, a "Cup-of-Water" theory is came up with to graphically show the importance of integrating them together.

7 "Cup-of-Water" theory

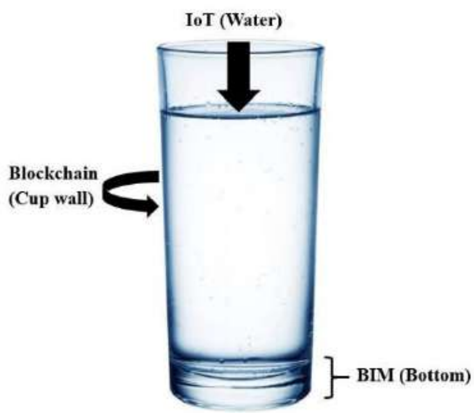

Figure 2. Cup-of-Water Theory

The information carrier, entity and flow can be taken as a cup filled with water, where water is building data and cup is the approach how these data are stored, transmitted and shared.

BIM (Bottom): The management of digital information for whole building lifecycle is the baseline of the revolutionary AEC/FM industry.

Blockchain (Cup wall): Redefinition the method of storage of high value single source of truth for AEC/FM industry.

IoT (Water): The entity of the object and data.

Three components are all compulsory in this system for the industry. Without BIM, the "water" cannot be conserved and managed. The method for regulating the object and data is meaningless. Without IoT, the cup is empty. The system is out of sync with reality. Without Blockchain, the 'water" cannot be conserved and managed in a security, transparency and convenient environment. The integration of these three technologies is the future of the AEC/FM industry.

8 Conclusions

In this paper, the definition, characteristics of BIM, blockchain and IoT in AEC/FM industry are presented through literature review. Then the interaction between these three technologies are analyzed with regard of their applications, benefits and limitations. The integration of BIM and blockchain can improve the safety and efficiency of the contract signing, project modification, asset management and supply chain management. But the applications lack dynamic realistic data of project without IoT. The integration of IoT and BIM brings about comprehensive data in the whole life cycle of a project, but these various formats of data require a stable method to be stored and transmitted. The sole combination of IoT and blockchain without BIM is infeasible because the project data cannot be digitalized. The integration of all these three technologies can access and organize the digital information of building project in the most effective and safe way. An example of building management system based on DAO shows the feasibility of integrating these technologies and huge significance to the building. Cup-of-Water theory is concluded to illustrate the structure of the relationship between BIM, IoT and blockchain during the whole building lifecycle. In this theory, BIM can be taken as "cup base", which is the fundamental of a digital building project. IoT is described as "water", which is entity of object data from the real world. Blockchain plays a role as "cup wall". It is cup wall that preserve water in a transparency, secure and convenient environment. At last, the national strategies of China and UK both promote a digitized and informationalized AEC/FM industry in the future. These three technologies are complementary and the "cup of water" have potential to lead an innovation AEC/FM industry in the future. Currently, the integration between BIM, IoT and blockchain is a complex and diversified process. The detailed methods for integration and integrated system structure need to be further developed.

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A review of IoT applications in Supply Chain Optimization of Construction Materials

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Abstract –

. The timely updates and delivery of construction material on a job site could have a significant impact on the overall duration, quality, and cost of the project. The study focuses on analyzing the role of Internet of things in providing a real-time update on the delivery and data for material handling in supply chain management, and review the role of IoT in the function of value addition that it could bring in the form of management of materials and communication to a project.

It is anticipated that within the next decade, the Internet will evolve into a seamless fabric of classic network and networked objects. The use of IoT coupled with smart sensing devices could help in the communication and material tracking with high accuracy and free of noises such as human error, workforce shortage, cramped budget, adverse weather conditions, and other environmental factors.

The study will explore and identify the various remote sensing devices and technologies that could be integrated and utilized into the live data feed for the information update, with a particular focus on the use of internet of things through electronic devices. The system would help project manager in schedule updates and improve material efficiency

Keywords –

Supply chain management; Internet of things; Material efficiency; Construction.

1 Introduction

In recent years, most of the manufacturing and distribution industries have paid much attention to Supply Chain Management (SCM). By adopting and investing money in the supply chain management, the big and renowned infrastructure companies have significantly reduced inventory and logistics costs. In addition, they have marked increment in the speed with which they respond to customer demand, and improved overall company competitiveness [1].

Due to these benefits and successful cases of the supply chain management, many industries are adopting the approaches of SCM and the construction industry is also one of the industries to adopt SCM [2]. The construction industry is usually characterized as a complex industry because of the high variability in construction environments and the complication of the construction process [3]. Despite the recent improvements in construction technology, material management remains an issue that has a lot of scope for improvement in construction projects [4]. It is relatively difficult to introduce SCM to the construction industry, because of the higher costs, longer-term durations, and complicated construction interface. However, SCM for construction materials is essential to have a successful construction management, because construction materials costs make up a considerable percentage of overall construction budget [2]. The use of the conventional practices might circumvent certain problems such as material shortages and suspensions but early and excessive material entry into the site comes up with whole different direct and indirect costs such as repeated handling, interest loss, and storage cost [5]. In absence of management for material supply operations, issues could reflect in terms of extra cost to the overall project budget, schedule update, and quality of the project.

The supply chain management is in the process of massive transformation from manual data compilation methods to the use of new generation of technologies where it is in the process of abolishing expensive and ineffective practices and embracing newer, faster, and efficient technologies and systems such as building information modelling, multi-dimensional scheduling, computer-aided design, and sensing devices to monitor, estimate, and track its progress and provide real-time schedule update and hassle-free management for the construction and built environment.

2 Literature Review

Supply chain management is in the process of meeting with newer technologies. Merlino et al. [6] mentioned that today's supply chain is not the same as past few years and in the recent year supply chain is not only impacted from augmented reality in material handlings and other components, but empowered from the newer technologies such as robotics, artificial intelligence, and big data. These technologies/concepts come under the Internet of Things (IoT) which is on the basis of algorithmic process, production decisions, govern automatic devices, and do forecasting and planning.

IoT could help to bridge the communication and technological gap that exists between two most important associates for the project that exists at the extreme ends of the built environment spectrum i.e. manufacturer and customer. IoT could help the industry personnel to get real-time schedule update with astonishingly precise values that could help the project manager to make better-informed decisions and exercise better control on the overall project.

The IoT uses various interconnected smart sensing devices that communicate and share data to solve a problem such as a schedule updating, material tracking, inventory management, transportation, staffing, and resource allocation in the industry. To overcome the problem, several tools such as Radio Frequency Identification Tags (RFID), Global Positioning System (GPS), Wireless systems, Bluetooth technologies, and high-end cameras could be used to maintain real-time information sharing and data gathering.

A review of some of the prior successful cases of IoT technology applications in SCM are as follows:

- Robotics is already revolutionizing all the operational territories in materials handling, providing new roles as supply chain providers to distribution companies such as Amazon or Ali Baba [6].
- By putting assets and endeavors in supply chain management, firms such as Wal-Mart and Dell have altogether decreased inventory and logistics costs, expanded the speed with which they react to the client request, and enhanced general organization competitiveness [1].
- After the implementation of RFID advancements, Procter and Gamble and Wal-Mart simultaneously diminished the inventory levels by 70%, enhanced service levels from 96% to 99%. These companies also managed to curtail administration costs by re-engineering their respective supply chains [7].
- Supply chain information transmission model based on RFID and IoT was utilized in pharmaceutical industry to realize drugs information retrieval [8].
- Application of IoT technology in textile SCM [9].
- Application of IoT in green agricultural products SCM [10].

2.1 Supply Chain Management in General

The Supply Chain Management (SCM) concept is an important development in the corporate logistics first proposed by Houlihan [11]. The concept underwent several modifications over the period of time and received numerous valuable inputs from various scholars. Supply chain management problem has multiple variables that make it a dynamic problem. An effectual and competent SCM can have a significant positive impact on quality, cost, and duration of a construction project [5].

The Supply Chain Operations Reference (SCOR) model is proposed by the Supply Chain Council in the year 2004. It is an exhaustive business process and performance measuring method designed to meet customer requirement from all perspectives. A supply chain model is developed in a hierarchical manner and used to carry out multi-dimensional equivalent comparisons with respect to performance. The user can provide a standard quantitative scrutiny of process performance by studying the behavior of SCM from the model and implementing adequate plans. SCOR helps to integrate internal and external systems. SCOR can likewise be utilized to assess current corporate performance against contenders, in order to enhance performance [5].

The SCOR model is the first standard reference model of supply chain process whose diagnostic tools cover all industries. The PLAN step is the most important component of the SCOR model which measures integration, process, reliability, and information technology (IT) to deliver a plan.

The SCOR breaks down the SCM process into five functions, namely Plan (P), Source (S), Make (M), Deliver (D), and Return (R). The five modules were arranged into an order of hierarchy based upon the fundamental elements. The demand and supply of the modules were planned and controlled. The various functions such as performance measure, applicable software features, and optimum solution were defined. It was found that SCOR model can help the industry personnel in solving management and optimization problems such as setting up periodic targets, trend determination, and property evaluation. The leading studies of SCM on construction applications and other industries are illustrated in Table 2.

2.2 Usage of Internet in SCM

The primary goal of the supply chain systems is multi-dimensional and includes cost minimization, improved levels of service, upgraded communication among supply chain companies, and raises the flexibility in terms of delivery and response time. By combining internet with the SCM can provide benefit to the industry in terms of numerous cost-saving opportunities and improvement of service for supply chain [12], for instance, traditional logistics practices were very slow due to face-to-face negotiation but owing to internet, the rate negotiation can now be carried out on the internet at a lower cost.

According to Lancioni et al. [12] research, it is shown that based on the ranking, the most popular use of the Internet for SCM is in transportation, followed next by processing, managing vendor relations, purchasing procurement, and customer service. Table 1 represents the ranking of internet applications in supply chain management.

Table 1 Ranking of internet applications by logistics decision area [12].

Application	% Using	Rank
Purchasing/Procurement	45.2	3
Inventory Management	30.1	5
Transportation	56.2	1
Order Processing	50.7	2
Customer Service	42.5	4
Production Scheduling	12.3	6
Relations with Vendors	45.2	3

2.3 Digital Supply Chain

In the era of the global and connected economy, the digital supply chain is becoming a most researched trend and it is also on the ramp to improvement and success [6]. Digital technology is taking place over the traditional operations and now every business has become a digital business and its impact on supply chain management is predominantly great. According to Yan et al. [8], by only applying the traditional way of SCM strategy cannot lead to winning comprehensive advantages in the market competition. Therefore, many companies/industries are understanding the essential factor of these changes and they have already started working to introduce digital technology into their operations, however, just adding technologies into the business is not the answer for all.

There are several digital technologies which could be counted under the Internet of Things (IoT) and could successfully qualify as a future of the supply chain. The digital technologies are:

1. Supply Chain and Augmented Reality (AR)
2. Supply Chain, IoT, and Big Data
3. Supply Chain and Radio Frequency Identification (RFID).

2.4 Augmented Reality (AR) as an aide to Supply Chain

According to Cirulis et al. [13], the prime objective of Augmented Reality (AR) is to augment the real world environment with virtual information that enriches human sense and abilities. AR technology is to combine virtual information with the real world [14]. This technology is usually used in real time and semantic context with environmental elements [13]. AR technology is very common on the TV channels like sports channels. For instance, on the TV sports channel, there would be a score on the captured video and that score is the virtual information that combines with the reality and there are a number of other channels or other daily routines are using AR technologies. Most industries are using this technology to compete in the market and this technology is also used in SCM. AR will provide benefits to the supply chain as listed below [6]:

Picking Optimization: By using AR, any professional can see a ‘digital picking list’ on a heads-up display. Professionals can select a building material and the digital display will calculate and guide them through the shortest and most efficient path through the warehouse for the package to be picked up. This information can also be saved in the Warehouse Management System simultaneously with the help of the cloud computing.

Freight/Container Loading: AR could replace the need for physical instruction because of the heads-up displays (picture google glass visuals). These displays have step by step instructions with the best methodology to load the container according to the size, dimension, and weight of the building material loaded into the vehicle. The information and data through AR can ensure optimum loading and thus help reduce freight cycles of the supply from warehouse to the construction site.

Dynamic Traffic Support: Most transportation vehicles (e.g. trucks) are equipped with GPS navigation, but AR systems are the natural successors. Heads-up and windshield’s displays would allow the driver to re-route shipments in real time without distracting the driver significantly. For example, a truck is loaded with a concrete bags and AR can show the driver critical information including the weight of the concrete bags, gasoline efficiency, the route to the reach to the destination and so on.

Facility Planning: AR can help the professionals to visualize their next facility in full scale even before the construction starts. The project managers can model their workflow through the site, test measurements, and estimate the raw material needed to carry out the various activities. The AR system can also help the planners to select potential suppliers for various building materials while maintaining an online database simultaneously.

Table 2 Key studies and developments of SCM in construction and other industries

Authors	Industry	Application
Walsh et al., 2004 [15]	Construction	Precise material required planning.
Tah, 2005 [16]	Construction supply chain network	Inter-relationship & influence amongst suppliers
Jeong et al., 2006 [17]	Manufacturing	Process control
Tserng et al., 2006 [18]	Steel Factory	Optimized model to minimize inventory cost & decision support system for raw material suppliers.
Klimov & Merkuryev, 2008 [19]	-	Supply chain risk identification & simulation-based risk evaluation
Miao & Xi, 2008 [20]	Dynamic supply chain environment	Artificial neutral networks for quantitative forecasting of logistic demand
Janacek & Gabrisova 2009 [21]	Enriched capacity facility	Formalize & study compactness of location
Miao et al., 2009 [22]	Supply chain reliability (SCR)	Incorporated fuzzy rule & cloud theory
Sarac et al., 2010 [23]	-	Production economics
Shin et al., 2011 [24]	Construction	RFID and wireless sensor networks
Gosling et al., 2012 [25]	Construction	Identification of sources of project uncertainty
Irizarry et al., 2013 [26]	Construction	Integrated BIM and GIS to track supply chain
Taticchi et al., 2014 [27]	-	Decision support & performance measurement
Dubey et al., 2015 [28]	-	Green supply chain
Formentini et al., 2016 [29]	Corporate Sustainability	Governance mechanism
Wu et al., 2016 [30]	Electrical & manufacturing	Green Partner selection
Niu et al., 2017 [31]	Construction	Process, information & decision making
Moon et al., 2018 [32]	Construction	Improve work efficiency of scaffold supply

2.5 Supply Chain, IoT, and Big Data:

The smart sensing equipment integrated with cloud computing and big data could be the next big thing that could provide a multidimensional solution towards supply chain optimization of building materials. Devices such as RFID, cameras, Laser tags, GPS, Bluetooth LE (iBeacon), Low-frequency LF tags, and Battery Assisted Passive (BAP) tags could be used to for an effective management of a project site. The 24/7 availability of real-time information update accessible on a wide variety of devices enhances the level of performance delivery of the industry and provides a firm base for consistent workflow [6].

Some of the most promising areas for the application of the IoT's and Big data in the construction industry are:

Reduce Reaction Time to Stimulation: The ability to readily meet the demands of a customer is one of the major areas of supply chain optimization. Cloud computing coupled with smart communication devices could help reduce the time lag between the order and shipment of the building material [33].

Inventory management: The inventory at a construction site or a warehouse can be tagged with smart sensing devices such as RFID tags which can help maintain a count of the available stock and also trigger a request for more supplies in case of the stocks getting below certain levels [34].

Prediction of Customer Needs: In the age where the customer satisfaction is of paramount value, smart organizations could use the services of the big data to point out potential customers and customize their product and marketing according to customer needs [35].

Locating construction equipment: The IoT can be used to locate and track the various construction devices such as machinery, excavators, scrapers, drilling machines, cranes, and booms. The tracking system can help maintain a count of the resources allocated at a site and formulate a strategic positioning of the equipment on a job site.

Improving the efficiency of Supply Chain: The cost reduction techniques, spending patterns, and material efficiency will continue to be the top priorities in the supply chain. IoT and big data could be used to improve upon these variables.

Remote operation of machinery: IoT enables the technicians to operate machinery from a distant location so that they could avoid potentially hazardous work conditions. The wireless networking of machinery and devices enables the technicians to carry out their work with the help of remote operated machines and robots.

Supply Chain Traceability: Traceability of construction manpower, material, and equipment is directly linked to risk. Big data and Global Positioning System (GPS) can be used to keep a count of the number, location, and database of the active hours at a construction site [12].

Safety and Risk management: The construction and civil infrastructure project sites can use the smart sensing devices to augment the onsite safety standards. Smart locating, imaging, Laser sensors, and tracking devices such as hawk-eye-vision cameras can be used to ensure the safety of the working personnel on a job site.

2.6 Supply Chain and Radio Frequency Identification (RFID)

The IoT expands the application of RFID as an automatic information collection terminal, RFID system is also included in IoT as an information entrance, because it recognizes the information by reading and processing the metadata which is stored in the RFID tags. Yan et al. [8] stated RFID as a "non-contract automatic identification technology named radion frequency identification, which can identify the still or move entities automatically."

Case scenarios for applying RFID technology in construction project management [36]:

Logistics and supply chain management (LSCM): The typical supply chain means the customer's ordered materials were shipped or transported by transportation vehicles from the factory to the material distributor to the on-site warehouse. In this process for every associated professional (e.g. buyers, project managers, truck drivers and so on) should know all the necessary information such as manufacturer, quality of the product, specification etc. and this could be possible by using RFID tags. Similar to any price tag that can be seen to any product and this has been seen in construction to tag the big components. With the addition of the other technologies like adding Global Positioning System (GPS) and Geographic Information System (GIS) with the RFID can add more accuracy in terms of tracking the construction materials [37].

Inventory Management: Maintaining inventory is a big task and has the particular importance in construction. In addition, by maintaining a good material inventory one can ensure the smoothness of construction process [36] and RFID technology can be utilized to improve the inventory management of construction materials. For instance, by keeping RFID reader in a storage area, it is easier to maintain the inventory because it can read the RFID tags that are attached with the materials and it can automatically update the inventory.

3 Advantages of IoT In Supply Chain

The smart sensing equipment integrated with cloud computing and big data could be the next big thing that could provide multi-dimensional solution towards supply chain optimization of building materials. Devices such as RFID, cameras, Laser tags, GPS, Bluetooth LE (iBeacon), Low-frequency LF tags, and Battery Assisted Passive (BAP) tags. The 24/7 availability of real-time information update accessible on a wide variety of devices enhances the level of performance delivery of the industry and provides a firm base for consistent workflow.

The services of cloud computing and big data can be used to operate, record, and store the raw and processed information from the machines, software systems, sensors, and people. The information stored in the cloud could be accessible through a wide variety of devices such as personal computers, tablets, mobile phones, etc. The information is free from physical limitation of location or time constraints.

The use of IoT coupled with smart sensing devices could help in the communication and material tracking with high accuracy and free of noises such as human error, workforce shortage, cramped budget, adverse weather, and other environmental factors.

Specific information about construction materials that need to be tracked and shared by using IoT technology during the SCM process include:

1. The visualization of the logistic patterns. Track quality, quantity, and cost of the resources. Compare the plans vs actual delivery, and monitor and inspect the delivered product [26].
2. Develop a decision-support system to generate a production and supply plan for the supplier and buyers of steel rebar [2].
3. Handle ready-mix concrete operations by following the position of trucks and observing the motion and status of concrete conveyances in real time [38].
4. Optimize vehicle routing and vehicle scheduling of logistics under uncertain systems [39].
5. Tracking system to improve the work efficiency of scaffold supplies [32].
6. Remote monitoring of the tools and equipment on a job site [40].
7. Facilitating the trouble diagnosis system and maintenance of construction equipment [41].

4 Discussion and Conclusion

In the current scenario, where the human workforce is expensive, scarce, and irregular in terms of performance, the digitization of the workforce and build environment can help the organizations to manage their performance in terms of cost, time, and quality of the end product. An array of smart sensing devices like RFID, LASER technology, BAP tags, and LF tags coupled with communication medium such as the wireless internet network could help boost the overall efficiency of an organization. The smart devices have the capacity to interact and communicate with the environment around them which consists of software systems, machines, devices, and people. Altogether, these systems are capable of providing a customized solution to the problem and help an organization to easily conduct operations such as data compilation, communication, quick response to stimulation and decision making.

The real-time data feed is uploaded to a cloud database and is easily accessible through a vast variety of devices such as mobile phones, tablets, pods, television, and computers. The information available through the digital medium powered by IoT is free from the constraints of location, time, space, adverse weather, human error, and other environmental factors. The real-time data updates can help the project managers and supervisors to track and monitor the operations at a construction site and help them exercise a better control of the overall project.

The ease of application and functions involved with IoT comes up with its own set of unique challenges, the dependency of the entire system over a constant source of power supply can’t be negated. In case of power failure, the whole facility could come down and put the organization into disarray. Additionally, the security of the data compiled through these systems is not theft proof. The digital systems and data are prone to hacking which possess a great security risk to the functioning, efficiency, and organizational structure of a firm. Furthermore, the greatest challenge that the digital systems face is the ever-changing and evolving nature of the technology itself. There are numerous numbers of research-work that constantly goes on into the digital field, this transpires into the technology getting sharper and being different with every passing decade. The change in the technology requires constant upgradation in terms of devices, software, and installation of new systems and training of the handling staff. The technological improvements can put transitional challenges, operational shifts, and financial burden on an organization.

The primary factor with respect to the full deployment of new technological advancements has been as of recently the human one. It is because the gap between innovation and human resources culture has augmented, not diminished. Incompetent plans of progress administration in organizations do not help in filling this void. A ton of work must be done in getting ready new trainers and instructors and the gap must be loaded with new floods of “tech-savvy professionals”, originating from the local digital youthful generations.

Major barriers to the achievement of success of supply chain optimization using IoT incorporates work environment culture, an absence of senior management commitment, privacy issues, improper support mechanisms and the dearth of education of management philosophy. Learning and training at all level in the industry are paramount to beat these boundaries.

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A Method of Providing a Panoramic Image Using Single Image Transmission System

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Abstract -

This paper describes a method of providing a panoramic image using single image transmission system. In recent years, demands for small robots performing inspection work by remote control are expanded. On the remote control of robots, to provide information of environment around the robots is important for operators. Multiple images are usually transmitted to the operators' sides. In some cases, a large or special image generated from multiple images by image processing units is transmitted to the operators' sides. In order to transmit multiple images, multiple image transmission systems are required. On the contrary, generating special images also require a dedicated image processing unit. However, small robots cannot mount such devices due to size limitation. Therefore, we develop a method of providing a panoramic image using single image transmission system. We assume that robots are too small to mount a dedicated image processing unit or multiple image transmission systems. This system is assumed to target cameras with analog outputs. An image which is different from a previously transmitted image is transmitted every transmission. Before the transmission, a special code is added into each frame to distinguish which camera acquires the frame. We develop a tiny processing board to mount the system on small robots. First, we explain a method of spherical projections to generate a panoramic image. Multiple images are transmitted with single image transmission system after adding the code into the images. Availability of our proposed system is shown by an experiment that providing a panoramic image using two cameras.

Keywords -

Small Inspection Robots; Remote Control; Multiple Cameras; Teleoperation; Single Image Transmission System; Analog Cameras

1 Introduction

In recent years, demands for robots for performing the inspection work by remote control are expanded. In some cases, these robots perform the inspection work in a narrow space where people cannot enter. The robots are required to be as small as possible. On the other hand, it is also necessary to provide information of environment around the robot for operators. On the remote control of robots, an image acquired from a camera mounted on the robots is provided to the operator. However, to recognize the environment around the robots is difficult with single camera. Therefore, many remote control robots are equipped with multiple cameras. In some cases, a large or special image is combined from multiple images on the robot. An image transmission system is required to transmit an image to the operator from the robot. In order to transmit multiple images, multiple image transmission systems are required. On the contrary, to generate special images requires a dedicated image processing unit. However, small robots cannot apply these methods due to limitation of sizes. We develop a small hexapod robot which is shown in Figure 1 for the purpose of assisting inspection work[1]. The robot is too small to mount USB cameras or multiple image transmission system. The robot is equipped with multiple cameras with analog outputs. A single image transmission system is mounted on the robot due to limitation of sizes. Similarly, the robot is also not equipped with a dedicated image processing unit. Nevertheless, a method of providing a panoramic image is required for the remote control of the small robot.

In this paper, we describe a method of providing a panoramic image using single image transmission system. In order to transmit multiple images quickly using single image transmission system, following requirements are satisfied.

1). All cameras are synchronized.
2). Cameras are switched at the same time that transmission of just one image is ended.
3). Received images can be separated to each camera's image in operators' sides.

About 1), we assume that all cameras are synchronized. Methods to satisfy 2),3), are described in the following. Availability of our proposed system is shown by an experiment of generating a panoramic image by using two cameras. This paper is organized as follows. Section 2 describes related work about providing information on remote control of robots. A method of generating a panoramic image is described in Section 3. In Section 4, a method of transmitting multiple images by a single image transmission system is described. By transmitting

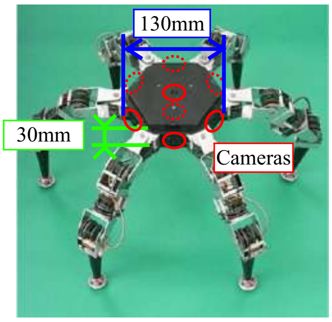
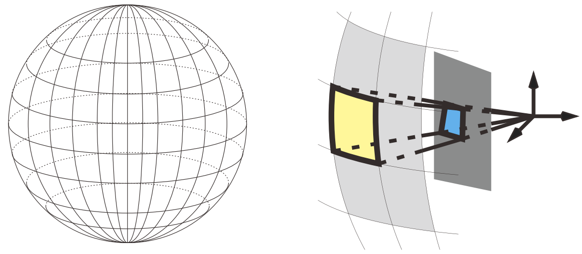


Figure 1. Hexapod Robot



(a) Projection sphere (b) Image projection to spherical surface

Figure 2. Spherical projection

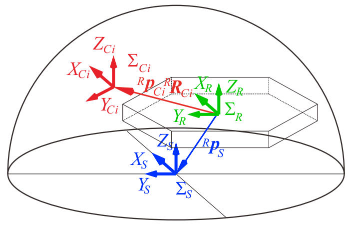


Figure 3. Coordinate system

the images in which added a special code, it is possible to distinguish which camera acquires the frame. Section 5 shows availability of our proposed system by an experiment of providing a panoramic image. Finally, Section 6 presents our conclusions and future work.

2 Related Work

In order to recognize environment around robots, multiple cameras are usually mounted on the remote control robots. However, it is difficult for operators to recognize environment around robots by multiple images. A method of combining multiple images to generate one special image has been studied. As a special image, there are panoramic images[2, 3, 4]. The panoramic images can be viewed omnidirectionally from the location of acquisition. Therefore, it is easier for the operators to recognize the environment around the robots by special images than by multiple images. Recently, there are omnidirectional cameras which can acquire panoramic images with one camera. However, the image resolution per viewing angle of these cameras is low. Another special image is a bird's-eye view image[5, 6]. An image looking down the robots is generated by combining multiple images. A bird's-eye view image helps operator to recognize the environment around the robots. In many studies, images generated with combining multiple images are provided on the remote control of the robots.

3 Generating Panoramic Image

3.1 Overview

This section describes a method of generating a panoramic image from multiple images. Multiple images are combined into a single image by projecting the images to a spherical surface. The spherical surface where images are projected on is divided by latitude and longitude. The images are projected to the spherical surface after images are segmented and transformed to accommodate various regions of the spherical surface.

3.2 Coordinate System

As shown in Figure 3, three coordinate systems, which are orthogonal and right-hand ones, are defined for calculation. The robots coordinate system Σ_R is fixed to the center of figure of robots' body. The cameras coordinate system Σ_{Ci} is attached to the camera mounted on the robot. Note that the subscription "i" means the camera number. The projection sphere coordinate system $\Sigma_{section}$ is fixed to the center of the sphere. The vector from O_R to O_{Ci}, expressed in Σ_R, is denoted as ${}^R\boldsymbol{p}_{Ci}$. The vector from O_R to O_S, expressed in Σ_R, is denoted as ${}^R\boldsymbol{p}_S$. The rotation matrix from O_R to O_{Ci}, expressed in Σ_R is denoted as ${}^R\boldsymbol{R}_{Ci}$. In this case, ${}^R\boldsymbol{p}_{Ci}$ and ${}^R\boldsymbol{R}_{Ci}$ is already known according to the specification of the robots.

3.3 Spherical Projection

Image planes are placed at a distance of focal length f_i from cameras. The vector from O_{Ci} to image planes expressed in Σ_{Ci}, is denoted as ${}^{Ci}\boldsymbol{p}_{0i} = [0, 0, -f_i]^T$. Then, normal vector of the image planes, expressed in Σ_{Ci}, is denoted as ${}^{Ci}\boldsymbol{n}_i = [0, 0, -1]^T$. Considering camera attitude and defining vector ${}^{Ci}\boldsymbol{p}$ as any position in 3 dimensions, an equation of image planes is as follows.

$$\boldsymbol{n}_i^T \cdot ({}^{Ci}\boldsymbol{p} - \boldsymbol{p}_{0i}) = 0 \tag{1}$$

The vector of position on the spherical surface ${}^{Ci}\boldsymbol{p}_F$, expressed in Σ_{Ci}, is calculated by Equation (2).

$${}^{Ci}\boldsymbol{p}_F = {}^{Ci}\boldsymbol{R}_R({}^S\boldsymbol{p}_F - {}^R\boldsymbol{p}_S) - {}^R\boldsymbol{p}_{Ci} \tag{2}$$

A vector of three-dimensional position on the spherical surface ${}^S\boldsymbol{p}_F$, expressed in Σ_S is calculated by Equation (3)

Radius of projection sphere r, latitude θ and longitudeϕ is necessary before the calculations.

$$^{S}\boldsymbol{p}_F = [\ r\sin\theta\cos\phi,\ \ r\sin\theta\sin\phi,\ \ r\cos\theta]^T \quad (3)$$

Then, a point which line from camera fixed position to the spherical surface intersects an image plane is calculated. A vector of position on image planes corresponding to position on the spherical surface $^{Ci}\boldsymbol{p}_p$ is able to be calculated from at a point which a line intersects an image plane.

$$t = \frac{\boldsymbol{n}_i \cdot {}^{Ci}\boldsymbol{e}_F}{\boldsymbol{n}_i \cdot \boldsymbol{p}_{0i}} \quad (4)$$

Therefore, a vector of position on image planes $^{Ci}\boldsymbol{p}_p$ is as shown in Equation (5).

$$^{Ci}\boldsymbol{p}_p = t \cdot {}^{Ci}\boldsymbol{e}_F \quad (5)$$

These processes are performed in all regions on the spherical surface. Then, images are projected on regions on the spherical surface. Conditions of $^{Ci}\boldsymbol{p}_p = \left[{}^{Ci}x_p, {}^{Ci}y_p, -f_i\right]^T$ within image planes is,

$$\begin{cases} -\dfrac{w_i}{2} \leq {}^{Ci}x_p \leq \dfrac{w_i}{2} \\ -\dfrac{h_i}{2} \leq {}^{Ci}y_p \leq \dfrac{h_i}{2}, \end{cases} \quad (6)$$

where w_i is the width of image planes, h_i is the height of image planes. When Equation (6) is not satisfied, $^{Ci}\boldsymbol{p}_p$ is removed.

4 Transmission System of Multiple Images

4.1 Overview

This section describes a method of transmitting multiple images via a single image transmission system. One image is able to be transmitted by using the single image transmission system. Another image which is different from previous transmitted image in every transmission is transmitted to transmit multiple images. On the other hand, the received image cannot distinguish which camera acquires the one. A special code is added into the image to distinguish cameras. First, the output signals of analog cameras are described. Then, the timing of exchanging images which are transmitted is shown. Finally, the special code is added into the images.

4.2 Composite Video Signal

This study targets cameras which output the composite video signal. There are some kinds of type. These video encoding processes are different. However, there are not large differences in the structure of the video signals. In the subsequent processing, any type can be applied by changing parameters. In the following, our system is explained by NTSC system which is widely used in Japan. The composite video signal is composed of a video signal and a synchronization signal. The synchronizing signal includes a vertical synchronizing signal, a horizontal synchronizing signal, and a color synchronizing signal. Using synchronizing signals, one frame of images is distinguished.

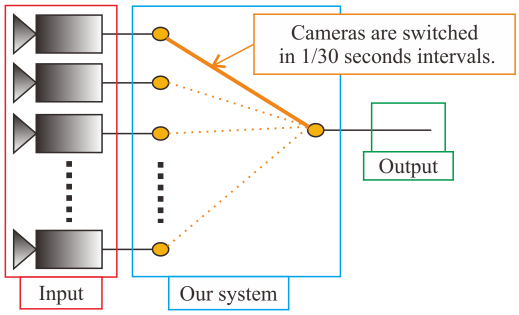


Figure 4. A system of transmitting multiple images using single image transmission system

4.3 A Method of Exchanging the Images

Figure 4 shows that a system of transmitting multiple images. Multiple images are transmitted by switching images which is transmitted in 1/30 seconds intervals. For example, we describe a method of exchanging images by using camera with an NTSC signal. In NTSC system, one image is composed of two fields which are even field and odd field. Each field has 262.5 scanning lines so that one image has 525 scanning lines. One scanning line has one horizontal synchronizing signal. In other words, one image has 525 horizontal synchronizing signal. On the one hands, a vertical synchronizing signal is changed in swapping odd field and even field. After switching the vertical synchronization signal from HIGH to LOW, 525 horizontal synchronization signals are counted to exchange the images.

4.4 Adding a Special Code into Images

A special code is added into images by using active video in composite video signal. Any line of an active video is replaced with the special code. By using the code in the images, a camera which acquires the image is distinguished. The code is composed of two colors which are white and black. By dividing a line into N parts, one line has the values of range from 1 to 2^n. In NTSC system, width of an image is 640 pixels. One line has the values of range from 1 to 2^{640}. Figure 5 shows relation between the code and the numerical value (N = 3). A process of adding binary code into images is shown in Figure 6.

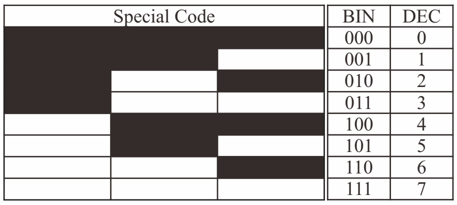


Figure 5. A special code and numerical values corresponding to the code (N = 3)

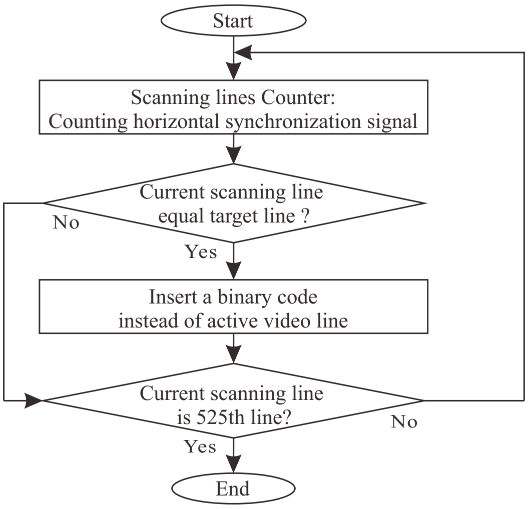


Figure 6. The process of adding a binary code into images

For example, the code is added into the first line of the image. 480 of 525 scanning lines are displayed as images. From 1 to 45 scanning lines are used for different purpose such as subtitle, vertical synchronization. Therefore, the first horizontal line in images can be changed to the special code by swapping 46th scanning line and the code. Figure 7 shows an image which added the code into the 100th scanning line. As a result, the special code in the images have been confirmed.

5 Experiment

5.1 Overview

Being able to provide a panoramic image is confirmed by using our proposed system. In an experiment, two images are transmitted to computer via single image transmission system. Prior to transmitting, the binary code is added into the images by using an experimental equipment. On the computer, the received images are combined into a panoramic image. As a result of the experiment, availability of our proposed method is verified. Problems of generating a panoramic image are also revealed.

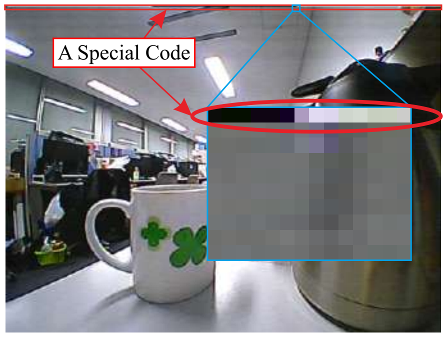


Figure 7. The image which added binary code

Table 1. The specification of computer

OS	Windows 10 Pro 64bit
CPU	AMD Ryzen™7 1700
GPU	NVIDIA®Geforce GTX-1060 6GB
RAM	16GB
Capture Device	PCA-DAV2

Table 2. The specification of cameras

Product name	MINI CCTV CAMERA 205M-WD
Resolutions	640 x 480
FPS	30
Horizontal view angle	about 110 degrees
Vertical view angle	about 95 degrees

5.2 Environment

Figure 8 shows a prototype device which is developed for the experiment. The device is composed of the video signal extractor, the camera exchanger, and the signal counter. The video signal extractor is made by referring to an article[7]. PIC is used for adding binary code and exchanging cameras. Two camera are synchronized before making the experiment. In this case, the two cameras are synchronized by means of injecting a clock signal which created by one crystal into two boards after removing the crystal on cameras boards. If using more than two cameras, clock signals which generated from a clock generator are injected in order to synchronize all cameras. Using the device, a binary code is added into images acquired from two cameras. Images outputted from the equipment are captured in the computer by a capture device. The panoramic image is generated from two images after separating the images. In this situation, one of codes added into the images is black line and the other is white line. Figure 9 shows a simplified image of experimental equipment. The cameras that used in the experiment are shown in Figure 10, and the specification of the cameras and the computer are shown in Table 2. The cameras are fixed to an experimental equipment as shown in Figure 11.

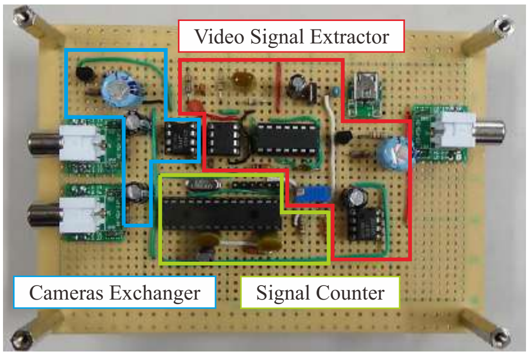


Figure 8. A prototype device to transmit two images using single image transmission system.

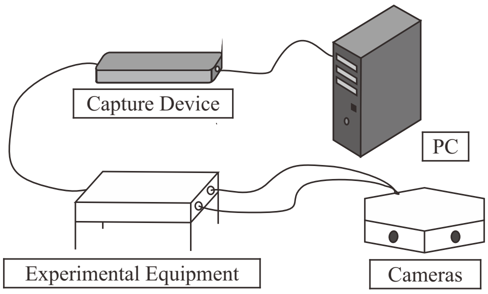


Figure 9. Experimental environment

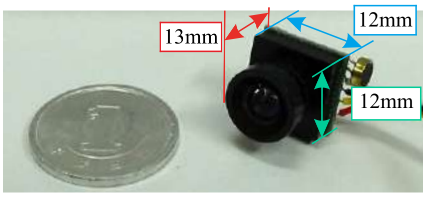


Figure 10. A camera used in the experiment

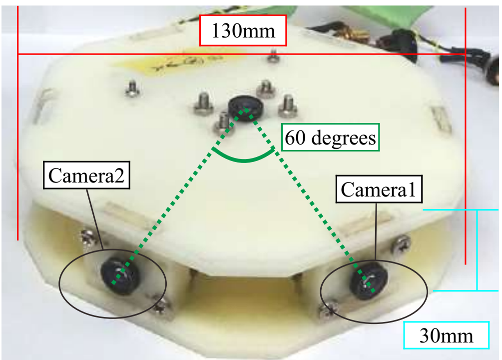


Figure 11. Experimental equipment

5.3 Result

Figure 12 shows the panoramic image which generated by using single image transmission system. It was confirmed that two images can be transmitted quickly and received images are separated to two images. The first line of the image acquired from Camera1 is a black line. Similarly, the first line in Camera2's image is a white line. A special code can be added to the image by using the device. Finally, two images are combined into the panoramic image by spherical projection. Using two cameras, to generating a panoramic image was confirmed. From the above, availability of our proposed method was verified.

5.4 Discussion

The received images are noisier than original images. The image noises might be caused by the video signal amplifier circuit. Our system has two video signal amplifier circuits. In order to reduce noise in images, it is necessary to modify the amplifier circuits. The panoramic image has a problem that a border among the image is not combined continuously. When the camera moves, to generate a panoramic image is difficult due to gap among the projected images. Furthermore, multiple images cannot be acquired from camera at the same time. For this reason, projection position should be changed to combine images correctly. On the other hand, the prototype device which is developed for the experiment is not too small to mount on the small robot. Therefore, to reduce the size of the device is required.

6 Conclusions

This paper presented that the method of generating a panoramic image using single image transmission system. At first, the method of generating a panoramic image with spherical projections was described. Then, multiple images were transmitted using single image transmission system. Prior to transmitting the images, the special code was added into the images to distinguish which camera acquired. Finally, availability of our proposed method was confirmed by the experiment that providing a panoramic image using two cameras.

In future tasks, it is necessary to confirm availability of the our method in the case of wireless transmission. Using more than two cameras, multiple images should be transmitted by the our method. To provide a panoramic image on the remote control, we will develop a remote control system for small mobile robots.

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Figure 12. A panoramic image and separated two images

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Holonic Execution System for Construction Management

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Abstract –

Ensuring high efficiency in construction through advanced planning techniques must be supported by the simulation of construction processes. In previous research, the potential for multi-agent based simulation to support the planning phase were successfully shown with regard to some typical construction tasks. Among the main benefits determined by this approach the following ones were reported: capability of simulating real-world processes and interaction among resources; powerful 3D visualization; optimal sizing of resources. However, those models are not easy to create, because of the absence of built-in blocks and the many relationships among single agents and between agents and context.

In this paper we propose the application of a novel holonic system for construction management, which is a sub-category of multi-agent systems. It combines the high and predictable performance promised by hierarchical systems with the robustness against disturbances and the agility of heterarchical systems. Holons are self-contained, stable, intermediate forms, that can be used to create a bigger whole. By using holons, designers aim to create complex systems that can be reused and redesigned much more rapidly than standard multi-agent systems. The approach was applied to the optimal scheduling of bored piles construction. Hence, a holonic construction execution system for bored piles tasks was developed. The holonic architecture was designed so as to integrate the DMAS pattern for scheduling optimization through stigmergy. The results of this paper showed the easy reusability of our simulation sub-systems and the potentials in terms of automatic optimal planning of construction works.

Keywords –

Construction management; holonic systems; multi-agent systems; VRP

1 Introduction

Lean construction principles are currently under development in order to improve the productivity of the construction industry. However, this process requires that general lean principles be adapted into practices that are tailored to the characteristics of construction projects. A number of initiatives are known in this field. An empirical study regarding the construction of a large hospital resulted in a set of lessons learned, which can be roughly grouped into three sections: lean engineering, logistics and purchasing, lean construction process [1]. A methodological and very popular approach, which was definitely organized by the lean construction institute, is the last planner system [2]: it helps increase the reliability of a planning system and thereby significantly improve its overall performance. Although really effective, implementing the last planner system in construction organizations over the long-term requires significant support for project teams by dedicated facilitators. Such levels of support are difficult to maintain, but in their absence teams tend to revert to traditional practices [3]. As a result, research is still very active in this field and novel methodologies are object of testing, such as the "kanBIM" prototype, which is a BIM-based workflow information system to help construction personnel implement pull flow strategies [4]. This latest approach highlights the importance of monitoring, control and continuous revision of the work plan, according to the status of work underway. Thanks to the advent of powerful computational tools, optimal work plans can be worked out by means of agent-based simulation approaches. This approach outperforms discrete event simulation, which, in fact, fails to incorporate the inherent variability that arises from the independent construction subjects' behavior as they interact on a construction site [5]. On the contrary, multi-agent simulation is suitable for modelling resources' behavior and interactions in complex settings, like in construction. These models are capable of specifying the characteristic of trade crews, their work methods, the amount of work, workspaces and dependencies between tasks. As a result, simulations encapsulate both variability and uncertainty of the construction workflow [6].

In this paper we study the feasibility of a new reference architecture for construction, that was successfully tested in manufacturing, and that can simulate the construction process. This new system is based on the use of holons, which can organize into holarchies, and own self-configuration and self-organization capabilities, thus resembling the behavior of the resources usually employed on and off-site, which must cope with the high variability and uncertainty typical of construction works [8]. In addition, simulation models are built on top of classes classified as agents, holons and functional blocks, which can be variously combined to perform optimal planning by means of optimization algorithms. In section 2 a brief overview of the scientific background will be provided. Section 3 will report on the basics of holonic systems and of the optimization algorithms we have analyzed. Then, Section 4 will present an application to the optimal planning of bored piles and presents a final discussion.

2 Scientific Background

Renovation works must be scheduled, budgeted and monitored and controlled until the end of work progress. The standard construction practice is commonly done applying diagram methods to sequence activities that are based on work packages defined according to a work-breakdown-structure. Then, progress management usually involves deviation analyses between the actual progress and the initial plan that is constantly being updated and revised. The scarce communication and the absence of automation requires the adoption of standard methods, such as face-to-face meetings and paperwork. This approach has been identified as an inhibitor to increasing productivity and a miscommunication and rework source, which can be improved by means of holonic execution systems. These systems are able to improve communication channels, coordination and cooperation, dynamic management. Also, they can take advantage of BIM-based structured information [8]. Several authors analyzed the great potentials of multi agent-based simulation, thanks to its ability of imitating real world process of systems, where the global behaviour emerges as a result of interactions of single agents [6, 9]. Agents can be active, proactive, autonomous, cooperative, adaptive and mobile. They interact to reach a global objective. However, holons can expose additional important features that resemble the real behaviour of construction execution, i.e. they organize into holarchies, where a system of holons cooperate to achieve an overall goal while negotiating with their own objectives [10]. Hence, they can reliably simulate the behaviour of cooperating agents in construction sites and the dynamics in such distributed operating environments [11] even if parameters change during the work progress [12]. Holonic models were successfully applied in manufacturing control, referring to the PROSA reference architecture [13]. In this application all entities in the “world of interest” were not only represented as agents, but also as entities in the environment, with which they communicate and interact. In addition, the Delegate multi-agent system (DMAS), that is part of holonic systems, allows any holons to delegate a responsibility to a swarm of “lightweight” agents [7]. This feature can be used to find out the optimal work planning prior to the execution phase, and to execute dynamic re-planning during work progress.

Automation in scheduling has been studied in the last three decades and several approaches were experimented [14]. Cased-based reasoning (CB) develops plans by remembering earlier and comparable situations. Genetic algorithms (GA) and neural networks (NN) perform optimization relying on a huge database, so their learning process must be fed by thousands of records. Hence, expert systems (ES, mainly using if-then-else structures) and model based approaches (MB, which simulate the execution process) look more reliable to be applied in construction. However, all these approaches tackle a unique aspect of the scheduling problem: CB is about optimal sequencing, GA on resource optimization and levelling, NN on time-cost tradeoff and optimization, MB on spatial reasoning. Some remarkable examples about MB simulated the construction process either by means of a set of differential equations [15], or an integrated mathematical model [16] or a probabilistic approach [17].

In this paper, we will study another approach and will test it in the execution of bored piles. Our model will conform to the PROSA reference architecture, which includes the DMAS approach, because it allows the re-planning occurring during execution. More importantly, this process allows us to evolve from single-objective optimization towards a multi-objective optimization problem based on ant-colony simulation. In this approach, every objective can be optimized by a different colony, that is cooperating and contributing to the whole process. In addition, every resource involved in the production process is capable of continuously re-planning her schedule as a result from unexpected occurrences, in fact performing dynamic scheduling. Finally, the setup of simulation models can be facilitated by the availability of a BIM model of the designed tasks.

3 Holonic Execution Systems

3.1 Description of Holonic Systems

In this paper we tested the feasibility of using the holonic reference architecture for the simulation of construction execution. The objective of a reference architecture is to specify a generic systems structure, the kinds of system components, their responsibilities, dependences, interfaces, data, interactions, constraints etc…[18]. Then, the reference architecture can be used as the basis for designing any system architecture, which refers to a particular system and focuses on a particular product.

Holonic architectures are made up of holons, which are autonomous self-reliant units, in the sense that they have a degree of independence and can handle contingencies without asking higher authority for instructions. They are stable intermediate forms, that can be used to create a bigger whole [13]. Holons are combined to form holarchies, which combine the positive characteristics of hierarchical and heterarchical systems. Hierarchical systems offer high and predictable performances thanks to their pyramidical structure (although they might lack in robustness). Heterarchical architectures allow for full cooperation between entities, that is arranged by means of negotiation, in fact increasing robustness [19]. Holons can function on their own, which increases robustness and, at the same time, it can function as a part of a bigger whole, forming a hierarchy with other holons for a certain period of time.

The three basic types of holons, which are adopted in the PROSA reference architecture for manufacturing systems, are order, product and resource, whereas staff is optional. Order holons are in charge of accomplishing tasks, they search for solutions and select among candidate alternatives the most attractive one; product holons provide order ones with knowledge about routing and processing sequences that are able to create proper products; resource holons drive their resource actuation and keep their internal state synchronized with the resource through appropriate inputs, such as sensor readings [7]. Holonic systems can operate just in case they include the world of interest, that is the part of reality in which the execution operates. As a result, the architecture of a holon usually comprises both the control system and the manufacturing system (Figure 1):

- The physical processing component, that is part of the world of interest;
- The physical control component;
- The decision making component that is part of the agent.

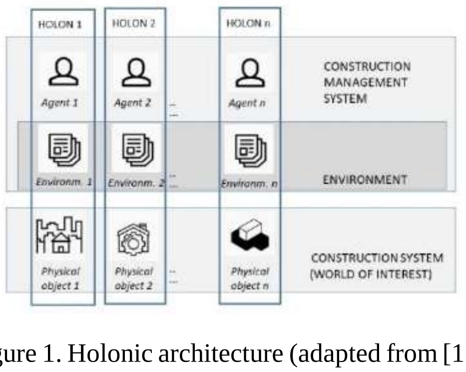


Figure 1. Holonic architecture (adapted from [13])

3.2 Holonic Execution Systems for Construction Management

Most construction tasks are affected by disturbances and variations in their operating environment. As a consequence, work plans that are generated before the process starts, are based on approximate resource performance and predicted operating conditions. For that reason, they need re-planning any time unexpected occurrences cause deviations from what expected. In addition, not two construction sites can be planned in the same way. Hence, multi-objective optimization problems must be integrated in management systems, in order to adapt the crews number and mutual organizations, according to real boundary conditions. In sub-section 3.2.1 an approach that is general enough while being capable of integrating optimization algorithms will be presented. Then, in sub-section 3.2.2 the multi-objective optimization algorithm that we used in this research work will be detailed.

3.2.1 The Architecture of the Holonic Execution System

The holons mentioned in sub-section 3.1 are expected to interact and share data with each other. Three basic types of interaction can be recognized [7]:

- Product-order interaction: the order holons interact with their corresponding product holon on how to correctly execute their task by using certain resources. In other words, the product holon provides the order holon with all possible next operations, and the order holon keeps track of the task being executed.
- Product-resource interaction: the product holon provides the resource holon with technological aspect to correctly process an order, e.g. the necessary process parameters to perform an operation.
- Resource-order interaction: resource and order holons mainly interact to commit operations to the resources. To this purpose, the resource holons provide the order holons with the results of virtually executed operations and reserve capacity when requested. Once a task is executed, the resource holon informs the order holon about the execution result and progress. Hence the desired coordination and control emerges in a self-organizing way from the interaction between the various holons.

In order for the above mentioned interactions to be effective, order holons must be able to reserve resource so as to optimize the overall schedule. In other words, holons must interact while seeking global optimization. Research manufacturing, found out that the behaviour of food-foraging ants, called stigmergy, is the best approach because it is capable of incorporating nonlocal information while employing only local reality-mirroring components [7]. To sum up, the following steps are performed in a stigmergic approach:

- In absence of any signs in the environment, ants perform a randomized search for food;
- When an ant discovers a food source, it drops a smelling substance, called pheromone, on its way back to the nest while carrying some of the food. The pheromone trail evaporates if no other ant deposits fresh pheromone;
- When an ant senses a pheromone trail, it will be urged by its instinct to follow this trail to the food source and will deposit pheromone itself on its way back to the nest.

This pattern is an emergent behavior of the ant colony, that is ordered and is robust against the uncertainty and the complexity of the environment. Although information about the presence of food is made available locally, it affects the global behavior of the colony and the state of the environment.

In order to integrate this behavior within the holonic architecture, the deposit of pheromones can be translated into order holons reserving time slots in these local schedules. In other words, "ant agents" travel virtually and execute virtually what an order holon might do for real. Finally, the order holon picks out the best solution among available alternatives. This architectural pattern is represented as Delegate MultiAgent System (DMAS), and is sketched in Figure 2. According to this pattern, the DMAS allows a holon to delegate a swarm of lightweight agents to perform an action to support the issuing holon in fulfilling its functions.

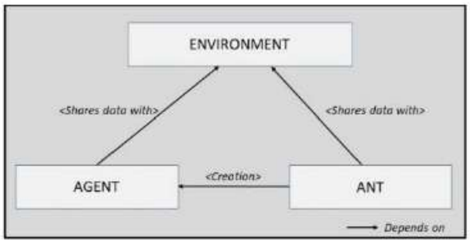


Figure 2. Delegate MultiAgent System (adapted from [7])

In the application reported in this paper, we developed a model involving resource, order and product holons (Figure 3), where the product holon exposes attributes that can be retrieved directly from a BIM model, and the holon order applies the ant-colony optimization algorithm described in the next sub-section to find out the optimal schedule. The architecture depicted in Figure 3 was built according to the PROSA reference architecture, which was successfully applied in manufacturing. The order holon is in charge of managing the schedule. It commits resources, both those ones which are in charge of executing the tasks and the resources that are consumed by construction works (e.g. excavated or drilled soil). To be noticed that there are several instances of "product holons", because each of them includes information about a possible technology for constructing the several types of piles that can reasonably be found in a building detailed design. Resources are sized according to the specific technology and to parameters, which can be inputted directly from the BIM model.

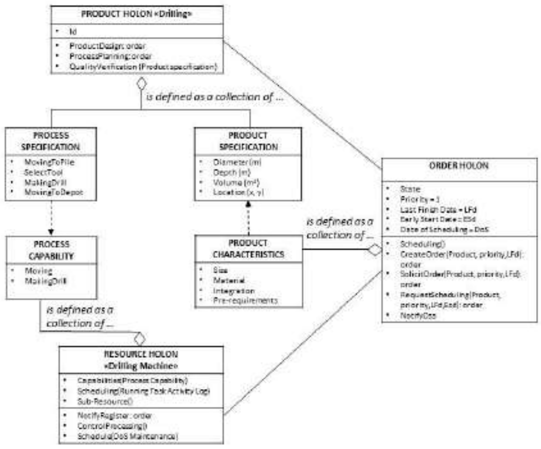


Figure 3. Suggested UML architecture for pile construction (adapted from PROSA)

3.2.2 Multi-objective Optimization Algorithm

As the case study analysed in this paper is the first task of bored piles execution (i.e. drilling), optimization was performed by means of vehicle routing problems. Indeed, driving drilling machines along the most cost-effective path recalls problems about routing optimization. More specifically, we refer to the multiple ant colony system for vehicle routing problems with time windows (MACS-VRPTW), which performs ant colony optimization [20]. Basically MACS-VRPTW is organized with a hierarchy of artificial ant colonies designed to successively optimize a multiple objective function: the first colony minimizes the number of vehicles while the second colony minimized the travelled distance. Basically, a VRP is composed of n customers served from a unique depot. Each customer asks for a quantity q_i of goods and a vehicle capacity Q is available for delivery. Each delivery cannot be split and the vehicle has to periodically return to the depot for reloading. On the overall, the problem is represented as a graph made of a node set $C = \{c_0, c_1, \dots, c_n\}$ and arcs $L=\{c_i, c_j\}$ to which a matrix of travel time values t_{ij} is associated. The goal is to find a set of tours of minimum total travel time, where each tour starts and ends at the depot c_0. Extensions to the basic problem include: service time for each customer; duration limit of each tour. But in this paper we applied the VRP with time windows, i.e. VRPTW. This problem includes for the depot and each customer c_i a time window [b_i, e_i], during which the customer has to be served between starting time b_i and end time e_i. The tours are performed by a fleet of identical vehicles. This approach is applied to the case study presented in this paper, and optimization is performed by means of ant colony optimization (ACS), and both the number of vehicles and travel time are to be minimized (i.e. multi-objective). To this purpose, two measures (i.e. heuristics) are associated to each arc: closeness (η_{ij}) and pheromone trail (τ_{ij}). The first is the inverse of the distance, the second one is dynamically changed by ants at runtime. Pheromone trails are used in conjunction with the objective function to construct new solutions: a higher probability is given to elements with a strong pheromone trails. Pheromone levels give a measure of how desirable it is to insert a given arc in a solution. At runtime, m ants build tours in parallel. Each ant is randomly assigned to a starting node and has to build a solution, by adding iteratively new nodes until all nodes have been visited. When ant k is located at node i, it chooses the next node j probabilistically in the set of feasible (i.e. have not been visited, yet) nodes N_i^k. The probabilistic rule is defined by Equation 1:

$$p_{ij} = \begin{cases} \dfrac{\tau_{ij} \cdot [\eta_{ij}]^{\beta}}{\sum_{l \in N_l^k} \tau_{il} \cdot [\eta_{il}]^{\beta}} & if\ \ j \in N_i^k \\ 0 & otherwise \end{cases} \qquad (1)$$

In fact, the process goes through two steps: exploration and exploitation. During exploration, with probability q_0 a node with the highest $\tau_{ij}[\eta_{ij}]^{\beta}$ is chosen, with the purpose of selecting the components to be used to construct a solution. During exploitation, the next components is chosen by maximizing a blend of pheromone trail values and heuristic evaluations. More specifically, with probability (1- q_0) the node j is chosen with a probability p_{ij} (Eq. 1). The procedure exploits two parameters: β weighs the relative importance of the heuristic value, while q_0 determines the relative importance of exploration versus exploitation. Once each ant has built a complete solution, this is tentatively improved using a local search procedure. Next, the best solution found from the beginning of the trial is used to update the pheromone trails. Then, the process is iterated starting again m ants until a termination condition is met. The best solution is used to modify the pheromone trail matrix (τ_{ij}), future ants will use this information to generate new solutions in the neighborhood of the best solution, as follows:

$$\tau_{ij} = (1-\rho) \cdot \tau_{ij} + \frac{\rho}{J_{\Psi}^{gb}}, \qquad \forall\ (i,j) \epsilon \Psi^{gb} \qquad (2)$$

Where $0<\rho<1$ and J_{Ψ}^{gb} is the length of J^{gb}, i.e. the shortest path generated by ants since the beginning of computation. Locally, when an ant moves from node i to node j, the amount of pheromone trail on arc (i, j) is decreased by the amount:

$$\tau_{ij} = (1-\rho) \cdot \tau_{ij} + \rho \cdot \tau_0 \qquad (3)$$

Where τ_0 is the initial value of trails. This algorithm was used with two objective functions: minimization of the number of tours and minimization of the total travel time. To this purpose, two independent colonies are used, one per each objective, but both share the variable Ψ^{gb}. Finally, time windows are used to limit the duration of the path. To this purpose, an active procedure is inserted in the algorithm, which, at every step when and ant moves between nodes i and j, it checks whether the movement violates time window constraints. Optionally, even vehicle capacities (i.e. payload) can be checked for violation, but it was not used in the application that will be shown in this paper.

3.3 Implementation of the Holonic Execution System

The MACS-VRPTW algorithm detailed in sub-section 3.2.2 was integrated in the DMAS architecture (Figure 3), as depicted in Figure 4. The order holon gets an order from the master schedule with task description, start and end dates. At time step t_0, the order holon delegates ant colonies to search for the best path. After the drilling process starts and disturbances or unexpected occurrences can take place changing boundary conditions, the order holon runs more simulations and performs on-line planning, i.e. continuous improvement of the initial work plan. The resources in charge of drilling piles were committed according to the best solution found out by the holon order itself. The algorithm was implemented in Matlab™ environment, because it facilitates the prototyping of the code. In the near future, integration within a multi-agent simulation environment (e.g. Anylogic) will be carried out. The main boundary conditions were:

- no maximum payload was assigned to drill resources, in fact assuming that they never come back to the depot until they finish their tasks;
- drills were not allowed to follow a path overlapping the nodes were piles had already been drilled; this was done by using a dynamic cost matrix;
- As all the parameters are dynamic (e.g. time window, cost matrix) when the algorithm updates the current best solution with a new one, the cost of the current solution is re-computed at each iteration.

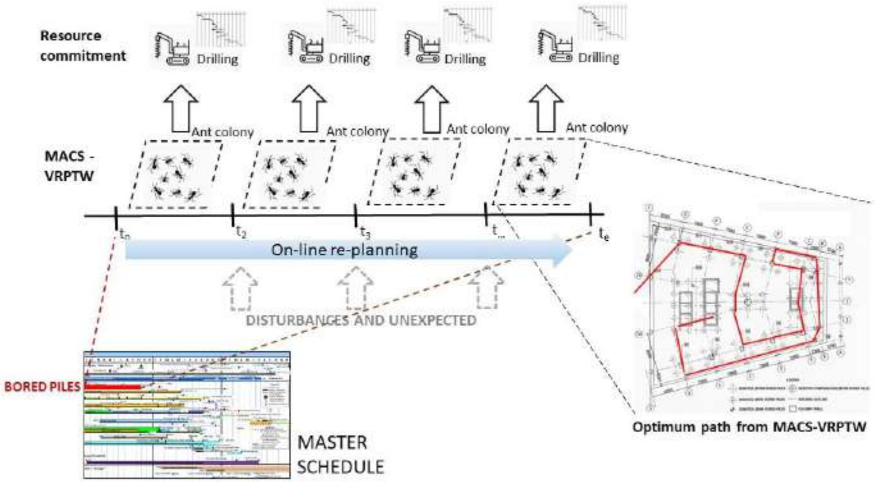


Figure 4. Sketch of the overall logic underlying the MACS-VRPTW algorithm.

The termination condition was set at 300 iterations. The main outputs provided by the algorithm are: sequence of nodes forming the best solution; overall cost of the solution; service (i.e. delivery) time to perform each pile drilling.

4 Testing of the Holonic Execution System

4.1 On-line Planning of Construction Works

4.1.1 The Case Study

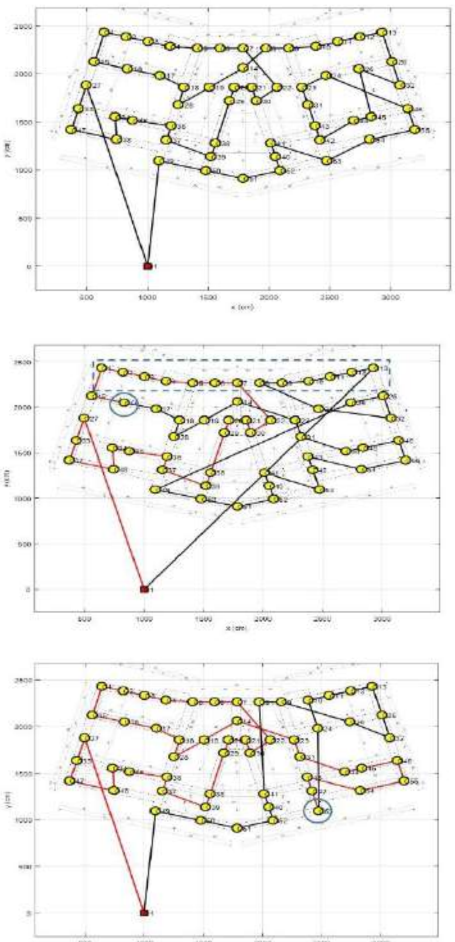
Pile construction was chosen as the test case for our proof of concept, because it poses several challenges: uncertainty generated by soil type, equipment efficiency and weather conditions; again, unexpected occurrences like site restriction and disposal of excavated soil ask for the application of a reliable on-line planning scheduling [18]. The drilling task only was simulated (excluding rebar cage positioning and concrete pouring). The resource holon assigned to each pile contained information about the volume, type of concrete, soil type, location, that were used by drills to estimate their task duration. This information was used as input for the application of the MACS-VRPTW algorithm. The set of piles was assumed to be arranged as shown in Figure 5.

4.1.2 Simulation of Scenarios

Two scenarios were simulated:

1. The site is initially fully available for drilling and there are no space restrictions; then, due to interferences with other crews, part of the site is restricted to access, so re-planning is necessary; after some time, the site becomes fully available again and the task is accomplished.
2. Drilling starts when the previous task is not finished, yet. So, just a portion of the site is available for drilling. After a while, the previous task gets accomplished and the whole site becomes fully available again and the drilling task can be accomplished, too.

Before starting the drilling process, the HES finds that the path marked on Figure 5-a and superimposed to the foundation plan is the best one, where the red squared node is the depot and the yellow circle nodes are the piles. In all figures, black lines form the path to be executed, whereas red lines form the accomplished path. While pile no. 16 is in progress (marked in a blue-coloured circle in Figures 5-a and 5-b), the site area within the boundaries of the blue dashed rectangular shaped area marked on Figure 5-b becomes restricted. As a result, the best path is re-planned, whose outcome is shown on Figure 5-b (piles between no. 1 and no. 13) and the drilling machine continues working according to this second work plan. The restricted area becomes available again while the drilling machine is doing pile no. 53 (blue-coloured marked circle on Figure 5-c). Hence, the on-line planning system computes again a new solution for the best path and the whole job is accomplished. In the second scenario, the site area included within the boundaries marked by the blue dotted polygon (Figure 6-a) is restricted due to the previously scheduled task. So the drilling machine is sent into the left side area of the site. Such a site area becomes unrestricted while the machine is drilling pile no. 4 (blue circled on Figure 6-b). As a result, the best solution is promptly updated and changes as shown on Figure 6-b. Also, the overall cost is updated as shown on Figure 6-c. Until the restricted area was not accessible, the best solution found was as costly as shown by the plot at iteration no. 150. But, on-line re-planning, which involved the second block made up of 150 iterations, caused the overall cost to decrease down to the value $1.8 \cdot 10^4$, which corresponds to iteration no. 300.



a)

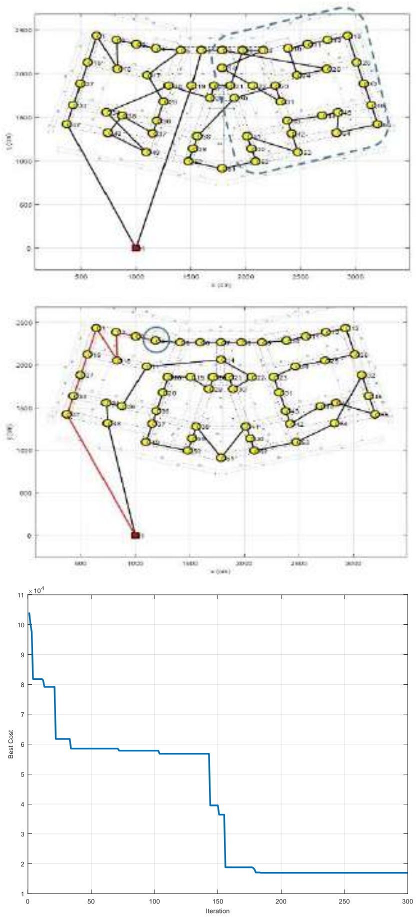
b)

c)

Figure 5: on-line re-planning relative to the Scenario no. 1.

4.2 Results and Discussion

This paper focused on the preliminary development of a holonic execution system (HEM) to implement on-line re-planning of construction activities.



a)

b)

c)

Figure 6: on-line re-planning relative to the Scenario no. 2.

The architecture used in this paper was adapted from the PROSA approach and the ACS-VRPTW algorithm was integrated to simulate the DMAS pattern. Simulation results are referred to the case of pile construction in the foundation of a building. It was shown that the HES is highly resilient to uncertainty and can cope with unexpected events, while minimizing the overall cost function. Thus, it is a good candidate for the implementation of lean management policies. In addition, the proposed architecture defines a valid general framework, based on which system frameworks specialized to several tasks can be developed. Further research will focus on the extension of the proposed architecture towards the realization of different construction tasks, for its enhancement and generalization. Finally, this approach is capable of facilitating the development of simulation scenarios relative to construction tasks, thanks to the reusability of the components forming the overall system architecture.

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4D BUILDING INFORMATION MODELLING: A SYSTEMATIC MAPPING STUDY

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Abstract –

Building Information Modeling (BIM) represents a procedural and technological transition that emerges as a change agent in the Architecture, Engineering and Construction (AEC) industry. 4D modeling refers to a BIM dimension that associates the 3D model of an enterprise with the planning schedule information, providing the visualization of the actual sequence of construction activity. Interactions with 3D models are discussed and debated extensively in research, when in fact, 4D modeling is less discussed, thus there is a knowledge gap that can be explored. In this way, this article aims to know the current scenario of the studies that approach the 4D modeling theme in an international context. For this, a systematic mapping study was performed, covering only the researches in scientific paper format published between the years of 2006 and 2016. After establishing inclusion and exclusion criteria, a total of 148 articles were analyzed in this study. In the logical organization of the subject phase, bibliometric indicators were applied for analysis of the sample regarding the temporal evolution of the publications, publications by country, institution and author, and most commonly used keywords. Finally, the articles were also classified as to their content, and 10 categories were identified for them. The category containing the highest number of articles refers to the barriers, opportunities and impacts observed in the implementation of BIM 4D. It also includes surveys that measure the 4D BIM utilization rate by professionals, companies and countries. The results show that the number of studies published on 4D BIM has grown over the years, with the United States being the country that produces the most in the area. This fact suggests that US policies to encourage the adoption of BIM have been providing positive effects, serving as an example for other countries.

Keywords –

Building Information Modeling; BIM; 4D Modeling; Systematic Mapping Study; Scientific Production.

1 Introduction

Building Information Modeling (BIM) means a procedural and technological change that is considered a very promising evolution in the Architecture, Engineering and Construction (AEC) industry [1]. BIM is disseminated as a broad process of improving the techniques of designing, planning, constructing, occupying/using and maintaining a building throughout its life cycle, based on a data model that contains all the necessary information to stakeholders [2]. BIM is a digital representation of the physical and functional characteristics of a building [3].

Therefore, Building Information Modeling can be understood as a process that uses a variety of tools capable of generating and sharing information about a given construction, which will help in decision making during its life cycle. In this way, BIM is evident from project conception to demolition of the construction. It is noteworthy that the AEC industry is increasingly open to approaches that associate elements of 3D BIM (geometric shapes in three dimensions) with time and programming information, aiming to improve Integrated Project Delivery [4].

One of the biggest problems in construction projects is that their increasing complexity has made it difficult to accurately predict some extremely important performance indicators, for example, the project schedule. 4D models allow project participants to communicate performance deviations based on commitments from coordination sessions, measure readiness of the upcoming tasks based on inter-dependencies of current schedule tasks and their constraints, and highlight locations that are at-risk of potential performance problems [5].

While interactions with 3D models are widely addressed and discussed in surveys, the uses of 4D modeling are less debated, so there is an "urgent need to explore and evaluate these models" [6]. According to There is a need for an improved interoperability between BIM and softwares of scheduling. Their related research efforts in this field have demonstrated advancements in utilizing 4D models, but remains to be done comprehensively leveraging of the intelligence of BIM for automated scheduling generation. To reach this purpose, a systematic mapping of the literature is done in relation to 4D BIM, involving only the works published in scientific paper format [7].

Thus, this research focuses on the study of only one of the areas of scope attributed to BIM, which is the effective planning of the construction. Hence, it is important to inform that a 4D model (3D model plus time dimension) is a powerful and effective tool in planning, capable of exposing the sequence of construction phases linked to a three-dimensional model of the building. Therefore, the visualization of the elements is tied to the exact time (phase) in which they are to be constructed. This allows an effective and tangible communication between the professionals involved in the construction, and with the client, improving the understanding of the project's lifecycle and its construction strategies.

2 Previous Studies

The authors haven't found any previous studies involving this kind of approach in the context of the international production of 4D BIM. However, it should be noted that the authors Pérez, Fernandes and Costa [8] have reviewed the literature on BIM 4D studies, focusing on logistics operations and workspace management (construction sites). For the accomplishment of the mentioned research, only 20 articles, published in the period from 2005 to 2015, were selected for use. The articles were classified according to their respective vehicle of publication, year and subject.

Although it contributes to the understanding of the production of articles on the mentioned theme, there is not the required deeping for the characterization of this production due to the low number of analyzed works. In contrast, the present study mapped 148 articles, classifying them into fourteen different categories and analyzing a series of indicators. It's important to highlight that the articles were searched in both Portuguese and English languages, and the period of coverage selected includes the years from 2006 to 2016.

3 Research Method

A Systematic Mapping Study was developed in order to obtain an overview of the publications about the uses of 4D BIM. By presenting a detailed and explained approach, the chosen method aims the future repetition of this work in a more comprehensive way by other researchers or the authors themselves. The starting point of this search was the selection of journals and databases that publish or store contents related to architecture, civil engineering, construction, planning and management methods, technologies and software related to 4D BIM. It seeks to identify the articles of greater relevance to the proposed mapping. The research design is illustrated in Figure 1.

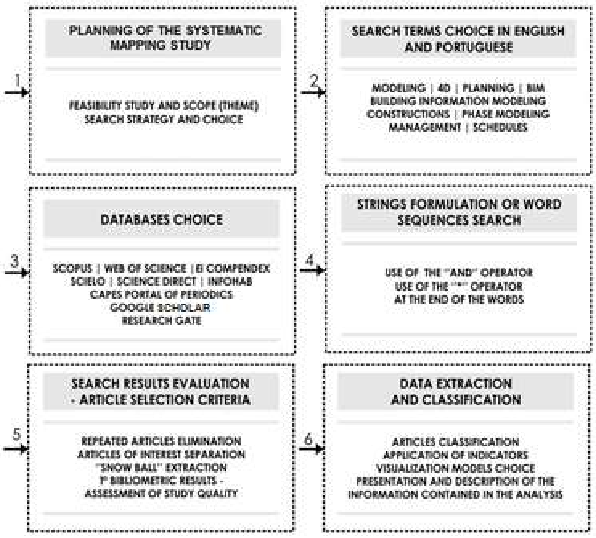

Figure 1. Methodological research steps

After the keywords were defined, the source search step was performed in two moments. In the first one, the publications were searched in the following digital databases: Scopus, Ei Compendex, SciELO, Science Direct, Web of Science, Google Scholar, the Capes portal of periodics and brazilian's Infohab (Centro de Referência e Informação em Habitação). Papers found in the ResearchGate social network were also tabbed. They led to a new search, characterizing the second moment, in which were included the collection of articles from the International Group for Lean Construction and electronic journals related to the industry of the AEC, as some of the Elsevier (Automation in Construction, Computers in Industry, Journal of Occupational Accidents, Advanced Engineering Informatics and Procedia Engineering), the EmeraldInsight (Construction Innovation, International Journal of Innovation Science, The International Journal of Logistics Management, International Journal of Operations & Production Management; International

Journal of Physical Distribution & Logistics Management, Journal of Engineering, Construction and Architectural Management) and the ASCE Library (Journal of Computing in Civil Engineering and Journal of Construction Engineering and Management). Other journals were found in the digital databases. Then, the Snowball Sampling mapping was carried out, in order to identify pertinent articles that were not previously selected. Snowball Sampling is a non-probability sampling technique that investigates the hidden population, which in this case refers to the papers that are not found in the search step [9].

At the end of this procedure, 314 articles were selected. Beyond the interval of time that was initially established, other criteria for the inclusion and exclusion of the data obtained were defined. It was necessary to have at least one keyword in the title, abstract, or keywords; and the access to the full text should be available for electronic consultation. Finally, articles that appeared in more than one base were eliminated, leaving a total of 148 articles.

The search results were moved to a Microsoft Excel spreadsheet and sorted according to their main subject. In the phase of logical organization of the subject, the following indicators were applied for the sample analysis: (i) time evolution of publications; (ii) publications by country, institution and author; (iii) most commonly used keywords; (iv) most used publication vehicles; (v) main subject.

4 Results and Discussions

In this section, the results of the international and national databases are summarized. Following the methodological procedures described in section 3, the search step resulted in a sample of 148 articles, in which 78 are from journals, and 74 from conferences.

4.1 Indicators

4.1.1 Time evolution of the publications

The evolution of the annual publication of the selected articles in the international search is showed in Figure 2, where it's possible to notice that all articles were published in a maximum of one decade. It is emphasized that there a considerable increase in publications happened after the year of 2014. The peak of the publications is marked by the year of 2015, with 33 articles published. In view of this, it is noted that the 4D BIM subject is recent and has not been much explored.

4.1.2 Publications per country, institution and author

The distribution of countries with more publications regarding 4D BIM, following the methodological procedures described in section 3, is presented in Figure 3. The most prominent country is the United States of America, with 40 articles, a value that is higher than the double of papers from the country in second place, which is Brazil. This result reinforces the SmartMarket Report study on the use of BIM in the United States, where it jumped from 40% in 2009 to 71% in 2012 [10]. The increase in the adoption of BIM is related to a national program called the 3D-4D-BIM Program, created in 2003 by the General Services Administration (GSA) in the USA. Subsequently, in 2006, the GSA decreed that all the new projected public buildings should use BIM at the conception stage, which also positively influenced the adoption of the technology [11].

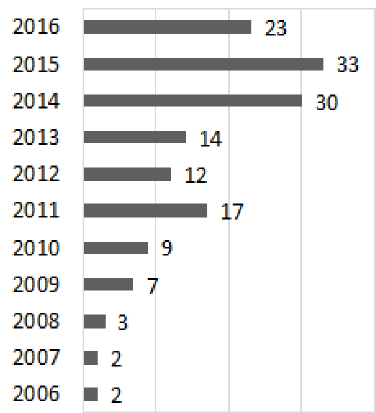

Figure 2. Articles published per year

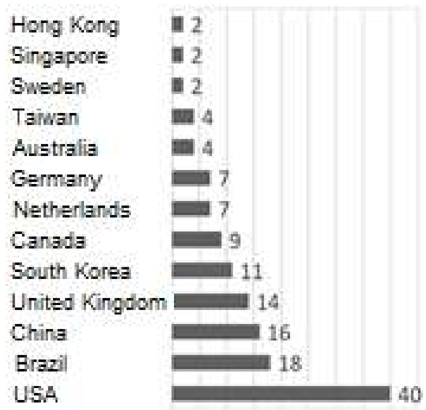

Figure 3. Articles published per country

The Figure 4 shows the number of institutions with more publications per country. Again, the United States of America appears in first place, with 15 institutions on the list, more than twice as many as the second, a position occupied by both China, South Korea and the United Kingdom, with 7 institutions on the listo of selected articles.

Figure 4. Institutions per country

Figure 5, however, represents the number of publications per institution. The university that publishes the most about 4D BIM is the University of Illinois, in the United States, with 11 articles, accounting for 27.5% of all publications in this country. Then, with 7 publications, are tied the institutions University of Twente, in the Netherlands, and Tsinghua University, in China.

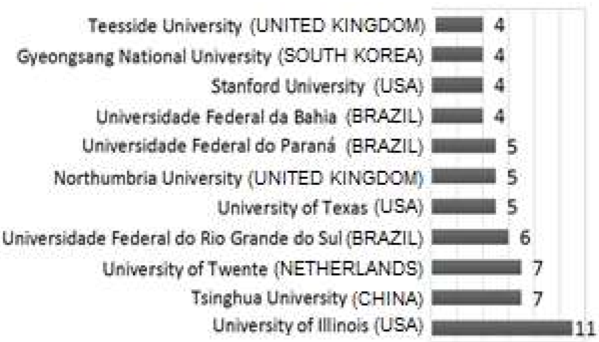

Figure 5. Publications per institution

Figure 6 shows the number of publications per author, but only those who collaborated in 3 or more articles on the subject, totaling 38 authors. In addition to these, 264 are present in the final sample of articles. The author with highest number of publications is Mani Golparvar-Fard, an assistant professor at the University of Illinois, in the United States. The second author on the list is Timo Hartmann, an assistant professor at the University of Twente, in the Netherlands. In the third place, two assistant professors are tied. They are LeenSeok Kang, from Gyeongsang National University, in South Korea, and Jianping Zhang, from the Chinese institution named as Tsinghua University.

4.1.3 Most used keywords

It is important to note that keywords represent the main subjects addressed in articles objectively, and are essential for tracking jobs quickly and accurately in a search. Thus, it's crucial for authors to choose the keywords of their articles carefully, otherwise it can hinder their propagation and the dissemination of their ideas. Figure 7 shows that the most used keyword in the articles was "4D", with 60 applications. Soon after, the word "BIM" comes up with 56 uses. In the third position comes the word "construction", with 48 uses.

Figure 6. Publications per author

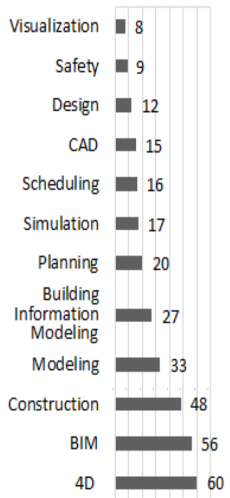

Figure 7. Publications per keyword

4.1.4 Most used publication vehicles

The journals in which it was possible to find the largest number of publications related to 4D BIM are those presented in Figure 8. "Automation in Construction" is highlighted, with 24 articles, followed by the "Journal of Construction Engineering and Management", with 11 publications.

Figure 8. Publications per Journal

The conferences (Figure 9) that concentrate more publications were two, the "International Conference on Computing in Civil and Building Engineering" and the "Conference of the International Group for Lean Construction", both with 12 articles. Soon thereafter, the event titled "Construction Research Congress" appears with 11 publications.

Figure 9. Publications per Conference

4.1.5 Main subject

In regard to identify he topics covered in the 148 articles chosen, a classification was made with 14 items. For a better understanding of the main subject categories, a brief explanation will be given on each one of them, in descending order of number of published articles.

The categorization generated Table 1, in which can be observed that the subject "Implementation of 4D BIM" was the most treated in the articles, with 51 apparitions. This category refers to research efforts that seek to identify challenges and opportunities encountered in the adoption of BIM 4D, at both organizational and governmental levels. In general, questionnaires are applied, and interviews are conducted to obtain insights from the AEC industry professionals. This classification also includes the growth rate in the adoption of 4D BIM by companies.

Implementation of 4D BIM	51
Logistics operations and workspace management	30
Dynamic planning - comparison between the as-planned and the as-built	23
Risk management in construction using 4D BIM	14
Management of space-time conflicts in projects	11
Integration between physical schedile and cost	6
Construction quality control through the integration of 4D BIM and other methods	5
Development and improvement of 4D BIM softwares	4
Comparison between different planning methods and 4D BIM	3
Development of components libraries	1

Table 1. Publications per main subject

Secondly, with 30 articles, is the "Logistics operations and workspace management" subject. The planning of logistics in a construction is fundamental to avoid waiting time, to manage the transportation of materials and waste, people movements and workflow of the various activities. Some problems such as lack of workspace, competing and restricted areas cause significant loss of time, thus being essential for construction planning.

The "Dynamic planning - comparison between the as-planned and the as-built" category, with 23 articles, is an actual performance analysis compared to the planned model for an early detection of initially idealized project designs.

In "Risk management in construction using 4D BIM", containing 14 articles, it refers to the evaluation of risks related to the safety and health of construction professionals associated with the work environment through BIM 4D.

The "Management of space-time conflicts in projects using 4D BIM " category has 11 articles. It refers to the the generation of modeling for the detection of conflicts between time, space and the 3D elements of projects, aiming the resolution of interferences before the beginning of construction. These problems can occur between the overlapping of activities in the schedule or different components of the building, such as, structure and installations, frames and sanitary pieces, among others.

The category named as “Integration between physical schedule and cost planning” contains 6 articles. It consists in papers that report the simultaneous use of 4D and 5D BIM softwares.

5 articles were put in the category called "Construction quality control through the integration of 4D BIM and other methods". It basically consists of integrating or comparing the use of BIM 4D with other methods, such as the Last Planner System (LPS). 4D scheduling is one example of synergy where BIM can be used to achieve lean effects.

The category "Development and improvement of BIM 4D tools" has 4 articles of the sample. With the increasing adoption of BIM, many tools are being developed and it is normal for existing ones to undergo improvement processes. As inherent in new technologies, one of the challenges related to 4D modeling tools is the lack of visualization patterns to represent construction elements and tasks, since each tool typically has its own standards.

With 3 articles in its sample, the ninth category is “Comparison between different planning methods and 4D BIM”. It’s a comparison of the acceptance of construction scheduling visualizations in 4D BIM and traditional planning tools, such as bar-charts and flowline-charts.

Lastly, only 1 article was found to the category named as “Development of a components library” category. It refers to the use of 4D BIM simulations to help in the creation of components libraries for projects.

5 Conclusions

This study aimed to characterize the international production of scientific articles in the area of 4D modeling. A sample of 148 papers was obtained in a time span from 2006 to 2016. The pioneering of this detailed research makes an important contribution to the identification of the subtopics related to 4D BIM.

This paper did not analyze the articles published in congresses related to 4D BIM, since most of them are not accessible to the researchers, unless they have participated in the events. The difficulty of finding conferences publications evidences the need to disseminate the articles produced by the students and professionals that make up the AEC industry. This may have caused a distortion in the search results, which identified that 49% of the publications came from events, while 51% were from journals. For this reason, it is recommended that other systematic mapping studies of the literature be done, including this kind of papers. It is noteworthy that articles of congresses contained in the research bases were counted in the present study.

The results show that the number of studies published on 4D BIM has been increasing over the years. It was also observed that the largest volume of publications occurred in 2015, with a slight decrease in 2016. The journal that most generated publications in the studied subject was the “Automation in Construction”, with 24 titles. The United States of America was the most representative country, with 40 publications. It also has the institution with the highest number of articles published, the University of Illinois, with 11 papers in its domain. This indicates that USA policies to encourage the adoption of BIM in public works have had positive effects.

Regarding the main subject of the articles, the fact that 51 of them approached the implementation of BIM 4D, totaling about 32% of the total sample, in which almost all of them are case studies, shows that the BIM methodology for planning is not only being studied in Academic world, but is also being applied in real construction projects.

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Facilitating the Communication of Rework Information to Craft Workers Using an Augmented Reality Process

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Abstract

Pipe spool fabrication is still highly dependent on skilled craft labour and thus is subjected to the productivity issues, such as rework, that plague the construction industry. Rework is a major challenge and is estimated to account for up to 12% of the total cost of a major project. Identifying geometric non-conformance that requires rework is done by pipe fitters and inspectors and its impact is commensurate with the stage in the assembly process at which the non-conformance is detected. Thus, improving the frequency and effectiveness of this process can reduce rework and help mitigate its impact. It is proposed to replace the traditional process with an augmented reality process, where a 3D as-built point cloud can be superimposed on the 3D BIM model of the design, facilitating the communication of rework information. An experiment was conducted to compare the time required to convey rework information using an augmented reality feedback process compared to a traditional feedback system. Participants were given a PVC pipe spool to assemble with either the augmented reality process or with a two-sided isometric drawing. The time spent conveying the rework and the iterations of rework that were completed in each instance were evaluated to compare how the use of visualization technology affects the communication of rework.

Keywords –
Rework; Pipe fitting; Augmented Reality; point cloud; 3D BIM; modular

1 Introduction

Modular construction has become an increasingly popular means of construction as it allows for greater automation and allows for more work to be completed in a controlled fabrication shop environment as opposed to on a construction site. Shifting construction from an exterior activity where it is impacted by the elements to an interior activity has helped reduce rework. Currently, rework is believed to account for 6 to 12% of the cost of a typical construction project [1]–[3]. However, not every task can be automated. This is particularly true for the piping industry, leaving it susceptible to project delays and cost overruns caused by rework.

The focus of this work is on piping elements, since they can account for up to 50% of the total cost of an industrial construction project and of module fabrication [4]. This is largely due to the nature of piping work and its dependence on skilled craft workers, as most components in a piping project are custom-made based on the design, by cutting and welding sections of pipe, elbows, reducers and tees. The raw materials coupled with the extensive hands-on time from craft workers makes piping portions of projects costly to complete and critical with respect to the project schedule. Additionally, current quality control methods for piping are time consuming, requiring use of conventional measuring tools and utilize traditional paper based drawings to convey information. This method is inefficient, as it is not conducive to the sharing of information regarding an assembly's fit for use amongst project stakeholders [5]. While this study is focusing on pipe elements, the general concept could be applied to other construction project components.

Craft workers conduct routine checks as they assemble to verify their progress thus far. The technology traditionally used to complete this work consists of hand tools tailored to measure the geometry of the pipe assembly. These include callipers, measuring tapes and spirit levels. Following the completion of an assembly, quality control personnel complete a final check before the assembly is deemed complete. Should an instance of non-conformance requiring rework be detected, the quality control personnel must take note of the issues and explain them to the craft worker. The craft worker will be responsible for remedying the situation through interpreting the information presented by the quality control person and comparing it with the design information presented on the isometric drawing. The work proposed in this study would facilitate the self-checking during the assembly process by the craft workers by providing them with quick visual feedback regarding their work in addition to assisting quality control personnel with conveying information to craft workers.

In a traditional industrial project, pipe fitters are given isometric drawings containing all the information pertaining to the assembly they are fabricating. These drawings represent the pipes as a single straight line using a 45°, 90°, 45° projection system [6]. These drawings provide information about assembly geometry, welds and components such as elbows and flanges. Isometric drawings can be hard to interpret depending on the geometric complexity of the assembly and the worker's experience and level of comfort with the drawing format. Studies have found that using a two-sided isometric drawing, one which contains a traditional isometric drawing on one side and then a two dimensional (2D) projected rendering of a three dimensional (3D) model increases productivity by making the design easier to interpret [4]. Studies have also shown that providing a worker with a 3D model has a similar effect [6], [7]. With the technology used to acquire 3D spatial data becoming increasingly more affordable, and the ubiquity of 3D models for construction projects, it is now possible to show craft workers the rework that needs to be completed by overlaying the 3D as-built scan over the 3D design model, simplifying the process of conveying this information.

2 Literature Review

2.1 Rework

Rework is responsible for losses of both resources and time in the construction industry and is a major contributor to projects being completed behind schedule and over budget. In an industrial project, measured rework is believed to be approximately 2.4% of the contract value, representing millions of dollars in losses [8]. Normal process iteration is not considered part of rework. In general, minimizing rework and its impact on a project's ability to meet its budget and schedule is viewed as the key in improving construction productivity [9].

It has been found that craft workers believe that 32% of their negative productivity is caused by the insufficient quality of the information they are provided, and this insufficient quality of information was deemed to contribute to reduced morale within the group of workers [10].

In addition to the direct costs of rework in construction, which may total up to 25% of the contract value, rework has an impact valued at 3 to 6 times its direct cost given the impact it has on workers and the decreased site moral experienced when workers are asked to redo work that was previously completed [11].

2.2 Augmented Reality

In recent years, enhanced digital reality has become increasingly prevalent as technological advances allow for higher quality digital environments at lower price points. There are two areas of enhanced digital reality: virtual reality and augmented reality. Virtual reality consists of an immersive environment while augmented reality is an enhancement of the existing surroundings by overlaying digital information [7]. Augmented reality is preferable to virtual reality for applications in the construction industry as it does not inhibit a user's awareness of their physical environment in the way that virtual reality does, making it a safer option for hazardous construction sites.

2.3 Information Formats

A number of studies have been conducted showing the impact of different information formats on the productivity and quality of work performed by craft workers.

In 2015, Hou et all [7] focused on improving productivity and performance through lowering the cognitive load experienced by craft workers using augmented reality. The study was executed on graduate students in construction, computer science, architecture and engineering. Students were tasked with assembling a PVC pipe system. Half of the students were given a 2D isometric drawing while the other were given a 3D model on a TV display. The model could be rotated by moving a hand-held remote sensor in the direction they wanted to move the model. This study found that the use of 3D models reduced the cognitive load experienced by the participants and reduced the time required to complete the assembly by 50%

In 2016, Goodrum et al [4] completed a study in which 54 pipe fitters were given different formats of information to assemble a pipe assembly. One group was given a traditional 2D isometric drawing. The second group was given a two-sided isometric drawing, which consists of a 2D isometric drawing with a 2D projection of the corresponding 3D model on the back. The third group was given a 2D drawing with a 3D printed model of the assembly. The latter two groups both benefitted from the additional information; however, the second group, the one with the two-sided isometric drawing, was the fasted group. The results of this study were the main motivation behind providing the participants who did not use the augmented reality application with a two-sided isometric instead of a standard isometric drawing in the current study as two-sided isometrics are now an industry best-practice.

In 2014, Dadi et al [6], recruited 26 individuals, both engineering professionals and craft workers to assemble a 3D structure. The individuals were separated into three groups and each group was given the design in a different format. One group had a 2D set of drawings, the second a 3D computer model of the assembly and the third had a 3D printed model of the assembly. The study found that 3D printed models increased direct work and lowered the required mental work load more than 3D computer models and 2D drawings.

While studies focused on the impact of information formats on a craft worker's ability to complete an assembly have been completed, this study will instead focus on how the information format affects a craft worker's ability to identify and correct errors in their own work.

2.4 3D BIM

The increased prevalence of 3D Building Information Modeling (BIM) over the last two decades is a major contributor to the feasibility of the process being investigated in this work, as the process is contingent on having access to accurate, updated 3D models. Utilizing BIM offers many benefits to project stakeholders. Projects that utilize BIM are able to achieve increases in productivity of up to 30% while reducing the Requests for Information and Change Orders by a factor of 10 [12]. With design errors and omissions having the highest impact on the project cost for industrial projects, adopting 3D models to better integrate the different aspects of the design can help reduce the cost of a major industrial project [13]. Project managers believe that 3D modeling is a worthwhile investment and, specifically for the piping industry, that failing to create a model will increase the cost of piping project by 10% [14].

2.5 3D Spatial Data Acquisition

The use of laser scanners to acquire 3D spatial data is well established in construction management [15]. Laser scanners have been used for automated progress tracking [16], [17] and for compliance checking of fabricated elements [18], [19].

While laser scanners are able to provide highly accurate and broad range data, the data requires processing to be used, often requiring that multiple scans be stitched together, making it difficult to incorporate the technology into real time processes. For this reason, portable structured light scanners present a unique opportunity to acquire 3D spatial data that does not require processing and can thus be used in real time. For this reason, a structured light scanner is being utilized in this work.

2.6 Research Motivation

In countries with high labour costs, it is imperative to incorporate new technologies to maximize productivity. With the strict tolerances provided on most projects and the lack of skilled labour in countries like Canada and the United States [20], finding the means to minimize the impact of rework once it is encountered on a project is critical.

While work has been done to assess the impact of rework on a project's schedule and budge, and studies have been competed to determine how the format used to convey design information impacts productivity, there has been no work done in assessing how the communication of rework helps reduce the impact of rework on a construction project.

3 Methodology

As part of a larger study being conducted by the University of Waterloo and Aecon Industrial West, an application was developed with the aim of increasing productivity and reducing rework in pipe spool assembly through the use of augmented reality. This same application was utilized to assess how using an augmented reality process assists quality control personnel in conveying information pertaining to rework that must be completed on an assembly to the craft worker creating the assembly.

3.1 Participants

Currently, the recruited participants are all engineering students. Participants were split into two groups, with one completing the experiment with a two-sided isometric drawing and having corrections verbally conveyed. The other group utilized the augmented reality process to complete the assembly and were actively involved in the quality control, utilizing the augmented reality process to obtain feedback on their work. As such, a total of 2 groups of participants were utilized in the experiment: engineers with drawings and engineers with the application.

A total of 30 students were used, 15 in each subcategory. There are plans in place to recruit craft workers to further this study and this effort is currently in the coordination stage.

3.2 Experiment Assembly

It was deemed infeasible from a financial, logistical and safety perspective to conduct the experiment using a welded metal pipe assembly as would be the normal use scenario for the augmented reality process once it is deployed. Thus, a spool utilizing 1.5" diameter black PVC pipes was designed for this experiment. To help simulate the act of tack welding, the team purchased flexible couplings shown in Figure 2. The connections require the participant to use a screwdriver to tighten the metal connector. This penalizes a participant for creating an incorrect assembly since the connection must be loosened, the components moved and then the connection reconnected.

The nature of these socket-based connections prevents some of the challenges pipe fitters typically experience in assembling components to be flush with one another. This prompted the design of a spool with a more challenging geometry than normally experienced in an industrial piping project to help create an assembly that requires the level of planning and attention to detail that assembling a proper metal pipe spool would require. This design was then shown to an engineer at Aecon Inc. who said that while the spool was more complicated than a typical spool assembly seen in their shop, it was not an unreasonable design.

The two-sided isometric drawing that was given to participants to convey design information is shown in Figure 1.

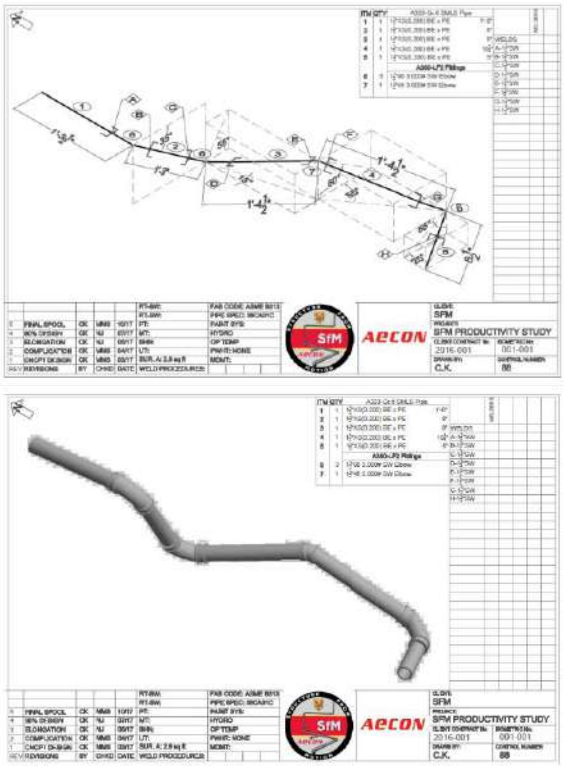

Figure 1. Both sides of the two-sided iso used in the experiment

Figure 2. Flexible elbow coupling used to simulate socket welds

3.3 Experiment Process

The participants were divided into two groups: one group working with a standard two sided isometric drawing and the other group working with the augmented reality process. Both groups were instructed to complete the same assembly. Figure 3 shows the set-up participants who used the augmented reality process were given to begin the experiment.

Figure 3. Initial set up of experiment

Figure 4. Structure IO, structured light scanner used for experiment mounted on an iPad

The workflow associated with both iterations of the experiment is shown in Figure 5. The steps enclosed in the red boxes are the main focus of this work. Both groups were given the same two-sided isometric drawing and assembled the same PVC pipe spool, however, the augmented reality group had rework identified by showing errors through overlaying a scan of the as-built assembly over the 3D design model while the group working with only the two-sided isometric drawing had their rework identified without the aid of the visual contrast comparing their erroneous assembly with the design model.

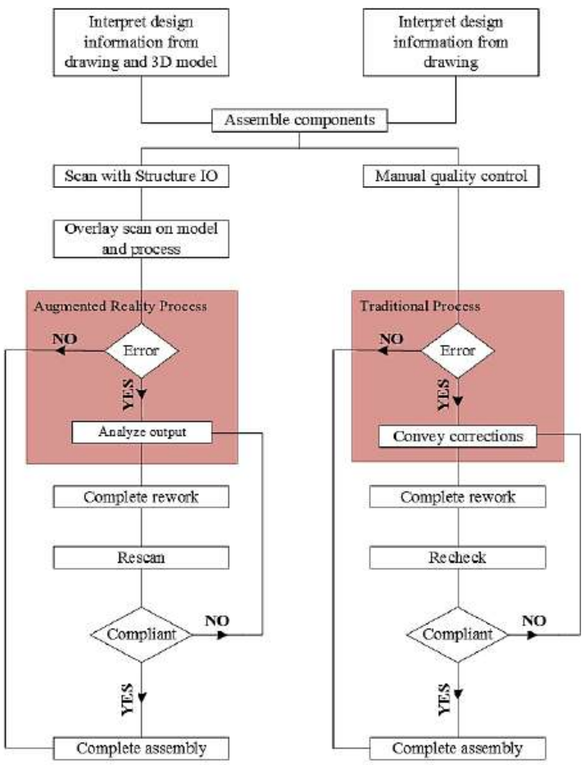

Figure 5. The workflows associate with both iterations of the experiment

Both groups were given the same traditional measuring tools and the same two-sided isometric drawing. In addition to the resources given to the participants who had information presented on only a static drawing, the participants using the augmented reality process had access to the 3D design model during the assembly process and were able to use a structured light scanner shown in Figure 4 to scan the assembly as they build it. This scanner is accurate up to 0.5 millimetres (mm) depending on how close the scanner is to the object being scanned [21]. A tolerance of 5 mm was set as the threshold for acceptance through multiple trials of scanning prefabricated components and comparing the scans to their actual dimensions. These participants were able to overlay the assembly, as they completed it, on the 3D design model to verify that what they had completed to that point was correct. These participants were also actively involved in the quality control process as they were the ones scanning the assembly, overlaying it on the model and doing the processing required to check if their assembly was compliant.

For participants using the static drawing, required rework was articulated and gestured to the participant by the experiment administrator who completed the quality control on the assembly.

3.4 Participant Assessment

Participants were administered two spatial cognition tests: a Card Rotation Test and a Cube Rotation Test created by Educational Testing Service (ETS) in 1976 [22]. This was done primarily to ensure that participants with higher spatial cognitive skills were not all grouped into the same category and inflating the results by comparing a group with higher spatial cognition against a group with lower spatial cognition. Participants were then grouped into 3 groups: having either low, medium or high spatial cognition. The groupings were determined by averaging the scores of the two tests. A fairly even distribution of scores was found across all the participant groups as is shown in Table 1.

Table 1. Distribution of spatial scores of participants

Score	App Participants	Drawing Participants
High (0.8-1.0)	3	3
Med. (0.6-0.79)	6	4
Low (0-0.59)	6	6

3.5 Data Analysis

Participants were filmed while assembling the pipe spool. The videos were watched and segmented into activities and durations to assess the participants' progress during the experiment. Figure 6 illustrates the average time spent on each activity for experiment participants who only had the drawing. Figure 7 shows the average time sent on each activity for participants who used the app.

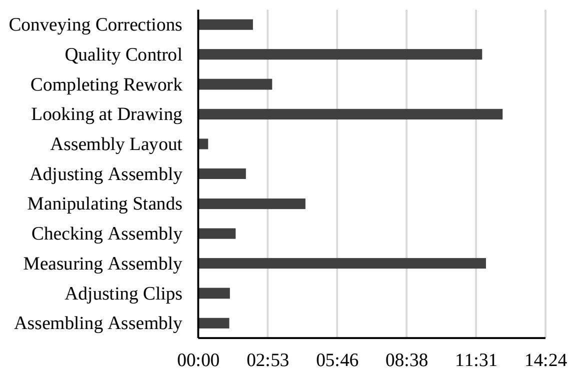

Figure 6. Average time spent on each activity for experiment participants using only the drawing

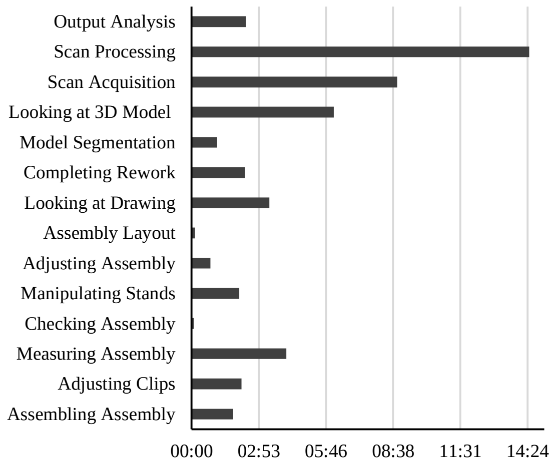

Figure 7. Average time spent on each activity for experiment participants using the app

In evaluating the videos, emphasis was placed primarily on tracking the activities of conveying the rework to be done and completing rework. Conveying rework was deemed to be any time where the administrator explained to the participant how their assembly failed to meet the required specifications in the case of participants using a traditional assembly and the time the participant spent assessing their own mistakes based on the overlay of the as built scan on the 3D model for a participant using the application. In both cases completing rework was deemed to be any time where the participants were modifying components that failed to meet the required specifications.

For both activities the time and cycle count were tracked. In the case of conveying rework, cycle count referred to the number of cycles of feedback that were completed. In the case of completing rework, cycle count considered the total number of times a participant modified an assembly component based on the feedback they were given regarding the work that had been completed thus far.

4 Results

The participant categories were divided into three clusters based on spatial cognition: low, medium and high spatial cognition as shown in Table 1 to compare how using the augmented reality application to convey rework affected participants of varying levels of spatial cognition. A total of 30 trials were run on engineers, 15 using the augmented reality process and 15 using the traditional drawing. Two participants had to be remove from the data pool that used the drawing as those two did not have any rework associated with their trials.

4.1 Conveying Rework

The times that were spent conveying the errors to the participants were totaled. An average of 2:26 was spent conveying corrections to participants with traditional formats while an average of 1:50 was spent conveying corrections to participants with the augmented reality process, a 25% reduction in the time required. Table 2 shows a summary of the time spent conveying corrections to the three groups. The use of the augmented reality process seemed to have the biggest impact on participants who fell into the medium spatial skills category. A number of the participants who fell in the low spatial skills category were unable to complete the assembly and eventually gave up, meaning that the times spent conveying corrections to them are lower than they should be as they do not represent the total time required.

Table 2. Average times spent conveying rework to participants based on spatial skill groups

Cognition Score	App Participants	Drawing Participants
High (0.8-1.0)	2:01	2:14
Med. (0.6-0.79)	1:47	3:07
Low (0-0.59)	1:33	1:54

4.2 Completing Rework

The time spent by participants completing rework was computed. The average time spent by participants using only the drawing and traditional quality control practices was 4:21 compared to 2:09 for participants who used the augmented reality process to assess their correctness. Using the technology led to a 50% decrease in time spent completing rework. Table 3 presents a summary of the time taken by each spatial group to complete the rework required for their assembly.

Table 3. A summary of the time taken to complete rework by both groups of participants

Cognition Score	App Participants	Drawing Participants
High (0.8-1.0)	1:27	4:30
Med. (0.6-0.79)	1:17	4:33
Low (0-0.59)	3:21	3:58

The number of rework cycles completed by each participant was also totaled. It was found that the average person using the augmented reality application had 11.73 cycles of rework while the average person using the drawing had 18.77 cycles of rework, a decrease of 37% when the augmented reality process was used. Table 4 presents a summary of the number of rework cycles by each group.

Table 4. Average number of rework cycles by both groups of participants

Cognition Score	App Participants	Drawing Participants
High (0.8-1.0)	10	13
Med. (0.6-0.79)	7.33	15.25
Low (0-0.59)	17	24

5 Conclusions and Discussion

It was found that using the augmented reality process reduced the time required to convey the required rework to participants by 25% and that it reduced the time they required to complete the rework by 50% with a 37% reduction in the number of rework cycles needed.

The data samples collected thus far were all using engineers, many of whom lacked experience working with hand tools and assembling products based on drawings. While their spatial skills and ability to interpret information was a factor in their work, the rework cycles could have likely been reduced if the participants were more experienced with working with the hand tools they were presented.

Somewhat surprisingly, the augmented reality process seemed to have the greatest impact on the group with medium spatial skills. From a qualitative assessment of the participants, the reason appears to be that the medium spatial skills participants were more likely to confuse themselves. They were fairly confident in their own interpretation of the information and were noticeably flustered when presented with information that did not align with their expectations. Participants with low spatial skills were more likely to accept what the experiment administrator told them at face value and didn't question the rework they were told to complete. The augmented reality process had the lowest impact on participants who had high spatial skills, likely because most of the rework these participants had was linked to their ability to perform the tasks of assembling and measuring the assembly, that is their ability to complete craft work, and was not as dependent on their ability to have the general correct assembly shape.

5.1 Participant Habits

It was observed that participants who had access to the augmented reality app utilized the app as a measuring tool in favor of actually measuring. It appears that participants realized that they would be able to verify the assembly with the application quicker than they would be able to actually perform the measurements with traditional measuring tools.

Participants with the application also appeared more comfortable checking assemblies they were less confident in. Participants with the drawing were more inclined to spend time checking the assembly before telling the experiment administrator that it was complete, whereas participants using the application were more likely to check it and modify the same piece multiple times. This may be because for the participants using the application the feedback on the rework to be done was self-given whereas the participants who had only the drawing to complete the assembly were being told by someone else that their work was wrong, lowering their morale.

5.2 Feedback from Participants

At the end of the experiment, participants were briefly presented the format of the other version of the experiment. Participants with the drawing often expressed that they would have found the visualization of the rework to be more conducive to their ability to complete it while several participants who used the augmented reality process expressed that they did not think they would be able to complete the assembly without the aid of the 3D model.

6 Future Work

At this time, experiment trials still need to be completed, particularly with craft workers. The intention was to evaluate 40 engineering students and 40 craft workers. At this time 30 engineering students and 4 craft workers were recruited. The sample of 4 craft workers was deemed too small to include in the work at this time.

The participants' skills working with their hands must also be taken into account. Additional trials could be conducted with engineering students who were more experienced working with their hands or they could be evaluated in groups based on their experience working with hand tools and assembling things. To help offset the impact of participants' skills, the participants could be recruited to complete a second spool of comparable difficulty with the alternate experimental procedure. Participants who used the traditional methodology could use the augmented reality process and those who used the augmented reality process could use the traditional methodology.

Additionally, using a more realistic spool could give participants a greater sense of purpose in completing the assembly. Finally, statistical analysis of the significance of the variance must be completed.

7 Acknowledgements

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Representation of the Joystick Using the Virtual Configuration

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Abstract -

Recently, facilities that are a foundation of industries such as roads, water pipes, and tunnels are getting old. Along with this, the demand on inspection in the decrepit facilities is increasing. The robots are introduced to inspection in these facilities. It is required that the operators can control the robots easily when facilities are inspected using the robots. However, the control device which the operators can operate the robots easily is different depending on the robots which are controlled and the inspection task. Therefore, a control device which enables us to control various robots is developed by us. The device can represent various operation manners by changing the shape. In this paper, a method of device control with a virtual configuration is described. A joystick is represented using the virtual configuration. The torques to be outputted to each joint of the joystick are calculated using the forces and moments which applied to the grip of the device by the operators. The calculated forces and torques are distributed to the torques which drive each joint in the device. Therefore, the joystick using the virtual configuration is represented. The usability of the proposed method is shown by verification experiments.

Keywords -

Virtual configuration; Remote operation; Control device;

1 Introduction

Recently, facilities that are the foundation of industries such as roads, water pipes, and tunnels are getting old. In this paper, these facilities are called the social infrastructures from now on. The demand on inspection in the social infrastructures are increasing along with the increase of the decrepit social infrastructure. There are many scenes where a judgment by humans is required in the inspection task of the social infrastructures. However, there are some situations that are difficult for humans to enter depending on the environment where the inspection task is performed. Therefore, it is desired to assist the inspection task is performed by humans with controlling the robots remotely. Against this backdrop, development and introduction of next generation robots for the social infrastructures are done in Japan since 2013[1]. On the other hand, the number of experts who inspect the social infrastructures is decreasing. Therefore, it is demanded to inspect efficiently even if an operator is not used to controlling the robots. Various robots which inspect the social infrastructures is developed[2][3]. Also, a hexapod robot for inspection in narrow environment is developed by us[4]. It is required that the operators can control the robots easily when the social infrastructures are inspected using these robots. On the othe hand, a control device and an operation manner are different depending on the robots which are controlled and the inspection task.

A cockpit and a control device which enables us to control various robots are developed by us (Figure 1). The control device has a virtual configuration represented by using a multiple virtual axes of rotation. A virtual axis of rotation which does not exist in the actual configuration is represented by combining multiple axis of rotation as shown in Figure 2. In this paper, a representation of a joystick using the virtual configuration is described. Hereinafter, The joystick which is represented using the virtual configuration is called the virtual joystick.

Overview of the virtual axis of rotation is described. In the case of the actual axis of rotation, the moments applied to the axis of rotation can be divided into a moment about the axis of rotation and others. Object rotates about

Figure 1. The cockpit which is developed by us.

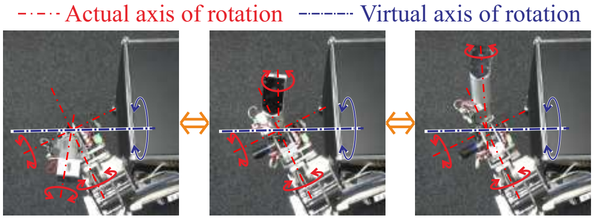


Figure 2. The actual axis of rotation and the virtual axis of rotation.

the axis of rotation by the moment about the axis of rotation. Hereafter, the moment about the axis of rotation is called the unconstrained force. On the other hand, the moments and forces other than the unconstrained force applied to the axis of rotation is received by the structure of the axis of rotation. The forces which received the moments and forces by the structure of the axis of rotation is called the mechanically constrained forces from now on. However, in the case of the virtual axis of rotation, the mechanically constrained forces cannot be achieved by the structure of axis of rotation. Therefore, the mechanically constrained forces are achieved by position control if the virtual axis of rotation is represented. On the other hand, control to achieve the mechanical behavior which want to be represented is performed about unconstrained force. The virtual axis of rotation is represented by the unconstrained force and the mechanically constrained forces. The unconstrained force is a spring force if the joystick is represented. The representation of the virtual axis of rotation is performed as follows. First, a coordinate system of the virtual axis of rotation Σ_V is fixed at a position where the virtual axis of rotation is represented. Then, the unconstrained force and the mechanically constrained forces required to represent the virtual axis of rotation are calculated. The unconstrained force and the mechanically constrained forces are represented by the forces which in each coordinate axis direction in Σ_V and the torques which about each coordinate axis in Σ_V to be outputted to Σ_V. The forces and torques are distributed to the torques which drive each joint in the device. The virtual axis of rotation is represented by the torques which drive each joint in the device.

The structure of this paper is as follows. First, related work is described in section 2. The control device which is developed by us is described in section 3. The methods of representing the virtual joystick and the virtual axis of rotation are described at the beginning of section 4. Then, the method of calculating the forces and torques to be outputted to Σ_V using the forces applied to the grip of the control device by the operators is indicated. The method of distributing the calculated forces and torques to the torques which drive each joint in the actual device is shown at the end of section 4. The usability of the proposed method is shown by verification experiments in section 5. Finally, conclusion is described in section 6.

2 Related Work

A lot of devices for controlling robots are studied. An equipment for controlling a mobile robot is developed by Yamazawa et al.[5]. Locomotion interface and immersive projection display are used in the equipment. The robot is controlled using the walking information of a operator. A cockpit for controlling humanoids is developed by Tachi et al.[6]. An equipment for controlling humanoids in the cockpit has the same configuration as the arm of humanoids. Humanoids are controlled by using the master-slave control system. These equipment enables us to control the robots intuitively. However, these equipment has only one operation target. Using a motion capture to control humanoids is studied. A system that control humanoids using optical motion capture is developed by Kurihara et al.[7]. Using the motion capture enables us to control humanoids intuitively. However, the equipment becomes large scale in the case of using motion capture. Hull which is a cockpit for controlling robots is developed by Institute Future Robotics Technology Center, Chiba Institute of Technology [8]. Hull has haptic interface. It is able to present the forces applied to the robot to the operator by using the haptic interface. Bilateral master-slave control is proposed for force feedback control to the operators[9][10] [11]. Among them, a bilateral master-slave control with different configuration is proposed by Arai et al.[12]. It is possible to combine the slave with high workability and the master with high operability by using the proposed method in document [12]. Further, there is an advantage that general versatility is enhanced and modularization is easy to perform. The master is given the torque which drive each joint of the master as the commanded value in the bilateral master-slave control with different configuration. Applying the bilateral master-slave control with different configuration to the device which is developed by us is considering.

3 The Control Device Which is Developed by Us

The control device which enables us to control various robots is developed by us. The device is shown in Figure 3. The device is composed with one prismatic joint and five revolute joints. A DC motor and a rotary encoder are installed on each joint to use the device as a haptic interface. An angle of each joint is acquired by the rotary encoder. A 6-axis force sensor is installed between 5th axis and 6th axis of the device. It is possible to measure the forces and moments which applied to the grip of the device by the operators using the force sensor.

The device can represent various operation manners by changing the shape. The operation manners that can be represented at present is shown in Figure 4. Joystick Mode in Figure 4(a) is a mode that represents a joystick on the market. 3D Input Mode in Figure 4(b) is a mode that represents the gaming device "*Falcon*" sold by Novint company. Any point on the three-dimensional space can be designated by 3D Input Mode. Dedicated Input Mode in Figure 4(c) is a mode exclusive to the hexapod robot which is developed by us. The configuration of the device in Dedicated Input Mode is the same as that of a limb of the hexapod robot. Therefore, it is possible to perform an intuitive control like actually grasping the limb of hexapod robot. Please refer to document [4] for details of the hexapod robot.

4 Representation of the Joystick Using the Virtual Configuration.

4.1 The Virtual Joystick

The control device which is developed by us can be represented various operation manners by changing the shape. However, the movable axes installed on the actual device may not be orthogonal in some cases. In that case, it cannot represent the joystick by using only axes of rotation installed on the device. Therefore, the virtual axis of rotation different from the actual axis of rotation as shown in Figure 2 is used. The joystick is represented using three virtual axes of rotation orthogonal to one another. The method of representing the virtual joystick is described below. First, a coordinate system of the virtual axis of rotation is fixed newly at a position where the virtual axis of rotation is represented as shown in Figure 5. The coordinate system is denoted as Σ_V. One of the coordinate axes in Σ_V is made to overlap with the virtual axis of rotation. In this example, Y-axis in Σ_V is made to overlap the virtual axis of rotation. The position of Σ_V is fixed. Further, only rotation about Y-axis in Σ_V is performed, thereby the virtual axis of rotation is represented.

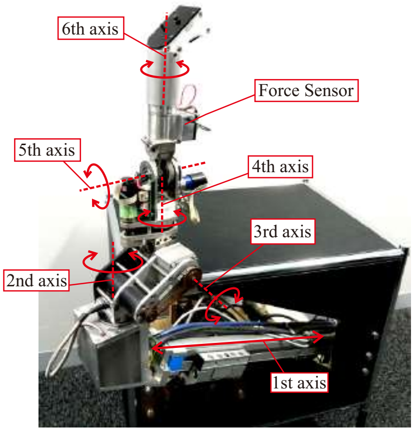
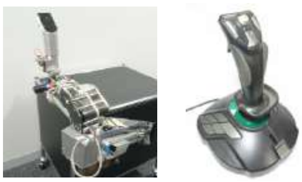
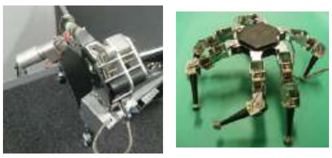


Figure 3. The control device which is developed by us.



(a) Joystick Mode

(b) 3D Input Mode



(c) Dedicated Input Mode

Figure 4. The operation manners that can be represented at present.

The forces in each coordinate axis direction in Σ_V to be outputted to Σ_V is denoted as ${}^V\boldsymbol{f}_v = [{}^V f_x, {}^V f_y, {}^V f_z]^T$. The torques about each coordinate axis in Σ_V to be outputted to Σ_V is denoted as ${}^V\boldsymbol{\tau}_v = [{}^V\tau_x, {}^V\tau_y, {}^V\tau_z]^T$. The unconstrained force and the mechanically constrained forces for representing the virtual axis of rotation are represented by ${}^V\boldsymbol{f}_v$ and ${}^V\boldsymbol{\tau}_v$. In this example, only rotation about the Y-axis in Σ_V is performed. Therefore, ${}^V\tau_x$, ${}^V\tau_z$, and ${}^V\boldsymbol{f}_v$ are the mechanically constrained forces. Also, ${}^V\tau_y$ is the unconstrained force. Since the joystick is represented this time, the unconstrained force is spring force. Also, the mechanically constrained forces are represented by position control. ${}^V\boldsymbol{f}_v$ and ${}^V\boldsymbol{\tau}_v$ are calculated using the forces and moments which applied to the grip of the device by the operators. It is impossible to directly output ${}^V\boldsymbol{f}_v$ and ${}^V\boldsymbol{\tau}_v$ to the virtual axis of rotation because the virtual axis of rotation does not exist in the actual configuration of the device. ${}^V\boldsymbol{f}_v$ and ${}^V\boldsymbol{\tau}_v$ are distributed to the torques which drive each joint in the device. The equilibrium of the force and moment in static mechanics is used for the distribution. The details are described below.

4.2 Each Coordinate System Used for Calculation.

Each coordinate system used for calculation is as follows. The coordinate systems of each joint and the force sensor are assigned as shown in Figure 6. A world coordinate system is denoted as Σ_W. The positive direction of

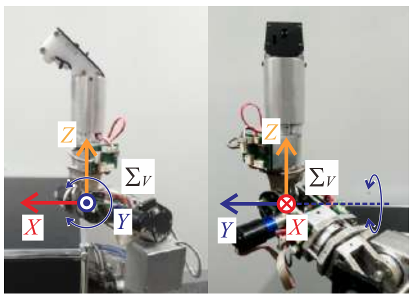


Figure 5. The position where the coordinate system of the virtual axis of rotation is fixed.

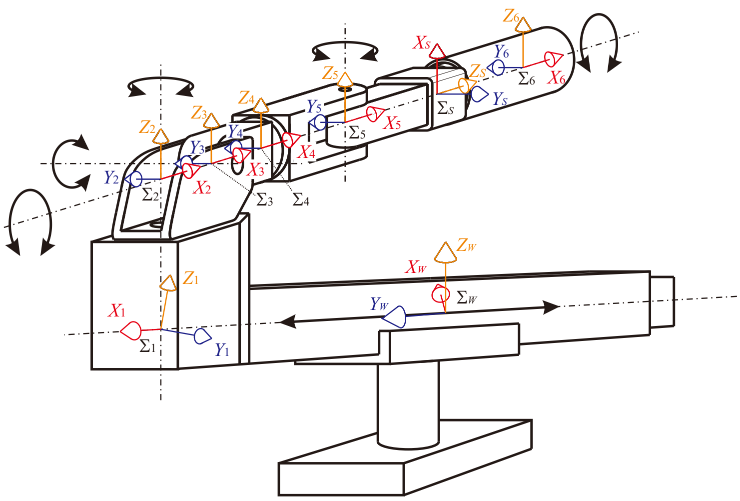


Figure 6. The position where each coordinate system is fixed on the device.

the X-axis in Σ_W is assigned in the same direction as the front direction of the operator. Also, the positive direction of the Z-axis in Σ_W is assigned as the upward direction perpendicular to the ground. The coordinate system of i-th axis is denoted as $\Sigma_i (i = 1, 2, \ldots, 6)$. Σ_1 is fixed at the intersection of 1st axis and 2nd axis. The X-axis in Σ_1 is the same direction as a movable axis of the prismatic joint. All $\Sigma_i (i = 2, 3, \ldots, 6)$ are the same posture in the case of the device is the initial posture. A coordinate system of the 6-axis force sensor is denoted as Σ_S. The origin of Σ_V is fixed to the same position as the origin of Σ_5 at this time. Also, the initial posture of Σ_V is the same as that of Σ_W.

4.3 Calculations of the Forces and Torques to Be Outputted to Σ_V.

${}^V\boldsymbol{f}_v$ is outputted to the origin of Σ_V as the mechanically constrained forces. Since the mechanically constrained forces are achieved by position control, ${}^V\boldsymbol{f}_v$ is calculated using Equation(1).

$$ {}^V\boldsymbol{f}_v = -\boldsymbol{K}_p \Delta\boldsymbol{p} + \boldsymbol{K}_d(\boldsymbol{0} - \dot{\boldsymbol{p}}) \quad (1) $$

${}^V\boldsymbol{f}_v (\in R^{3\times1})$: The forces in X-axis, Y-axis, and Z-axis direction in Σ_V to be outputted to the origin of Σ_V[N].
$\boldsymbol{K}_p (\in R^{3\times3})$: Proportional gain matrix.
$\Delta\boldsymbol{p} (\in R^{3\times1})$: Deviations of Position in X-axis, Y-axis, and Z-axis direction in Σ_V from the initial position of the origin of Σ_V[m].
$\boldsymbol{K}_d (\in R^{3\times3})$: Differential gain matrix.

${}^V\boldsymbol{\tau}_v = [{}^V\tau_x, {}^V\tau_y, {}^V\tau_z]^T$ are calculated as follows. Since ${}^V\tau_x$ and ${}^V\tau_z$ are the mechanically constrained forces, these are achieved by position control in the same way as ${}^V\boldsymbol{f}_v$. Therefore, ${}^V\tau_x$ and ${}^V\tau_z$ are calculated using Equation(2).

$$ {}^V\tau_i = -k_p \Delta q_i + k_d(0 - \dot{q}_i) \quad (i = x, z) \quad (2) $$

${}^V\tau_i$: The torque about i-axis in Σ_V to be outputted to Σ_V[N·m] $(i = x, z)$.
k_p: Proportional gain.
Δq_i: Angular displacement about i-axis in Σ_V[rad] $(i = x, z)$.
k_d: Differential gain.

On the other hand, ${}^V\tau_y$ is the unconstrained force. Since the joystick is represented by using the virtual axis, the unconstrained force is spring force. Therefore, ${}^V\tau_y$ is calculated using Equation(3). The forces and moments which applied to the grip of the device by the operators acquired from the force sensor are used for the calculations.

$$ {}^V\tau_y = {}^V F_x \, l - k_{pj} \Delta q_y \quad (3) $$

${}^V\tau_y$: The torque about Y-axis in Σ_V to be outputted to Σ_V[N·m].
${}^V F_x$: The force in X-axis direction in Σ_V applied to grip of the device by the operators[N].
l: Length from the origin of Σ_S to the origin of Σ_V[m].
k_{pj}: Proportional gain used for representation of the joystick.
Δq_y: Angular displacement about Y-axis in Σ_V[rad].

It is possible to represent the virtual axis of rotation about the X-axis in Σ_V by using Equation(4) instead of Equation(3). Also, it is possible to represent the virtual axis of rotation about the Z-axis in Σ_V by using Equation(5) instead of Equation(3). In that case, ${}^V\tau_y$ is calculated using Equation(2) as $i = y$.

$$ {}^V\tau_x = -{}^V F_y \, l - k_{pj} \Delta q_x \quad (4) $$

$$ {}^V\tau_z = {}^V M_z - k_{pj} \Delta q_z \quad (5) $$

${}^{V}\tau_i$: The torque about i-axis in Σ_V to be outputted to Σ_V[N·m] ($i = x, z$).
${}^{V}F_y$: The force in Y-axis direction in Σ_V applied to grip of the device by the operators[N].
${}^{V}M_z$: The moment about Z-axis direction in Σ_V applied to grip of the device by the operators[N·m].
l: Length from the origin of Σ_S to the origin of Σ_V[m].
k_{pj}: Proportional gain used for representation of the joystick.
Δq_i: Angular displacement about i-axis in Σ_V[rad] ($i = x, z$).

4.4 Calculation of the Angular Displacement About Each Coordinate Axis in Σ_V.

The angular displacement about each coordinate axis in Σ_V are necessary to calculate ${}^{V}\boldsymbol{\tau}_v$ using Equation(2)-(5). However, the virtual configuration is different from the actual configuration. Therefore, the angular displacement cannot be gotten directly using the rotary encoder installed on each joint of the device. The calculations of the angular displacement about each coordinate axis in Σ_V are performed as follows.

A initial coordinate system of the virtual axis of rotation is denoted as Σ_{V_0}. It is supposed that Σ_{V_0} becomes Σ_V by operating the device. The positions of the origin of Σ_{V_0} and Σ_V don't be changed. It is supposed that ${}^{V_0}\boldsymbol{R}_V$ can be calculated by forward kinematics at this time. A rotation matrix from Σ_{V_0} to Σ_V is denoted as ${}^{V_0}\boldsymbol{R}_V$. Then, ${}^{V_0}\boldsymbol{R}_V$ is expressed by Equation(6) using R_{ij} $(i, j = 1, 2, 3)$ that are known parameters.

$$ {}^{V_0}\boldsymbol{R}_V = \begin{bmatrix} R_{11} & R_{12} & R_{13} \\ R_{21} & R_{22} & R_{23} \\ R_{31} & R_{32} & R_{33} \end{bmatrix} \tag{6} $$

On the other hand, the angular displacement about each coordinate axis in Σ_V can be represented by the roll, pitch, and yaw angles because the joystick is represented. Therefore, the rotation matrix can be calculated using a representation by the roll, pitch, and yaw angles. The roll, pitch, and yaw angles are denoted as ϕ, θ, and ψ. The rotation matrix ${}^{V_0}\boldsymbol{R}_V$ from Σ_{V_0} to Σ_V is given by Equation(7) using ϕ, θ, and ψ.

$$ {}^{V_0}\boldsymbol{R}_V = \begin{bmatrix} C_\theta C_\psi & -C_\theta S_\psi + S_\phi S_\theta C_\psi & S_\theta S_\psi + C_\phi S_\theta C_\psi \\ C_\theta S_\psi & C_\theta C_\psi + S_\phi S_\theta S_\psi & -S_\phi C_\psi + C_\phi S_\theta S_\psi \\ -S_\theta & S_\phi C_\theta & C_\phi C_\theta \end{bmatrix} \tag{7} $$

Here, $S_\phi = \sin\phi$ and $C_\phi = \cos\phi$. The same applies to θ and ψ. Equation(8) is obtained from Equation(6) and (7).

$$ \begin{aligned} &\text{if } \sin(\theta) = 1 && \begin{cases} \phi = 0 \\ \theta = \dfrac{\pi}{2} \\ \psi = \operatorname{atan2}(R_{23}, R_{22}) \end{cases} \\ &\text{if } \sin(\theta) = -1 && \begin{cases} \phi = 0 \\ \theta = -\dfrac{\pi}{2} \\ \psi = -\operatorname{atan2}(R_{23}, R_{22}) \end{cases} \\ &\text{otherwise} && \begin{cases} \phi = \operatorname{atan2}(R_{32}, R_{33}) \\ \theta = -\operatorname{asin}(R_{31}) \\ \psi = \operatorname{atan2}(R_{21}, R_{11}) \end{cases} \end{aligned} \tag{8} $$

However, the values of ϕ and ψ can not be uniquely decided in the case of $\sin(\theta) = \pm 1$. In this case, it is assumed that $\phi = 0$. From the above, ϕ, θ, and ψ are calculated.

For example, the case of applying to the our device is described. Σ_{V_0} is fixed by us so that the postures of Σ_{V_0} and Σ_W are the same. Therefore, ${}^{V_0}\boldsymbol{R}_V$ can be expressed as Equation(9).

$$ {}^{V_0}\boldsymbol{R}_V = {}^{W}\boldsymbol{R}_V = {}^{W}\boldsymbol{R}_6\,{}^{6}\boldsymbol{R}_V \tag{9} $$

Here, a rotation matrix from Σ_W to Σ_6 is denoted as ${}^{W}\boldsymbol{R}_6$. A rotation matrix from Σ_6 to Σ_V is denoted as ${}^{6}\boldsymbol{R}_V$. Σ_V always follows the movement of Σ_6. Also, the posture of Σ_6 becomes the same as that of Σ_V when rotated only $\pi/2$ about Y-axis in Σ_6. Therefore, ${}^{6}\boldsymbol{R}_V$ is always given by Equation(10).

$$ {}^{6}\boldsymbol{R}_V = \begin{bmatrix} \cos(\pi/2) & 0 & \sin(\pi/2) \\ 0 & 1 & 0 \\ -\sin(\pi/2) & 0 & \cos(\pi/2) \end{bmatrix} = \begin{bmatrix} 0 & 0 & 1 \\ 0 & 1 & 0 \\ -1 & 0 & 0 \end{bmatrix} \tag{10} $$

On the other hand, ${}^{W}\boldsymbol{R}_6$ can be calculated by using forward kinematics, thereby R_{ij} $(i, j = 1, 2, 3)$ in Equation(6) are obtained. ϕ, θ, and ψ are calculated using R_{ij} $(i, j = 1, 2, 3)$ and Equation(8).

4.5 Distribution of the Calculated Forces and Torques to the Torques Which Drive Each Joint in the Device.

In this section, the method of distributing ${}^{V}\boldsymbol{f}_v$ and ${}^{V}\boldsymbol{\tau}_v$ to the torques which drive each joint in the device is described. The same idea as calculations of the each joint torques which are balanced with the forces and moments applied to the end effector in the robot manipulators is used[13]. ${}^{V}\boldsymbol{f}_v$ corresponds to the forces which applied to the end effector of the robot manipulators. Also, ${}^{V}\boldsymbol{\tau}_v$ corresponds to the moments which applied to the end effector of the robot manipulators. The each joint torques which are balanced with the forces and moments applied to the end effector are calculated in the case of a robot manipulators. However, ${}^{V}\boldsymbol{f}_v$ and ${}^{V}\boldsymbol{\tau}_v$ are outputted to Σ_V by using the torques which drive each joint in the device in the case of the virtual axis of rotation. Therefore, keep in mind that signs are different when calculating the torques of the robot manipulators and the virtual configuration.

${}^{V}\boldsymbol{f}_v$ and ${}^{V}\boldsymbol{\tau}_v$ which are calculated using Equation(1)-(5) are the forces and torques expressed in Σ_V. ${}^{W}\boldsymbol{f}_v$ and ${}^{W}\boldsymbol{\tau}_v$ which are ${}^{V}\boldsymbol{f}_v$ and ${}^{V}\boldsymbol{\tau}_v$ expressed in Σ_W are given by Equation(11) and (12) by the equilibrium of force and moment in static mechanics.

$$ {}^{W}\boldsymbol{f}_v = {}^{W}\boldsymbol{R}_V {}^{V}\boldsymbol{f}_v \tag{11} $$

$$ {}^{W}\boldsymbol{\tau}_v = {}^{W}\boldsymbol{R}_V \, {}^{V}\boldsymbol{\tau}_v + {}^{W}\boldsymbol{p}_V \times ({}^{W}\boldsymbol{R}_V {}^{V}\boldsymbol{f}_v) \tag{12} $$

The position vector of Σ_V expressed in Σ_W is denoted as ${}^{W}\boldsymbol{p}_V$. Cross product of vectors is denoted as "×". ${}^{W}\boldsymbol{p}_V = [{}^{W}p_x, {}^{W}p_y, {}^{W}p_z]^T$ and Equation(13) are defined by us.

$$ [{}^{W}\boldsymbol{p}_V\times] = \begin{bmatrix} 0 & -{}^{W}p_z & {}^{W}p_y \\ {}^{W}p_z & 0 & -{}^{W}p_x \\ -{}^{W}p_y & {}^{W}p_x & 0 \end{bmatrix} \tag{13} $$

Accordingly, Equation(11) and (12) are expressed by Equation(14).

$$ \begin{bmatrix} {}^{W}\boldsymbol{f}_v \\ {}^{W}\boldsymbol{\tau}_v \end{bmatrix} = \begin{bmatrix} {}^{W}\boldsymbol{R}_V & \boldsymbol{0} \\ [{}^{W}\boldsymbol{p}_V\times]{}^{W}\boldsymbol{R}_V & {}^{W}\boldsymbol{R}_V \end{bmatrix} \begin{bmatrix} {}^{V}\boldsymbol{f}_v \\ {}^{V}\boldsymbol{\tau}_v \end{bmatrix} \tag{14} $$

The relationship between the torques which drive each joint $\boldsymbol{\tau}(\in R^{6\times1})$, ${}^{W}\boldsymbol{f}_v$, and ${}^{W}\boldsymbol{\tau}_v$ is expressed by Equation(15) using Jacobian matrix $\boldsymbol{J}(\in R^{6\times6})$.

$$ \boldsymbol{\tau} = -\boldsymbol{J}^T \begin{bmatrix} {}^{W}\boldsymbol{f}_v \\ {}^{W}\boldsymbol{\tau}_v \end{bmatrix} \tag{15} $$

Therefore, the relationship between ${}^{V}\boldsymbol{f}_v$, ${}^{V}\boldsymbol{\tau}_v$, and $\boldsymbol{\tau}$ is expressed by Equation(16) from Equation(14) and (15).

$$ \boldsymbol{\tau} = -\boldsymbol{J}^T \begin{bmatrix} {}^{W}\boldsymbol{R}_V & \boldsymbol{0} \\ [{}^{W}\boldsymbol{p}_V\times]{}^{W}\boldsymbol{R}_V & {}^{W}\boldsymbol{R}_V \end{bmatrix} \begin{bmatrix} {}^{V}\boldsymbol{f}_v \\ {}^{V}\boldsymbol{\tau}_v \end{bmatrix} \tag{16} $$

${}^{V}\boldsymbol{f}_v$ and ${}^{V}\boldsymbol{\tau}_v$ are distributed to the torques which drive each joint in the actual device using Equation(16).

5 Verification Experiments

5.1 The Representation of the Virtual Joystick

A experiment is performed, thereby it is confirmed that the virtual joystick is represented by using the proposed method. The joystick with one virtual axis of rotation is represented in the experiment. The virtual axis of rotation is installed as shown in Figure 7. The forces in lateral direction and longitudinal direction against the virtual axis of rotation are applied to the grip of the device and a behavior of the device is observed. The spring scale is used to understand easily and visually the forces that applied to the grip of the device. Measurable range of the spring scale is 0 to 2 kgf. The behavior of the device in the case of the virtual axis of rotation is not represented is also observed for purposes of comparison. The device is only performed gravity compensation when the virtual axis of rotation is not represented.

The top-view of the device is shown in Figure 8 as the experiment result. The result in the case of performing only gravity compensation without the virtual axis of rotation is indicated by a red frame in Figure 8. Also, the result in the case of the virtual axis of rotation is represented is indicated by a blue frame in Figure 8. Small red triangles are put in Figure 8 in order to easily understand elongation of the spring scale. The grip of the device should move on the red dashed line in Figure 8 if the virtual axis is installed as shown in Figure 7.

The grip of the device is leaning in the direction to which the forces were applied in the case of the virtual axis of rotation was not represented. And the grip of the device is moving away from the red dashed line. On the other hand, the following results were obtained in the case of the virtual axis of rotation was represented. The grip is rotating about the virtual axis of rotation when the forces were applied in lateral direction against the virtual axis of rotation. And the grip of the device is moving on the red dashed line. Also, it is confirmed by looking at the spring scale that the forces applied to the grip of the device are increasing as angular displacement from initial posture is increasing.The grip is not leaning even if the forces which applied to the grip increased when the forces were applied in lateral direction against the virtual axis of rotation. From the above results, it is considered that the virtual joystick has been represented by using the proposed method.

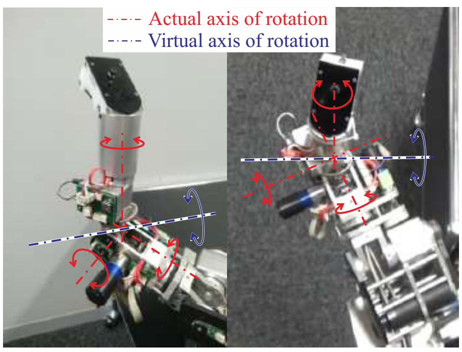
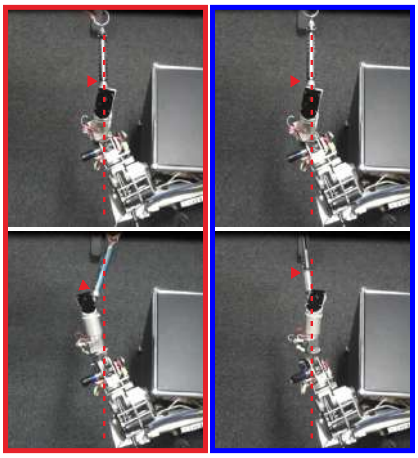
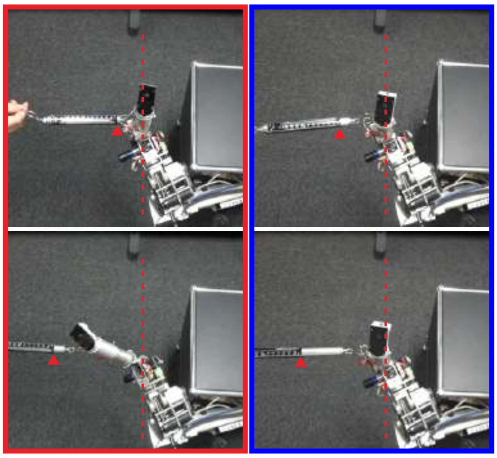


Figure 7. The place where the virtual axis of rotation is installed.



(a) lateral direction



(b) longitudinal direction

Figure 8. The behavior of the device when forces are applied in lateral direction and longitudinal direction against the virtual axis of rotation (Red frame:Without virtual axis of rotation, Blue frame:With virtual axis of rotation).

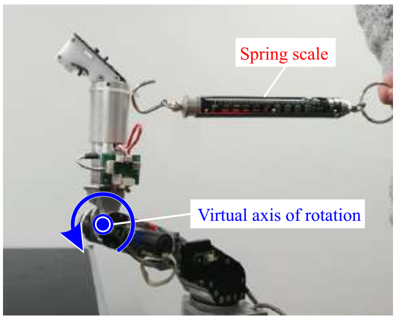


Figure 9. The environment in which the experiment is performed.

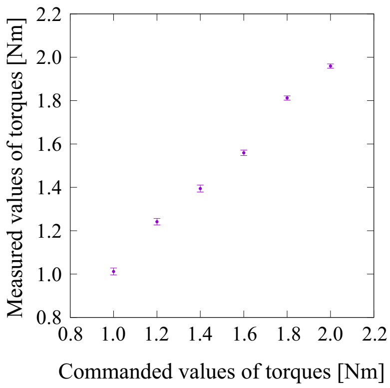


Figure 10. The relationship between the commanded values of torques and the measured values of torques.

5.2 The Torques Outputted to the Virtual Axis of Rotation.

The torques to be outputted to the virtual axis of rotation are distributed to the torques which drive each joint in the device by using Equation(16). A experiment is performed, thereby it is confirmed whether the required torques are actually outputted to the virtual axis of rotation by the torques which drive each joint in the device. The experiment is performed as follows. The environment in which the experiment is performed is shown in Figure 9. A commanded torques to the virtual axis of rotation are given. The commanded torques are distributed to the torques which drive each joint in the device by using Equation(16). The forces outputted to the grip of the device at this time are measured using the spring scale. The torques actually being outputted to the virtual axis of rotation are calculated. The measured values of the forces and the distance from the point where the forces were measured to the virtual axis of rotation are used for the calculation. The measured values of torques and the commanded values of torques are compared. 1.0, 1.2, 1.4, 1.6, 1.8, and 2.0 N are given five times respectively as the commanded torque.

The relationship between the commanded values of torques and the measured values of torques obtained from the experiment is shown in Figure 10. The horizontal line is the commanded values of torques, and the vertical line is the measured values of torques. The points are the mean values of the measured values of torques. The error bars are standard deviation. Figure 10 shows that the ratio between the commanded values of torques and the measured values of torques is about 1 : 1. Also, the standard deviation is small. Therefore, it is considered that the required torques are actually outputted to the virtual axis of rotation by the torques which drive each joint in the device.

The above results show that it is possible to output the torques commanded by us to the virtual axis of rotation. Therefore, it is considered that the bilateral master-slave control with different configuration proposed in document [12] can be applied to the device with the virtual configuration.

6 Conclusion

In this paper, the representation of the joystick using the virtual configuration was described. The coordinate system of the virtual axis of rotation was fixed. The virtual axis of rotation was represented with performing only rotation about one coordinate axis of the coordinate system. The method of calculating the forces and torques to be outputted to the coordinate system using the forces moments applied to the grip of the control device by the operators was shown. Then, the method for obtain the angular displacement about each coordinate axis in the coordinate system required for the calculations of the forces and torques was shown. In addition, the method of distributing the calculated forces and torques to the torques which drive each joint in the device was shown. The virtual axis of rotation was represented using the above methods. Finally, the usability of the proposed method was verified by performing the verification experiments.

On the other hand, there are two problems in the proposed method. First, the equation in static mechanics is used when the forces and torques are distributed. Therefore, the movement with large inertial force is not considered. Then, the virtual axis of rotation was represented in only one position. It is thought that the representation of more operation manners becomes possible by representing virtual axes of rotation at multiple position. The future task of this study is to deal with these problems and further extend the representation of the control device with the virtual configuration.

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Value Stream Mapping of the Design Process in a Design-Build Firm

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Abstract –

With a scenario of intense difficulties faced by the construction industry, improvements of the productive processes are demanded in order to make them more efficient, optimizing resources such as human, materials and financial ones, aggregating quality to the delivered product. Thus, this study aims the application of a methodology of improvement in the design process, under the lean approach, in a design-build firm, including the usage of the tool Value Stream Mapping (VSM). The VSM is initiated from the first contact with the customer to the final design and construction documents delivery. As a result, high levels of interruption and waiting for information have been detected. It has been verified a total lead time of 50 days, with only 21.28% corresponding to the effective execution time of activities. The analysis of the negotiation phase indicates a consumption of 32% of the total cycle time and in the design phase it was observed that just 30.68% of the time is utilized on activities which generate value for the customer. Besides, there is a loss of €84.93 in materials and services. With the implantation of kaizens, it is proposed to lower the total lead time in half of the initial amount. Therefore, the simple usage of lean tools contributes to reduce waste.

Keywords –

Lean Thinking; Lean Design; Value Stream Mapping; Design Management; Design Process; Architectural Executive Design; Private Sector.

1 Introduction

Low productivity is one of the biggest challenges facing the construction industry in the world economy. Brazil and the European Union, for example, play about 15% and 75% of United States productivity respectively, indicating that there is a gap between them (Mello and Amorim [1]).

Therefore, it is more and more necessary the adaptation to new technologies and way of production from the industry making the processes more efficient, increasing in the optimization of human resources, materials and financial, but also aggregating quality to the delivered product.

In this context, there are some studies that aim to improve construction processes. Generally, these researches seek to adapt theories, methods and tools originated from manufacture to the construction sector. Lean Construction, originated from the Lean Thinking, which aims to gain quality and productivity through the reduction of waste in the construction sector. This approach has generated positive results and stabilization of the constructive processes, but there are not many studies on the application of the Lean within the administrative scope of the design firms. Thus, the gap of the knowledge that this paper seeks to fill is the application of the VSM tool in a design firm.

Studies like Lima et al. [2], Tilley [3] e Melo et al. [4] prove that problems with the design quality and documentation in the construction industry have a significant impact on the efficiency of the construction sector and are the main factors for the rework in design and projects phase.

This paper consists on the application of a methodology of improvement of the design process, adapted from Freire and Alarcón [5], in a design firm based in Natal, Brazil. The firm develops design activities, budgets, licensing and consults. The team is composed by two engineers and an intern, being this one responsible for aiding the engineers.

2 Theoretical reference

2.1 Lean Thinking

The Lean Thinking is a generalization of the Toyota Production System (TPS) (Womack et al. [6]). Idealized by the engineer Taiichi Ohno, the TPS emerges as an application of a new manufacturing technology at the Toyota Motor Company, automobile industry, after the Second World War. Its principle is based on increasing the productivity through the complete elimination of waste, defined as everything that does not aggregate value, structured in two pillars: The Just in Time and Autonomation. In this system one item is only produced when it is necessary and in the correct amount (Ohno [7]).

In the battle against the waste, main principle of the Lean Thinking, Rother and Shook [8] created the Value Stream Mapping (VSM), based on the maps of material flows and on information utilized by Toyota. The VSM is considered the most important tool in the fight against waste.

2.2 Lean Thinking Application

Freire e Alarcón [5] proposed a methodology to improve the design process and applied on 4 designs of a design firm specialized in the civil engineering, mining and industrial area. The suggested methodology by the authors is based on the Lean Design approach, which considers the application of the conversion models, flow and value to the processes of design elaboration, seeking to identify and eliminate the waste and activities which do not aggregate value.

Tilley [3] analyzed, through a literature review, that if the implementation of the Lean Design has the potential to reach the necessary quality improvements. He concluded that a Lean Design Approach has the potential to improve significantly the way the design process is managed, aggregate value to the internal customers and to the final customer and minimize the waste in the construction process through designs and documentation of better quality.

Koskela et al. [9] points out that the design management is chaotic and improvised. The authors applied the Lean approach in the design management of construction of a building with 7.600 m^2 in Finland, through the usage of the Last Planner system, method that used to be applied only in construction phase. The design was compared to another similar design, previously carried out by the same planners and at the same location using the conventional way of planning. The results indicated a decrease of 30% in the design time comparing to the traditional planning method, the process of the design as a whole was more disciplined in comparison with the design managed in the conventional way. Koskela et al. (1997) observed that the application of the Last Planner generated a superior process of design in all aspects and that all the involved parties saw the approach as something really positive and everybody wanted to use the method in future designs.

Lee et al. (2010) proposed the application of Lean concepts in the elaboration of proposals of megaprojects of infrastructure. The research is a case study concerning the development of a proposal of a Design-Build-Operate-and-Maintain (design, construction, operation and maintenance) project of US$ 500 million in the public sector. The study discusses the concepts of Design Constraint Analysis Choosing by Advantages (CBA), set-based design, cross functional teaming, colocation, and Target Value Design (TVD). The results indicated improvements in the collaboration between teams and in the integration between the process of design and cost estimate, and by consequence, a better performance on the conception of megaprojects and delivery of a more competitive proposal.

3 Research Method

The research method used in this paper is an adaptation from the method used by Freire and Alarcón [5] to achieve improvements in the design process. Based on concepts and Lean Design principles, the authors consider the design process composed of three models: conversion, flow and value. According to the researchers 4 stages are necessary, such as:

1. **Diagnosis and evaluation**: It aims to determine the current conditions of the process under the perspective of flow and value. At this stage Freire and Alarcón (2002) consider necessary and complementary the application of five actions to a complete comprehension of the design process. They are: the obtainment of performance indicators, the value mapping stream, execution of interviews, the achievement of the time distribution in the process, the identification of waste and opportunities of improvement.
   In this research the utilized performance indicators are based on Lima et al. [2]: Processing Time (PT), Lead Time (LT) and PT/LT percentage. Adapted from Freire and Alarcón [5] the time percentages are defined according to the distribution of activities in the process: Data collection, design, consultations, exception or rupture, time of waiting for information and time of inactivity. The study also proposes indicators for the analysis of the negotiation time compared to the time of project and to the total time.
   The Value Stream Mapping (VSM) was performed according to Tapping and Shuker [11], focusing on the information flows. The data utilized to produce the map were obtained from direct observation,

interviews and analysis of documents (through the observation of the date and time of emails and app messages, and the notes from the team's reports as well) within 3 months of follow up. Divided in 5 meetings which add up approximately 13 hours of data collection with the team of the design-build firm. It has been obtained the time distribution in the process by the VSM interpretation and analysis, the identification of waste and opportunities for improvement. Through the interpretation and VSM analysis it was obtained the time distribution in the process, the identification of waste and opportunities of improvement.

2. **Implementation of changes:** based on the stage of diagnosis and evaluation it suggests the implementation of changes in the process depending on the types of waste and problems found. In this stage the authors proposed the usage of 7 tools of improvement, classified according to the 5 areas of improvement (customer, administration, design, resources and information - CAPRI): interactive coordination; intranet; checklists before the design; checklists after the design; Quality Function Deployment (QFD); value stream mapping and training.

   It is not mandatory the application of all suggested tools by Freire and Alarcón [5], but those compatible with the company's necessities, according to the areas of improvement (CAPRI). In this study just some of the aforementioned tools were adopted.
3. **Control:** It aims to control and assess the effects of the changes made in the process. It consists on following control measures such as the time distribution and performance indicators, verifying the effectiveness of the improvements.
4. **Standardization:** It aims to introduce permanent improvements on the working methods of the company, through the formalization of changes, as well as implementing the ongoing improvement to design process through the reapplication of the methodology.

   In this study the stages 3 and 4 will not be applied because they do not fit the purpose of the research.

4 Findings and Discussions

4.1 VSM Current state

This phase comprehends the diagnosis of the current situation of a design-build firm which has as an external customer an owner of a supermarket with 382.50 m^2 of built area. Figure 1 illustrates the value stream mapping of the design package and complementary documents for purposes of legalization, atypical situation of the firm. The initial contact with the customer was via an instantaneous message app with the engineer, followed by a visit to the site. Next, due to the need to consult the appropriate procedures to legalize the project after built it, it is done a visit to SEMURB (Environment and Urbanism Department). From that, it is set up and proposal and sent to the customer.

After waiting some time for the customer to reach out, there is the negotiation phase, with adjustments of the values, payment method and, lastly, contract signing at the supermarket. The team visits the project to data collection for the architectural executive design (AED) sketch, after some mishaps. Ultimately, with all the measures of the building collected in the field, the intern begins the digitalization of the data collected and the location of the points for the drainage design. When the file is received, there is the first review of the architectural executive design.

In the next phase, there is the sewage and drainage design sizing and respective specifications. In the drainage design some doubts about the position of the water tank on the roof came up. Therefore, there is a waiting time for information, due to other ongoing activities and the engineer just reaches out on the next day to obtain the answer from the customer and next, an interruption of a working day because of external factors not related to this VSM. The architectural executive design is resumed, followed by another interruption.

The engineer starts the draft of the drainage design from the data collected during the technical visit and, once it is concluded, it goes to the intern in order to finalize the design. For the execution of the RIV (Neighborhood Impact Report), the engineer consults with the SEMURB to eliminate doubts and requests the customer data such as: Schedule of the garbage truck, data of the sanitation in the area and public transportation; and, the property title. After receiving them, they can be included in the RIV.

The team schedules another technical visit for the approval of the architectural executive design, with a wait of 2 days due to incompatibilities of schedules among the team, and other data for the RIV: working schedule of the supermarket, number of employees, way of solid waste packaging and water table level. On this visit, the customer decides to incorporate one more floor in the architectural executive design. Afterwards, there are two working days with no activities connected to the customer's design. Coming back, the team works in parallel: the intern proceeds with the architectural executive design, the engineer works on the elaboration of the schedule and the other engineer finishes the RIV, designs the fire design and continues the architectural design from the last update from the intern.

The intern includes some architectural design changes demanded by the customer, corrections on the

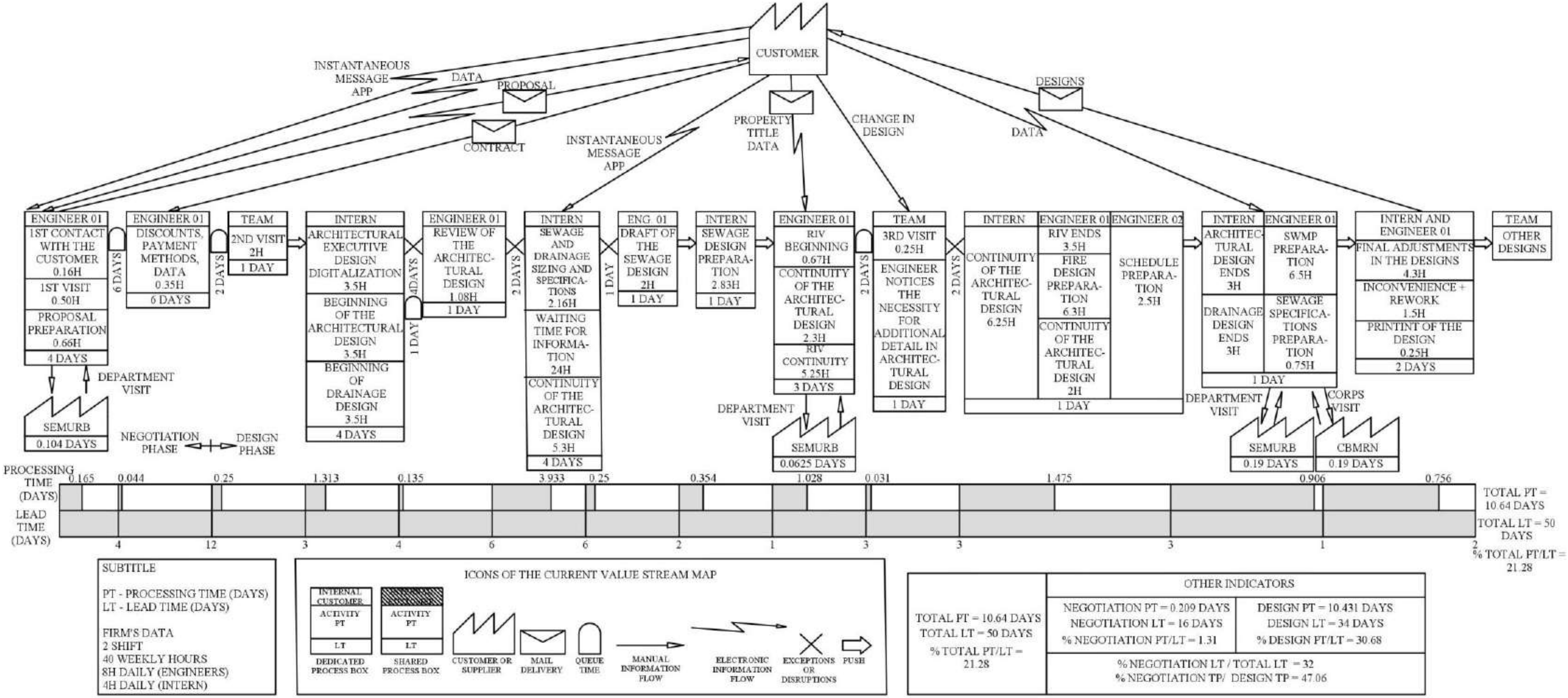

Figure 1. Current State Map.

drainage design, then conclusion and organizes the layout of printing of the architectural design. In parallel, the engineer consults with SEMURB and the CBMRN (Military Firefighter Corps of Rio Grande do Norte State), through the Engineering Technical Service (SERTEN) about the access stair on the fire design of the first floor. With the data which were requested from the customer, it is done the solid waste management plan (SWMP). The engineer requests the sewage memorial already finalized by the intern, but to avoid the waiting for information, elaborates a new sewage memorial.

Together, the engineer and the intern make final adjustments on the designs and plot the boards and reports, but because of the lack of colorful printer cartridge ink, the boards of AED are not printed and because of this they decide to send them to a print shop. Having the printed designs, the engineer delivers to the customer, however noticing some flaws on the printing of the architectural boards, this is corrected and plotted again by the print shop. Lastly, the designs, reports and specifications are delivered in person to the customer.

Summing up the lead time of each activity results in the total lead time of the process. In the study, it was verified a lead time of 50 days, from which only 10.64 days correspond to a processing time. Therefore, the activities do not aggregate value correspond to a total of 78.72% of the process.

The process can also be divided in two sub processes: the negotiation phase and the design phase, after getting the contract signature from the customer. The negotiation phase presents a lead time of 16 days, from which just 1.31% represent the actual time of value aggregation. In the design phase, the lead time corresponds to 34 days. From these days, only 10.431 equals the lead time of each activity. In other words, the only activity which adds value to the process is the design process, but only 30.68% of the cycle time is used for that. It is important to point out that the established deadline by the parties on the contract for execution of the activities was 30 days, surpassing in 4 days what had been previously defined. On the feedback the design-build firm cites modification in the architectural executive design as a motive.

Facing the expressive time of lead time negotiation, this value was compared to the total LT and design LT. As a result, it was obtained 32% and 47% of the time, respectively, indicate the negotiation percentage. This shows the high time consumption with the customer, which could have been done by another professional.

There were identified activities which do not aggregate value to the process: Wait of information from external or internal customers, wait for updated designs and documents

On the system, computer lagging, interruptions due to other customers (conversions of the digital file versions or plotting). And routine tasks of the technical room such as: plotting, folding the site plans, signature collections, stamps, answering the telephones (Lima et al. [2]). It also identified how much cost the wastes indicated in Table 1 and Table 2.

Table 1. The cost of the 3rd technical visitation (unnecessary)

Waste	Cost (€)
Transportation	5.14
Hourly cost of team work (1h25)	30.78

Table 2. The cost of the printings with errors

Waste	Cost (€)
Material	14.80
Transportation	5.14
Engineer’s rework cost (1,5h)	17.44
Engineer’s work hourly cost (1h)	11.63

The total cost of these wastes result in € 84.93 (Adjusted according to the currency exchange rates on January 7th, 2018), the current year.

By the time this research was conducted, the design team had other 7 ongoing designs, shifting the priority of other activities between parallel designs.

4.2 Future state map

Aiming to reduce the waste, the suggested value stream modifications are next, illustrated on the map of Figure 2.

1. **Technician assistant of engineering:** The time wasted by the engineer could be minimized if the first contact with the customer for negotiation goals (such as visits and elaboration of proposals) were through a technician assistant of engineering. Besides, the technician would be responsible by the consults with external institutions, when requested.
2. **Reducing the validity of the proposal:** The reduction of the validity of the proposal from 30 to 10 working days pressures the customer to return to contacting the firm as fast as possible, reducing the answer time from the customer.
3. **Communication optimization:** In the negotiation phase, it is suggested the contact from a phone call and confirmation via email with the with a deadline established in the proposal.
4. **Interactive coordination:** It is proposed the possibility that many subjects are designed simultaneously, providing more interaction among the team, in order to avoid interferences as much as possible, allowing a parallel correction, reducing

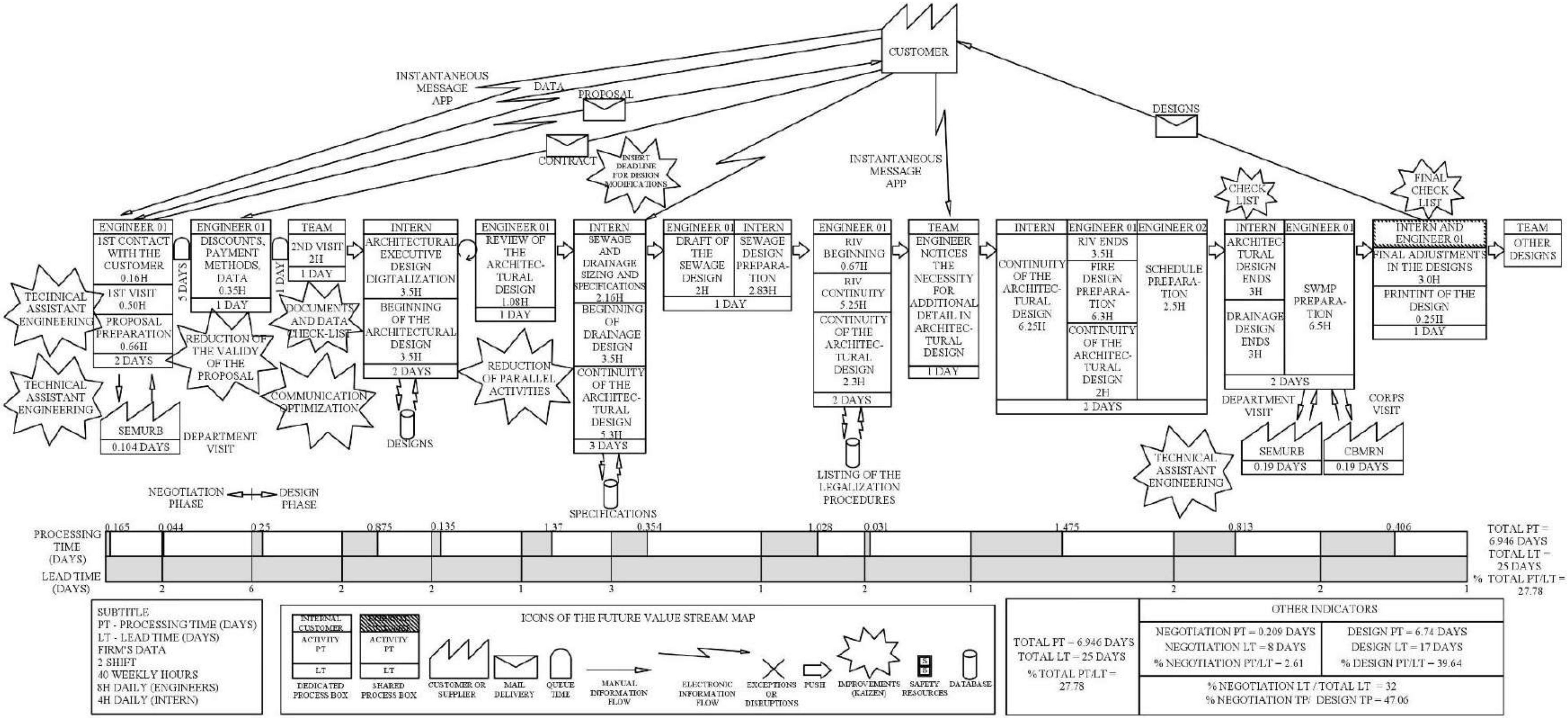

Figure 2. Future State Map.

the time of wait for information and reducing the cycle time of the drawings. It can be adopted through the implementation of auxiliary software, in BIM platform.

5. **Creation of a database (designs, sizing spreadsheets, memorials, legalization procedures and checklists):** The use of a database, with designs and documents templates, speeds up the process of digitalization and helps to reduce the PT. Analogously, it is suggested the creation of pre-programmed sizing spreadsheets, calculation specifications and legalization procedures for the daily situations. It is also proposed the usage of checklists to verify which documents and data will be necessary throughout the design process, as well as a final verification after the project is finished.
6. **Reduction of parallel activities:** It is suggested to prioritize the current design, avoiding this way the interruptions in the elaboration and corresponding documents.
7. **Use of task manager:** The software aids in the analysis of invested time in the performance of the activities. It is possible to create tasks, attribute tasks and count automatically the time effectively used in each activity. This way the team can oversee itself.

As a result of a future VSM, the total lead time of the process is reduced in half, 25 days. The total PT is also reduced, 6.946 days. In other words, the activities which do not aggregate value correspond to 72.22% of the total process time.

The negotiation phase presents a lead time of 8 days, being less than the proposed time of 10 days. In the design phase, the lead time corresponds to 17 days, from which 6.74 represents the time of execution of each activity. Thus, it is reduced the time of waste on activities that do not aggregate value in 8.96%, resulting in 60.36%. This change contributes to deliver the design within the deadline. Regarding the indicators related to the negotiation time percentage, it was kept constant in 32% of the total PT and was elevated to 47.06% the design PT. The time spent per discipline is illustrated in Figure 3, before kaizens.

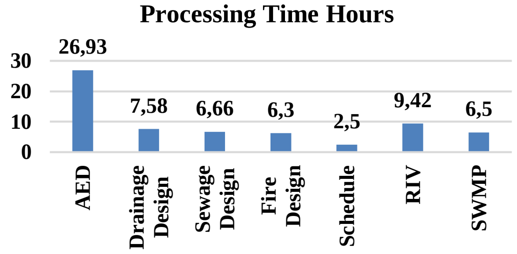

Figure 3. Processing Time Hours per discipline.

4.3 Implementation Plan

Many improvements were suggested to the design-build firm in study, and with the intention of applying the same, a plan of implementation was created. This plan targets the gradual integration of changes to the work procedures, providing the best way of team adaptation to the new techniques.

Under the supervision of the engineer, the insertion of the interactive Coordination through the use of BIM tools is divided in two stages: acquisition of the computational tool and team training. It is estimated a duration of 1 month for the first stage, which involves a cost-benefit research to choose the *software* and purchase. The team training stage lasts 3 months, divided in 1 month for each member of the team. This one was escalated in a way that the activities of the firm were not interrupted.

The *checklists* can be elaborated in 1 month, being 15 days for each list. It is necessary, for this activity, the internal data gathering of the firm about essential information for the elaboration of documents and designs of recurrent typologies at the company, under the shared responsibility between the engineer and the intern. The modifications of the proposal validity and insertion of deadlines in the contract must be done within 10 days by the engineer.

Concerning the creation of a database (designs, memorials and legalization procedures) it is expected 2 months of activity, assigned to an external consultant (a *freelancer* engineer). Regarding the hiring of a technician assistant of engineering it has been established a deadline of 6 months to the engineers. This extended time is due to the priority of the aforementioned improvements, besides the current limitation of physical space and the company’s budget organization.

Among the suggested changes, just the alteration of the validity date and the hiring of a *freelancer* engineer were not deemed valid by the firm’s engineers. Some of the attributions that were suggested to the technician were vetoed, as well as negotiation and elaboration of proposals.

5 Conclusions

The use of the VSM *lean* tool is essential in the identification of value adding and non-value adding activities to the selected processes flow. In this study, the VSM indicated that the lead time in the activities is fairly elevated if compared to the execution time, for the total cycle time as well for the negotiation and design phases. The study points out as reasons the long waiting time for information from the external and internal customers and interruption of the activities to deal with activities related to other customers. To minimize or eliminate the waste is did a plan of implementation of improvements and just part of it is validated by the firm, due to costs originated from these changes.

The biggest obstacle reported by the engineer to count the time spent by the team members on the execution of the design. On the one hand, they not only worked in the design-build firm, but also on the outside, making it harder to establish the actual time spent on the design-build project. On the other hand, there is no linearity in the activities due to other needs: technical visits, consultation with public institutions, possible future clients and reception of phone calls regarding the projects of the company (clients and others), shifting the focus of the ongoing activities. Another important reported challenge is to make the team adopt the changes made, despite the results and observations from this study. The fact that the team is neither Lean nor expert at this philosophy imposes difficulties to the adoption of new techniques and mainly the change of attitude in the organization. The engineer notices not only the need to show the losses and offer solutions, but also to transform the culture and organizational thinking of the company; the training of the current and the new members about the Lean approach also stands out.

At first the firm was reluctant to recognize that the design lead time surpassed the established deadline of 30 days. Thus, the results of the VSMs were eye opening so the team could accept that there was room for improvement in their production process. As future perspectives, the engineers decided to hire an intern of engineering and initiate a software course to BIM architecture concept. Due to the fact of not being a lean firm, the suggested changes have some barriers at first, but ones that decrease as long as the team lives their benefits (Leite and Neto [12]).

Overall, the Lean Design approach provides gains of quality to the design process. With proven improvements in the reduction of the cycle time, waste and rework, besides the delivery of more value to the customer in less time and with less cost if compared to the current design techniques.

As a limitation of the paper, there is not a mapping of activities done during the interruptions of the studied flow and other current processes in the firm in the same period of this research. For future studies, the paper suggests executing the same method of research at other bigger firms, with the performance of similar activities and mapping the current state, developing the future VSM and comparing the results.

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Robotic Inspection Tests of Tunnel Lining Concrete with Crack Light-section Device on Variable Guide Frame

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Abstract –

There are approximately 10,000 road tunnels in Japan. Human visual inspections of the tunnels must be conducted once every five years. However, presently, the number of inspection engineers is insufficient and the cost incurred for the inspection is significantly high. In conventional crack inspection methods based on an image processing, inspection engineers process many images off site. However, these methods require a lot of effort to identify the cracks and dirt manually.

We have studied a brand-new robotic inspection method to measure the crack positions automatically by using high-resolution texture/depth images that are acquired based on the light-section method. In this report, we present the study outline and introduce the devices developed. Furthermore, we present the inspection results of tunnel lining concretes by using our method in contrast with both an actual road tunnel made by the conventional piling method and a simulated actual-size tunnel we made by the NATM method.

Keywords –

Tunnel inspection; Crack detection; Depth-image

1 Introduction

The Japanese government decided to periodically inspection the road tunnel once every five years since 2014. In principle, the inspection should be performed by near visual inspection to the tunnel overall length. The results of the inspection and diagnosis were recorded and saved, and a decision was made to classify the diagnostic results of soundness on a unified basis. Against such a background, issues such as a shortage of engineers and lack of budget to inspect road tunnels are becoming apparent [1].

Close visual inspection of a road tunnel is conducted by inspection experts, who observes the surface of the lining concrete in the vicinity using an aerial work platform or the like. The experts measured and recorded the degree of the changes in the cracks, floats, steps, efflorescence, honeycombs, water leakage and the like. The representative method to support the experts is based on an image processing [2]. Often, the method requires off-line image process for a large amount of image data of the concrete lining surface. Because the common method of the image processing recognizes dark pixels with cord-like arrange as the cracks, a dirt or the like can be erroneously detected as a crack. Various methods have been made to prevent these false detections, but some challenges still remain for completely automatic crack detection.

In order to solve these problems, the automatic crack inspection device based on the light-section method have proposed and developed to support close visual inspection [3]. The device is the one of the component of our robot system shown in Figure 1, called “Variable guide frame vehicle” developed for traffic-free tunnel inspection [4]. In this paper, we describe an outline of the device, and the results of the performance validation experiments of the device in contrast with both an actual road tunnel made by the conventional piling method and a simulated actual-size tunnel we made by the NATM method.

2 Mobile Light-section Device Developed

The authors have made it possible to distinguish between cracks and dirt by obtaining depth images as a three-dimensional shape of the concrete surface. In various methods to acquire the three-dimensional shape, a light-section method was adopted considering both the high resolution with 0.1 millimeter/pixel order and the portability for wide area inspection over kilometer order.

The light-section method acquires a three-dimensional shape by causing the slit-light and the area camera to move relative to an object for scanning, while maintaining a certain angle. It is based on the property that the slit-light deforms accordingly. By using the slit-light of a white LED, a color image (visible image) whose coordinates are coincident with the three-dimensional information can be obtained.

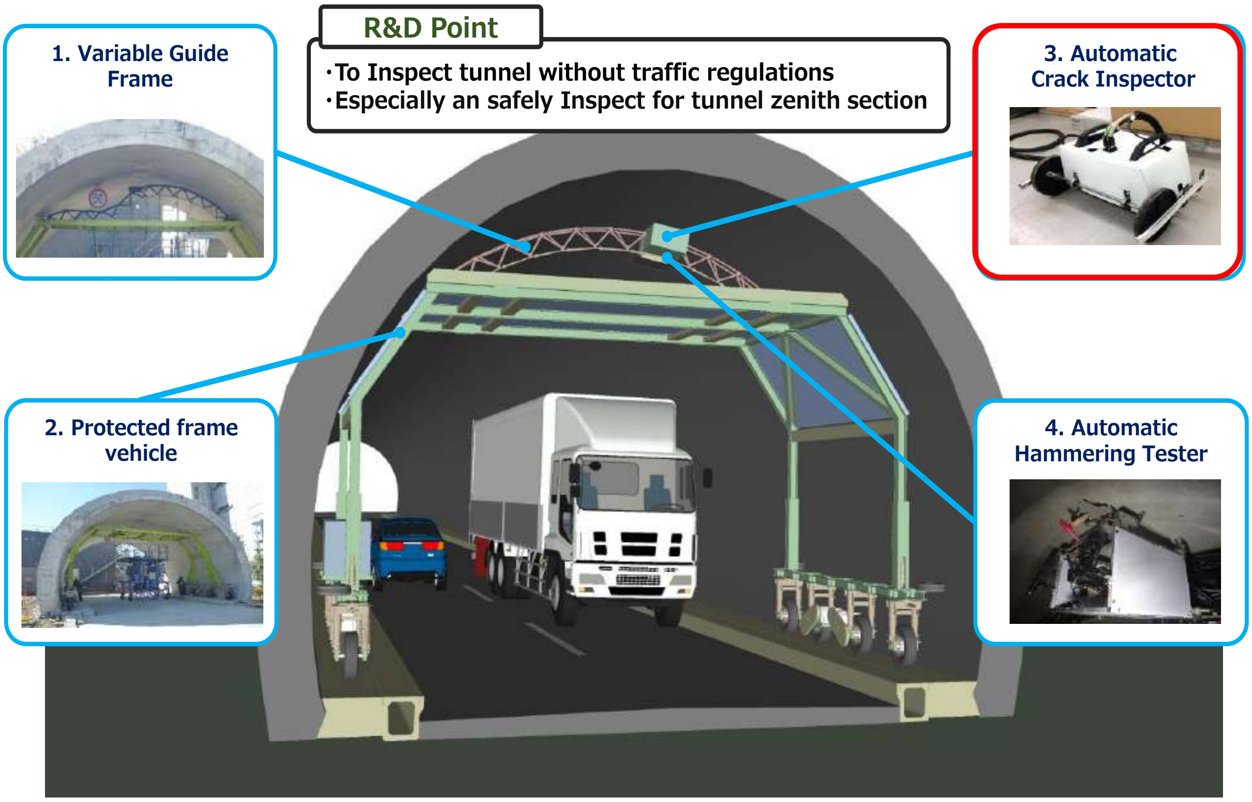

Fig. 3 Concept of our method of tunnel inspection (mobile light-section device is in red square at upper right)

The authors made the device for an automatic concrete crack inspection that can implement the mobile light-section method by combining the wheel and encoder, and robotic scanning of the lining concrete surface (Figure 2). Our image processing software for the device was configured as shown in Figure 3. An image is photographed according to the scanning distance, and the light-section processing is performed when the images are accumulated. Based on the generated depth image and color image, the cracks are automatically detected (see [3] for more details). The detection results are integrated on a stitched image with about 10 square meters, and are used for the measurement of the crack length and the investigation of the closed cracks that has a risk of chip out to a road. Our system could be performed these processes onsite.

Figure 4 shows an example of a color image and a depth image obtained by scanning the same object. In the depth image, it is possible to distinguish between real cracks and simulated cracks drawn with felt pen (black, brown and green) and chalk (white) near the actual cracks. In order to verify the performance of the automatic inspection of cracks by this device, for each of the 10 concrete test samples, the detection rate (the detected crack length dividing by the actual crack length) and the false detection rate (the number of erroneously detected pixels divided by the total number of detected

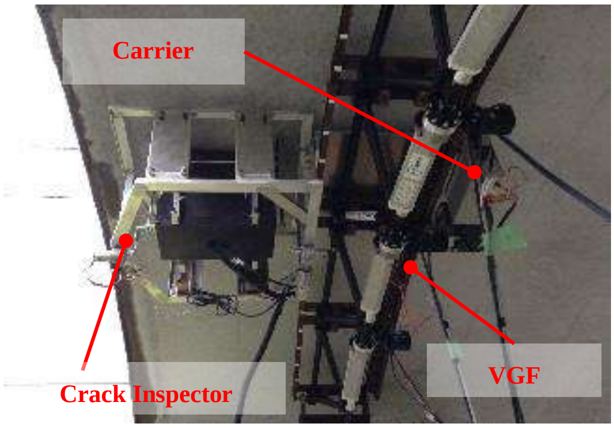

Figure 1. Our light-section device prototype

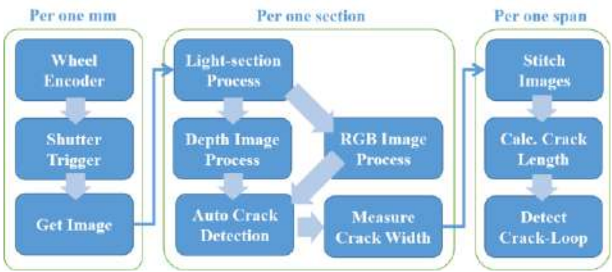

Figure 2. Crack inspection flow by our device

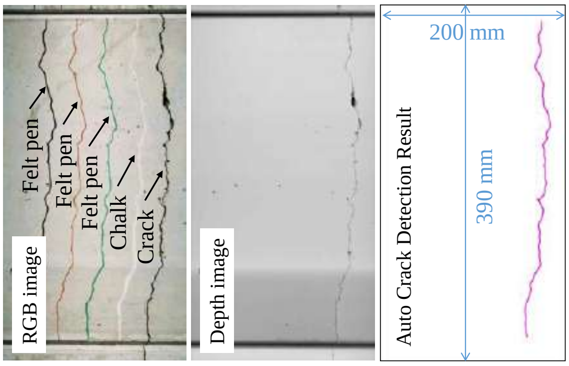

Figure 4. Automatic crack detection result example by using a concrete test sample with simulated dirt lines and a chalk line

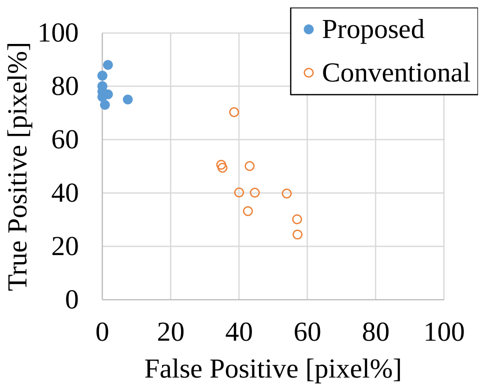

Figure 5. Automatic Crack detection accuracy by using 10 concrete test samples

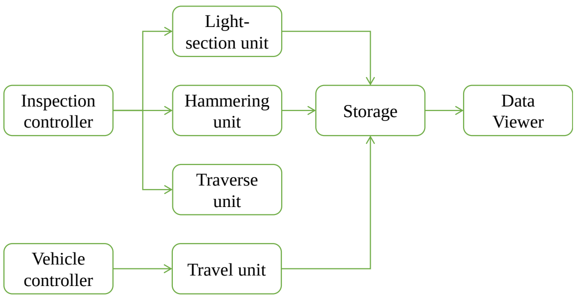

Figure 6. Inspection process by VGF vehicle

pixels) was evaluated and plotted as shown in Figure 5. The cracks were detected by using only the depth image. On the other hand, for comparison, the detection rate by a commercial software and the color images was also shown in the figure. The crack detection rate by our method was greater than 73% and the false detection rate was less than 8%, both of which were confirmed to be superior to those of the conventional method. The main cause of false detection was surface bubbles near the cracks. However, the misdetection of felt pen or chalk was 0%.

Figure 6 shows an inspection process for our system. The variable guide frame vehicle has 4 features. The 1st is a variable guide frame. It enables avoidance of speed signs and luminance and so on. The 2nd is a protected frame vehicle. It enables traffic-free inspection and ensures safety of road users. He 3rd is the mobile light-section device. The 4th is the robotic hammering device (see [5] for the details). These features enables robotic tunnel inspection method we have proposed.

3 Test on NATM simulated tunnel

The depth image and color image were obtained by scanning the lining concrete surface using the light-section method on the actual-size simulated tunnel made by NATM method. The scan range was ~5.4 m in the circumferential direction of the arch part, as shown in Figure 9, and ~10.3 m in the axial direction. Considering the overlapping portion in the short axis direction, the effective scan width was 400 mm. 26 strips of image were taken and stitched as Figure 7 and 8. A white part on these figures is a place of speed sign.

Based on the obtained texture/depth images, crack detection software is used to automatically detect the cracked parts from the images of each scan; the width and length of the crack are obtained by counting the detected pixels semi-automatically as shown in Figure 9. This was done by an operator specifying two points on the screen and automatically counting the pixels in a straight line connecting the two points. The width and length of the cracks thus obtained were compared with those obtained using the conventional method (close visual observation) by a skilled checker.

The measurement results of the crack length are shown in Figure 9. The upper numbers on the side of the cracks are crack width. The lower ones are crack length ratio against with the close visual inspection results obtained by skilled workers as shown in Figure 10. When comparing the measured value by our method with the value by skilled workers, it was found that the crack length shorter than the values obtained by a skilled worker, however, bold cracks (width >= 0.5) in results are almost same.

4 Test on tunnel made by piling method

The depth image and texture (color) image were also obtained on an actual road tunnel made by conventional piling method. The scan range was ~3.4 m in the circumferential direction of the arch part, and ~3.7 m in the axial direction. The effective scan width was 400 mm. 10 strips of image were taken and stitched as Figure 11 and 12. A white part on these figures is a place of speed sign.

Based on the obtained texture/depth images, crack detection is used to automatically. The length of the

Figure 7. Panoramic texture image of a tunnel lining concrete made by NATM method

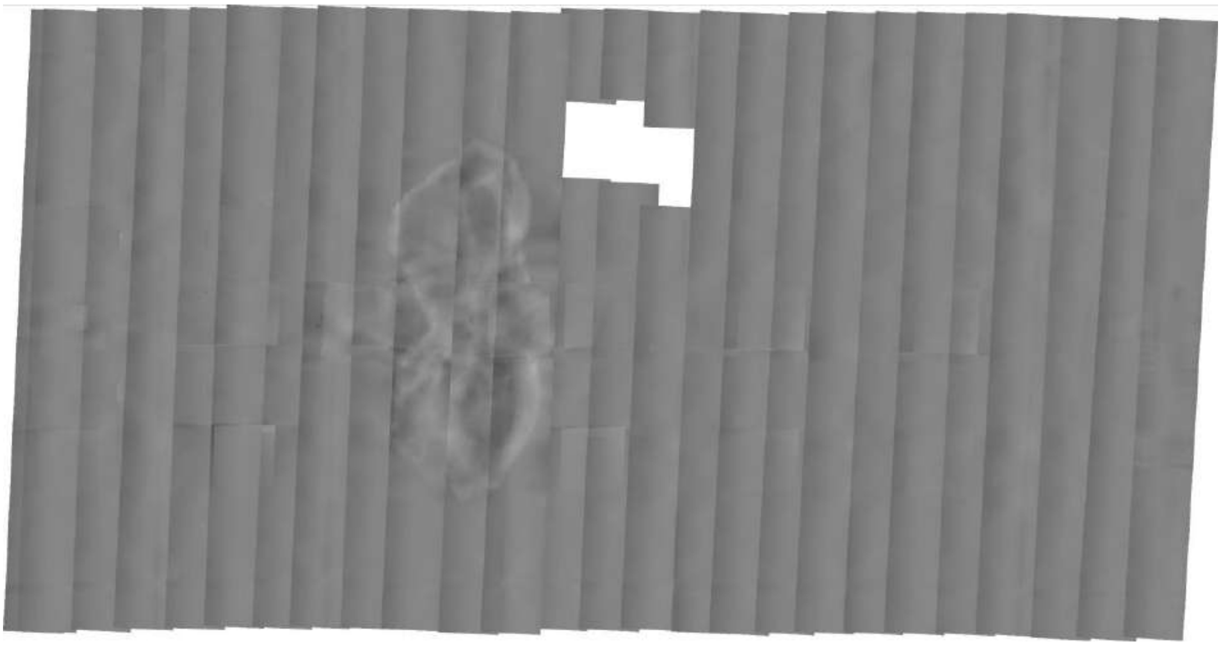

Figure 8. Panoramic depth image of a tunnel lining concrete made by NATM method

crack are obtained by the same way as shown in Figure 12. The values on the figure means the same parameters of the Figure 9.

The crack detection rates of the above two tunnels and CMI tunnel results (reported in [3]) are shown in Figure 13. The rate was over 90% when excluding the cracks with a width of less than 0.5 mm and with an efflorescence. The false-negative of the detection especially occurred for the crack with an efflorescence. The most of the false-positive occurred at the bug-holes in concrete near the cracks or the construction joints. Currently, we are investigating ways to distinguish the cracks and the bug-holes more clearly using a cord-like structure of the cracks and a circularity of the bug-holes.

5 Conclusions

We developed an automatic crack detection method by using both depth and texture images. In order to obtain these images in about 0.1 mm/pix resolution

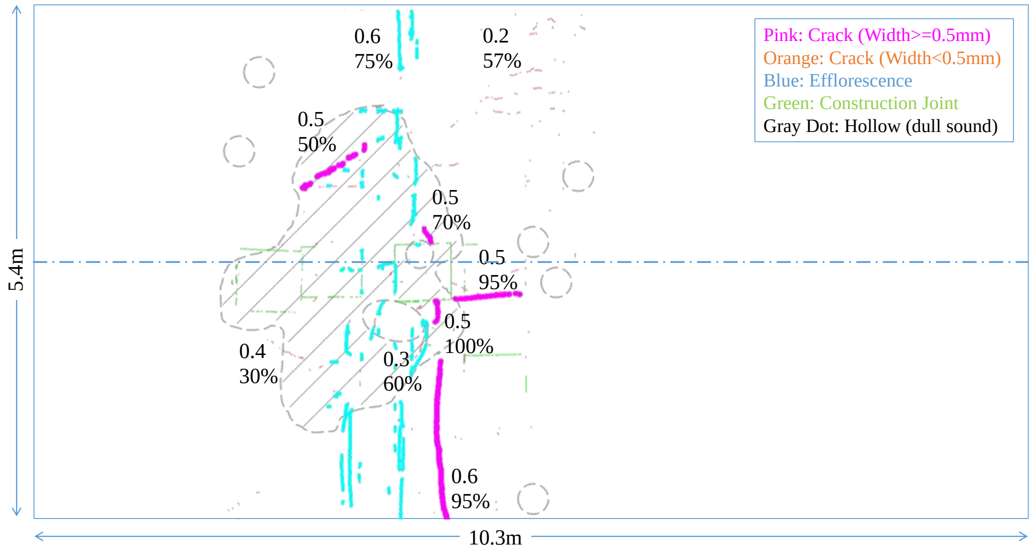

Figure 9. Inspection result by our method with crack width and crack detection rate

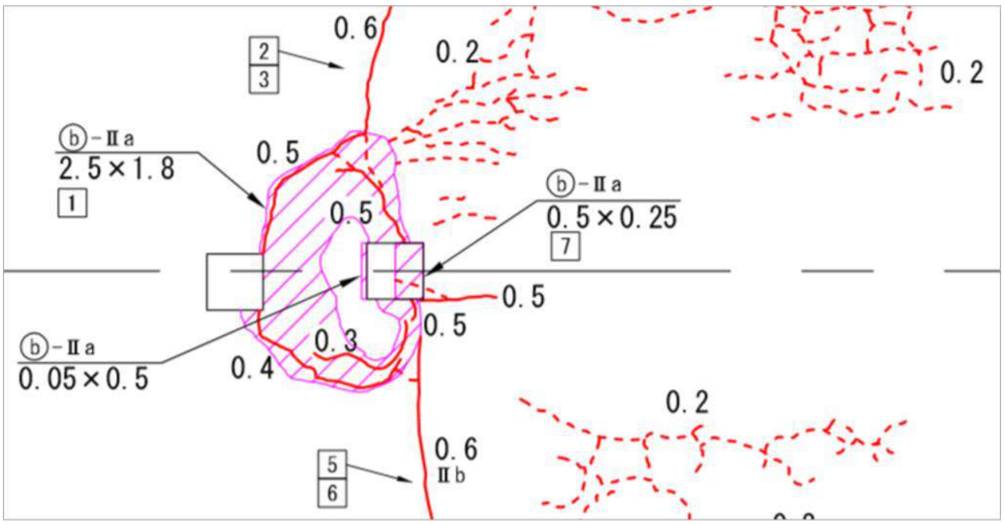

Figure 10. Inspection result by conventional method by inspection experts

quickly, we developed crack inspection device based on the light-section method. We inspect two type of tunnel ceilings by our device equipped with the variable guide frame vehicle. These results showed that the proposed technique has a crack detection performance equivalent to that of humans.

Currently, the authors are brushing-up the tunnel inspection method using this device for improving the detection accuracy of crack detection software.

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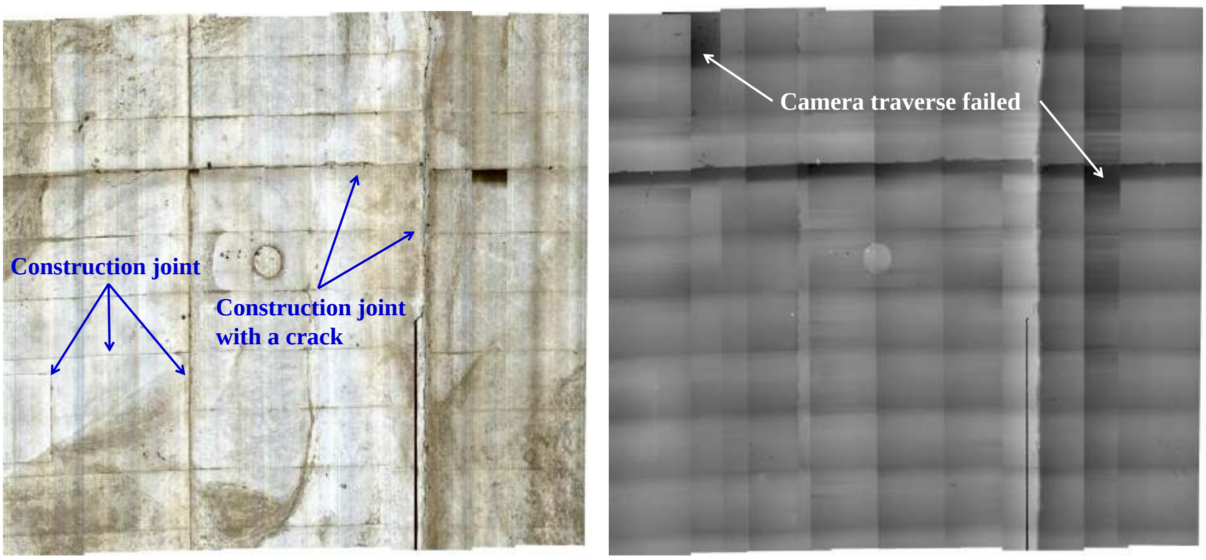

Figure 11. Panoramic image of a tunnel made by conventional piling method (L: texture, R: depth)

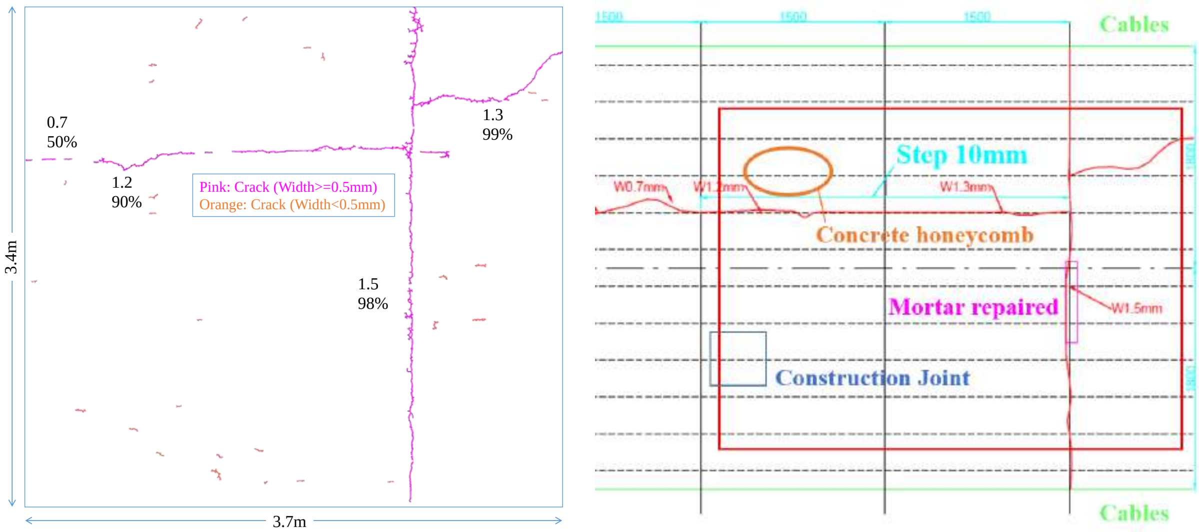

Figure 12. Crack inspection result with crack width and detection rate (L: by our method, R: by experts)

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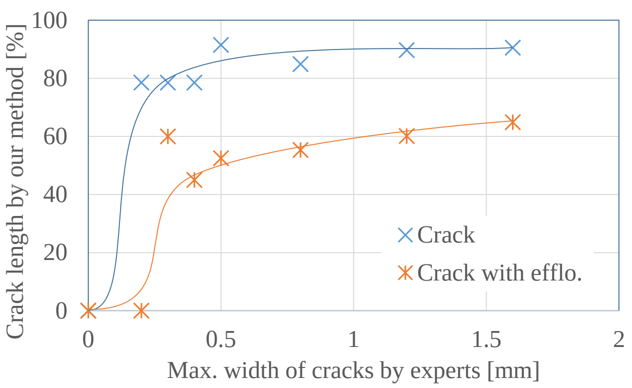

Figure 13. Crack length against the max width

Generative Architectural Design and Build Strategies based on the Mapping of Human Behaviour

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Abstract –

The introduction of robotics in construction offers the possibility of implementing design processes that incorporate unforeseen levels of complexity. Not only does this allow for the construction of high degrees of formal differentiation, but for the conception of projects with a high-resolution integration of performative qualities. These performance aspects can include environmental and economical properties but also social and cultural mechanisms, which can be monitored through the tracing of human activities within architectural and urban spaces.

This research presented here focuses on technologies and work flows that enable on-site data collection and construction implementation, in separated design and build phases or in an integrated process with continuous feedback. It discusses a series of small projects that explore new scenarios for the creation of architectural structures, experimenting with mobile and low-cost fabrication devices, connected to generative design algorithms driven by sensory technologies. These projects show that instead of working directly with the geometry of the final outcome, architects can begin to script individual and unique processes for generating structures, using rule-sets that capture the intelligence and underlying logic of materiality, organisation and spatial performance.

We advocate a new paradigm where the architect is a 'process designer', aiming to generate emergent outcomes where the inherent complexity of the project is generated towards specific performance criteria related to human activities and inhabitation.

Keywords –

On-site sensing and construction technologies; Human Activities Monitoring; Computational design; Emergent design; Custom robotic devices; Digital construction;

1 Introduction

As robotic fabrication and assembly devices are being introduced to construction sites, it becomes possible to re-think the entire process of how architectural projects are materialised. Construction processes no longer rely on inefficient communication protocols towards manual workers and manual tools but can directly be connected to digital 3D models created by the design team. This could increase quality, reduce errors and cost, and potentially reduce construction time. It could also be used to deliver projects of increased complexity, due to the system's ability to perform large amounts of operations at high precision. As robotic devices are becoming mobile and able to work collaboratively, this paradigm can be applied to the scale of the building site instead of being limited to the working envelope of a single device.

The direct communication between design software and construction technologies signifies a fundamental shift in the possibilities of design, as projects can potentially be conceived and built with a much higher resolution of material properties and with a high degree of internal differentiation rather than repetition. Instead of applying robotic tools to the production of sculptural or decorative complex geometries, there is the much more radical opportunity that presents itself: the incorporation and integration of several layers of functional complexity.

The architectural design, and therefore the design process as well, could start to incorporate complex properties of a building's performance within its environment, generated through detailed simulations and real-world data gathered through sensors, measurement and mapping processes. Performance could be understood within the context of physical environmental and climatic conditions such as sunlight, wind, temperature and noise and this is indeed one of the great potentials of digital design processes, to deliver increased building quality, efficiency and improved spaces designed around human comfort. But performance analysis can also be applied to how buildings perform within their socio-political context, from an economical perspective or as an environment for human circulation and inhabitation. Within the practice of planning office layouts for instance, it is already commonplace to consider the interplay between the comfort, psychology and productivity of employees and the arrangement of furniture can directly influence the economic success of a company. The layout of shelves and the product placement in supermarkets is designed to increase sales of the most profitable items, taking into account the visual navigation and behavioural psychology of the customers. Through increasingly precise monitoring systems that build up large data-sets of statistical analysis of human activities, the design processes that optimise spatial layouts are increasingly being automated, informed by semi-intelligent processes such as machine learning.

While commercial applications might be the driving force behind the rapid development of data-driven design, there is an opportunity and arguable an obligation of academics and practitioners within the architectural discourse to critically examine the possible positive and negative consequences of these new processes. The monitoring of people's behaviour through CCTV, online communication and mobile devices might have a potential dystopian dimension, but if done in an appropriate and acceptable manner, this could offer a wealth of knowledge to architectural and urban design processes. Instead of focusing on the commodification of user data for profit driven operations, architects and planners could calibrate their designs towards social interaction, human comfort and health. Where architectural and urban spaces are required to house social activities and community formation, generative design processes can be used to monitor human behaviour and define the properties and organisation of spaces to stimulate this in the most effective way. Data-driven processes could be used in the design stage of a project, as well as for the continuous management or adaptation of the project throughout its life.

2 Precedents: Mapping human behaviour

One example of research into the social dynamics of public spaces is the work by sociologist William H. Whyte, who's publications include The Social Life of Small Urban Spaces (Whyte 1980). His aim was to understand why certain plazas remain empty and unused, while others were well loved and heavily used as leisure spaces and social condensors within the city. He used manual techniques of measuring, counting, mapping and other forms of direct observation to understand the relationships between specific physical characteristics of the space, and the human activities that would occur. His work resulted in design guidelines on principles such as visibility, accessibility, seating, greenery and environmental conditions such as sun and wind, many of which were consequently applied by municipal governments in different cities in the United States. Whyte served as a mentor to Jane Jacobs, who wrote The Death and Life of Great American Cities (Jacobs 1961), which famously argued for the conservation of organically grown neighbourhood qualities, recognising the value of the rich mix of complementary programs that emerge around walkable neighbourhoods.

A continuation of research into the underlying principles of human decision making within urban environments can be found amongst the highly varied initiatives that can be considered part of the 'smart city' movement, that has been referenced by academic and professionals in various locations in recent time. The idea of a ‘Smart City’ was first introduced in the 1990’s but has recently attracted more high-profile projects and attention, resulting in several projects and policies that are being executed around the world today. The goal of a Smart City is to use technology to create economic, social and environmental improvements. This challenge is not only related to design and planning issues but is also aimed at the economic and political frameworks that guide urban development. ‘Smart City’ projects aim to understand the urban ecologies - the invisible networks of human activities that drive the materialisation of the city.

The sociologist Jennifer Gabrys has written about the "new wave of smart-city projects that deploy sensor-based ubiquitous computing across urban infrastructures and mobile devices" (Gabrys 2014). She notes the potential positive ambitions of these project to improve sustainability but also warns of the potential dangers of monitoring and managing data on citizens. Referencing the French philosopher Michel Foucault (1926 – 1984) who has written extensively about mechanisms of power and control exercised by the state, and how its manifestations in the structures of buildings and the city can be understood as a 'bio-political machine'. Gabrys argues that smart-city design processes should focus on the performance of urban environments as demonstrated through the behaviour of people within them rather than collecting data on citizens and populations. The sensitive subject of monitoring human activity should be approached with the necessary safeguards to ensure privacy and data protection of individuals and allow for open-endedness towards behavioural patterns and demographics.

3 Methodology: Generative Design

This paper will present a series of small projects undertaken in the context of various academic research and teaching programs at the Architectural Association in London, organised under a larger research agenda into generative design and build processes based on the mapping of human activities.

The practice of generative design is well established within multiple design and engineering disciplines and can be defined as a computational design process aimed at creating the best possible solution towards specific performance criteria. It can be considered a sub-category of the larger field of parametric design, which is a terminology that merely indicates that certain parameters or relational modelling techniques are considered during a design process. The practice of generative design assumes that there are clear goals for the design solution which makes it particularly suited to be conceived as data-driven design, evaluating potential design options against detailed contextual information.

The potential role of generative design processes has been identified early on by Mitchell and McCullough (1991), who contemplated the implications of computational processes being able to address a complexity of parameters and interactions, much greater than could be handled by human cognitive processes alone. They emphasized however that instead of promoting 'automated design procedures', there remains a central role of the designer's intellectual capacity, using critical judgement towards the employment of algorithms, the input of data parameters and the definition of the evaluation criteria. Generative design in this context is employed as operating on the underlying relationships rather than formal characteristics of the built environment. As Lima and Kós write, "this form of algorithmic or parametric modelling transcends the understanding of the computational paradigm as a mere promoter of complex forms, and contributes to processes capable of forming models that contemplate several parameters involved in the functional, environmental and of the cities and the buildings they contain" (Lima and Kós 2014).

Within our research, we interpret the practice of generative design as a methodology that has a clear logic and consistent step-by-step translation of design information over time. This allows for the design process to ‘generate’ traceable solutions which can be evaluated against the performance criteria that informed the design process in the first place. This approach to the use of rule-sets allows us to generate site-specific outcomes within the limitations of a particular context, allowing projects to take full advantage of and contribute to environmental, programmatic and connectivity characteristics of the surroundings.

3.1 Project 1: 'Point-Cloud'

The first project that was undertaken to test rule-based design methods and in-situ digital fabrication and construction technologies, was a small experimental

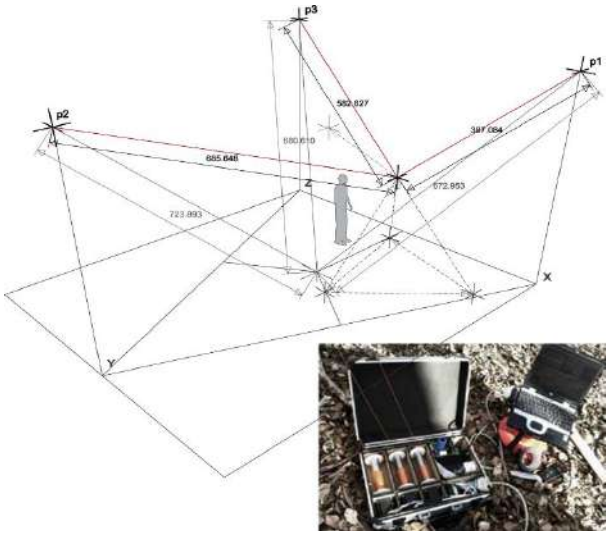

Figure 1. CNC cable robot, used as point indication device

structure situated within the forest of the Dorset campus of the Architectural Association.

The project used a custom-built cable robot device, designed to act as a 3D location point indication device on site. It functioned through a computer numerically control (CNC) protocol to manipulate the length of three wires on spindles attached to stepper motors. The wires were installed in a site by attaching three pulleys to existing trees or buildings around an empty area. This system is adaptable and scalable: a wide range of sites can be turned into a CNC working envelope. The CNC machine was connected to a laptop with the widely used G-Code control software Mach 3, allowing to move the wire pointer to a specific coordinate in 3D space similar to how the cutting head is moved around on a three axis CNC milling machine (Figure 1).

The project explored a digital work-flow which translated 3D scanned data of people movements and densities towards a corresponding cellular structure to be built on site. The movement data was collected by using a KINECT 3D camera to gather point cloud data of human bodies within the site over a time period of 10 minutes. A semi-automated design work flow was set up to handle the translation of the point cloud information from the 3D scans to the specific geometry to be built, using cell-packing and tessellation algorithms (Figure 2). The design method was calibrated to translate higher intensities of movement into increased densities within the structure, visualising previously invisible qualities on site and guiding subsequent visitor movements along specific paths.

The construction system was deliberately designed as part of a human-machine collaboration, envisioning a scenario in which the device is only used for its most important task: the translation of detailed construction

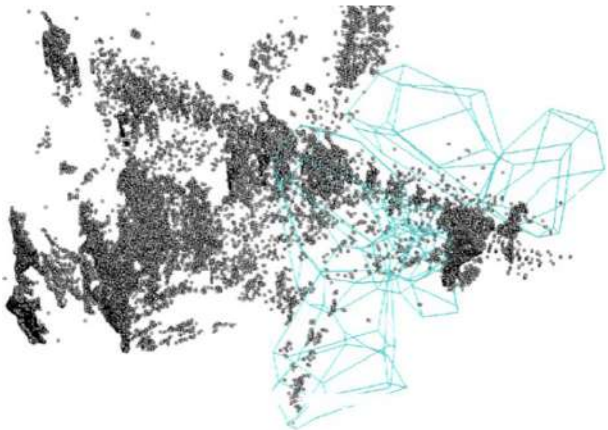

Figure 2. 3D scans of people movements through the site, translated into a triangulated structure through a generative design process

information from a digital model containing three-dimensional point locations onto a 1:1 building site. The human collaborators did tasks which they can do better than machines, such as the manual handling and connecting of building elements (Figures 3 and 4).

Figure 3 and 4. Human collaborators installing timber elements guided by the cable robot pointer, resulting in a variable density triangulated structure

The 'Point-Cloud' project demonstrated the potential of a generative design process based on site-specific data, however the design properties of the physical structure did not attempt to change or contribute additional functionalities related to the movement within the site. Successive projects have been set up to incorporate this ambition, not just responding passively to the data gathered on site but aiming to introduce improvements to the conditions found.

3.2 Project 2: 'Emergent Constructions'

The second project within our line of research consisted of a medium sized architectural pavilion designed to offer a temporary cluster of spaces and seating elements to visitors of a large shopping mall in Kuwait. Using digital cameras to record the movement of people through a central atrium space, the prevailing pattern of visitor flows was mapped in relation to the entrances and attraction points within the mall. Data regarding user density and sight lines between the pavilion location and the surrounding amenities was translated into the design of a pavilion that would create an intervention on the existing site. This intervention would generate activity, intervene with general paths of circulation, and create a louvre effect between the internal spaces and the context to offer varying degrees of privacy for the people inside (Figure 5).

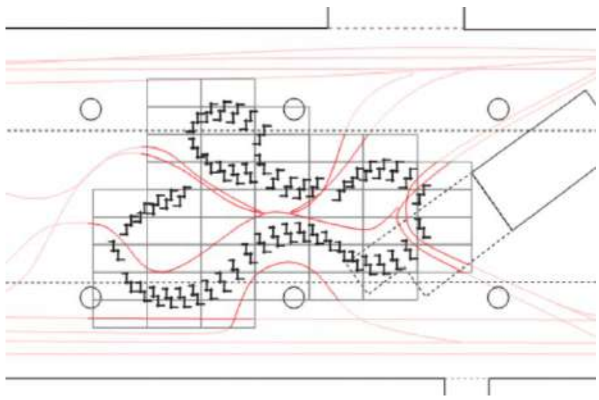

Figure 5. Pavilion space constructed through louvre walls that mediate privacy

The qualities of space that result cover a range of social interactivity scenarios including private space for a single occupant, and larger group spaces for dynamic social interaction and play. The programmatic possibilities were further enhanced through the incorporation of furniture elements such as benches and stools. The result of the generative design and construction exercise was a pavilion that manifest itself as a field condition, distributing a large amount of self-similar elements with varying properties and relationships within the circulation space of the mall to intensify and enrich its spatial and programmatic possibilities (Figure 6).

The pavilion as a field of elements with different heights, density and functions created a varied architectural landscape that has specific intentions for

Figure 6. Pavilion spaces designed to separate visitors from the surroundings and stimulate social interaction

stimulating social interaction built into it. The multiple possibilities of use and interpretation however allowed the users to create their own social patterns and interactions, exploring unforeseen modes of engagement with the design at the many in-between spaces of the pavilion. The role of the architecture was conceived as creating a stimulating environment with a strategic purpose and agenda, without being over-prescriptive or inflexible but instead creating an open-ended system for appropriation by the users of the mall.

The principle of feedback between architecture and users is something that is explored further in the subsequent projects. This research follows on from an important precedent titled "Seek", exhibited in Jewish Museum in New York in 1970 by Nicholas Negroponte.

This installation consisted of a glass display case filled with small cubes that could be rearranged by a robotic arm connected to a camera and computer system. The display was inhabited by gerbils, who continuously moved the cubes around. The robotic arm was used to help organise the arrangement of the cubes, not according to a fixed blueprint but based on rules that tried to interpret the preferences of the gerbils. Throughout this process over time, the aim was to let an ideal inhabitable landscape design emerge out of the negotiation between the inhabitants and their environment.

3.3 Project 3: 'Emergent Field'

The third project titled 'Emergent Field' explored a similar generative, rule-based design strategy that monitored people movement through a particular forest site and materialised this as a field of timber sticks placed vertically within the terrain. This material system was chosen for its ease of construction and the compatibility of the geometries with the CNC controlled device that was going to be used, which was the same cable robot device as introduced in project 1, described previously. The vertical nature of the sticks would allow the wires of the cable robot to be moved in between the elements, if the movements of the pointer were choreographed to drop down vertically each time it would indicate a new location point. This characteristic would enable the system to build additional pieces inside areas that had already been populated with sticks.

The project explored a process where the final formation was not known at the beginning of the construction process but was allowed to emerge throughout a series of iterations consisting of movement tracking, generative design translation and construction. A digital camera facing vertically downwards towards the build area was used to take snapshots over a period of time of people locations. A simple piece of software was used to process the images, selecting areas of red colour as all people in the experiment were asked to wear red head coverings. The recorded site occupation density patterns were automatically translated into geometrical patterns for the timber stick formations using a generative design process based on simple rules (Figure 7). The movements were recorded during breaks in between the building activities, when people were asked to freely pass through, explore or inhabit the forest site.

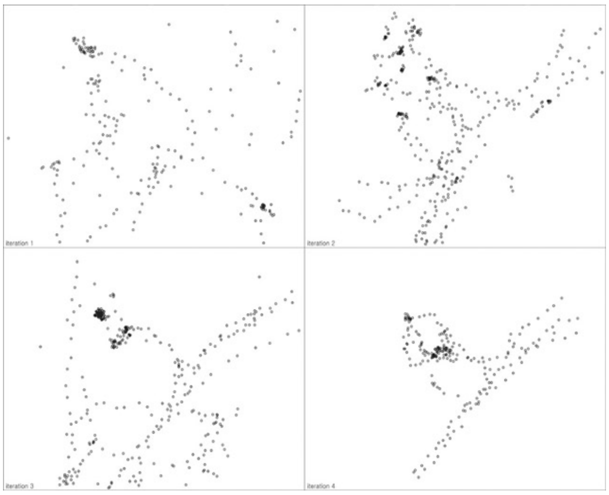

Figure 7. Density maps generated by web-cam monitoring of people, showing the iterative refinement of pathways and hangout spaces

Each iteration resulted in a construction pattern that added additional density in areas which the people hadn't occupied, gradually articulating the edges around movement pathways and inhabitation spaces with rows of vertical sticks. The initial layers of elements within the site were placed with a generous spacing, in order to allow users to move in between the sticks that were

Figure 8. Final installation of the field of elements on site, using a web-cam suspended from the trees and a cable robot pointer device

placed, still suggesting adjustments to the patterns that was gradually emerging. The gradual refinement and articulation of circulation and inhabitation areas occurred within both the digital design model and the physical space, thus allowing the final design to informed through the active negotiation between material and users around the real experience of the installation in the site (Figure 8).

The outcomes of the project might seem abstract and show a significant reduction in the amount of functionality compared to the previous project, yet the iterative design and build process signifies a radical improvement in the process of design conception and data management. Instead of 'friezing' a data-set containing site information, the relevant parameters are continued to be monitored throughout the construction process, allowing to building design to keep adjusting to new information from the site caused by the intervention being placed. The feedback loop between a structure on site and the resulting user activities around it, allows for a design process to continuously monitor the performance of its output and learn how to make improvements within it.

3.4 Project 4: 'Public Space Furniture'

The fourth project continued to build on to a series of experiments inspired by Negroponte's 'Architecture Machine'. It was executed with help of several students and used the terrace of the Architectural Association as a testing ground. A web-cam pointing towards the space was used to record people inhabiting the terrace, documenting their position, duration of stay and distance to others (Figure 9). A set of computational rules was then applied on to these maps, instructing the human assistants in the project to place furniture elements around the site. Specific rules and policies were explored to award or discourage certain behaviours, for instance place furniture in positions that would encourage social interaction between people or instead create separations in between different people. The experiments produced emergent outcomes where an architectural structure would grow over time without predetermined design. Users interacted with the structure through sitting, leaning, placing coffee cups, etc. and generally staying longer and engaging in different activities than they would have normally done within this site.

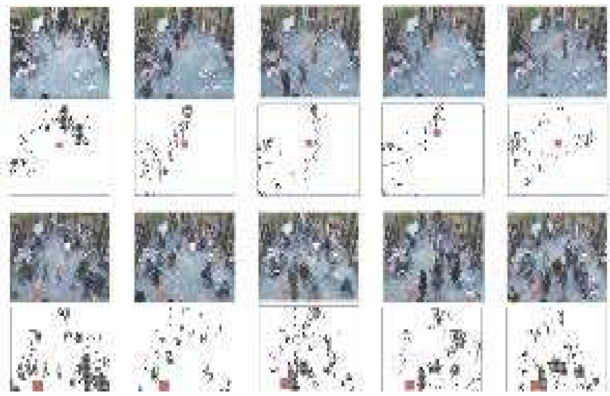

Figure 9. Snapshots of people monitoring as seen through the web cam and as analysed by blob-tracking algorithms

An initial furniture system was implemented using plastic crates, which led to increased social interaction within the site and engagement of the visitors with the experiment. In the second phase, a custom designed CNC fabricated furniture system was deployed that allowed for cantilevering elements and incorporated open and closed panels to be able to block sight lines and create privacy (Figure 10).

Figure 10. Sequence of iterative furniture placements and usage based on people monitoring and specific response policies

The experiments conducted as part of this project added yet another level of complexity to the body of research, testing specific reactionary social policies as part of an iterative scan and build process that incorporates feedback loops. The high amount of variables in the experiments makes it difficult to evaluate with precision which rule-sets or furniture configurations are more effective than others, and the project was mainly intended as a proof of concept that this type of process could be built.

3.5 Project 5: 'Data-Space'

The fifth and most recent project in the series is by no means a final development as it was intended to offer even a higher degree of speculation and open up additional avenues of contemplation about continuous monitoring and feedback systems embedded within the built environment. Titled 'Data-Space', it was developed by the author in collaboration with faculty and students specialised in interaction design from the ArtEZ University of the Arts in Arnhem, The Netherlands, as well as with collaborators from within the Architectural Association. The project explored the use of a field of nodes that each incorporate a sensor and LED lighting, allowing monitoring and communication with people within the site in a distributed and scalable way, as opposed to the previous projects which were limited by the use of a digital camera. The nodes were arranged in a gridded field and suspended above the ground, creating a virtual ceiling embedded with infra-red sensors to create a real-time data stream of user locations. The data was collected via wireless communication in a central computer, that was able to determine the speed, duration of stay and distance in between people. A series of evaluation algorithms were paired with rules for analysis and implementation of certain feedback action, in the form of animated lighting patterns that were displayed around the visitor location(s) (Figure 11).

The additional complexity in this project lies in its capacity to collect data over longer periods of time and communicate not just passive reactions that directly translate sensor input, but instead send out intelligent signals. Protocols that were tested in the project were for instance to entice users to move along light pathways or to reward desirable behaviours such as closeness between two people. When the site was occupied by too many people at once, the system would display 'angry' ripple patterns to indicate to people that it wanted them to leave. There is significant potential in the further development of these systems and an intended provocation towards observers, as the system acts as a metaphor for new types of surveillance systems that are gradually being implemented within society. The scalable nature of these systems both in area size and time allows them to be applied to a range of applications including office layout optimisation, public space furniture, shopping mall design and the planning of services and infrastructure at the city scale. The output would not have to be constrained to electronic communication but can be connected to construction methodologies as discussed in the previous projects. The high complexity of the system and limited time and means for our experiments allowed only initial testing rather than a methodical exploration of the wide range of possibilities.

Figure 11. 'Data-Space' – field of nodes containing infra-red sensors and LED's, tracking human activities and communicating intelligent signals.

4 Conclusions and Future Research

The research presented in this paper explores the conceptual opportunities found within the integration of sensors, material growth systems and robotic devices into generative on-site design and construction strategies. It has focused in particular on the conceptual implications of the introduction of new technologies for the nature of the design process itself, the changing role of the architect and the potential attitude towards processes of negation between inhabitants and their built environment.

It has shown how the monitoring of human activities can be used to inform consequential design adjustments that can be implemented right away, adapting the final outcomes better towards the intended functionalities. By creating feedback loops between the mapping of human behaviour and construction implementation, it is possible to explore strategies for fabrication where the final construction is not predetermined, but instead is producing emergent qualities based on the decisions and desires of human agency within society.

There are several key potentials of this new approach towards design and construction:

Design decisions may be taken in relation to a detailed understanding of a site and context, where the detailed and multi-faceted performance of a building within its environment can be experienced and tested rather than speculated upon from behind the screen of a computer. This should allow buildings to become be better adapted to perform within their context, with high-resolution integrated functionalities and environment-specific, performance-based features.

The increased control over production offers a democratisation of design decision making and facilitates negotiation between different parties in the design process. The role of the architect using these methodologies may shift from controlling the end result to designing a process-based, quality driven generative method, allowing successful methodologies to be implemented towards a range of programs and sites.

The research may increasingly incorporate intelligent behaviours, mimicking processes of self-organisation as observed within nature or in the growth and adaptation of cities. Providing an alternative vision to static and idealised architectural solutions, these methodologies are able to deal with the contingencies and complexities of dynamic social, cultural, economic processes and other forms of human interaction that drive the materialisation of our architectural and urban environments.

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'Emergent Constructions' was developed by Jeroen van Ameijde, Sulaiman Alothman, Mohammed Makki, Yutao Song and Manja van de Worp.

'Data-Space' was developed by Jeroen van Ameijde in collaboration with Ping-hsiang Chen, Howard Chen, Zachary Mollica, Luis Rodil-Fernández and students.

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Evaluation of building use scenarios by crowd simulations and immersive virtual environments: a case study

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Abstract –

Virtual reality (VR) is becoming common in the AEC/FM industry, closely linked to BIM implementation. VR tools can be used to anticipate operational issues, simulating them in a virtual prototype since early design. The paper investigates such a topic in relation to access, space and use performance of an existing hospital facility. A case study has been developed considering a pavilion where both medical and food spaces are located, causing a clash between flows of end-users in critical time-slots. Crowd simulations and immersive virtual environments have been tested as occupancy evaluation tools. Post-occupancy evaluation (POE) data have been translated into a dynamic simulation of the existing occupancy conditions within the BIModel of the pavilion and considering various profiles of end-users. Subsequently, both the BIModel and the crowd simulation have been imported into a game engine to be visualised and experienced in a VR-headset, switching from the analysis of flows to the perspective of end-users (i.e. able-bodied users, person in a wheelchair, visually-impaired person). The use of VR enables a clear visualisation and communication of the existing conditions. Moreover, POE data translated into a dynamic simulation of the building use scenario could be applied for the pre-occupancy evaluation of internal layout reconfigurations. Finally, the combined use of crowd simulation and immersive VR enables the users to perceive crowding in the occupancy evaluation and adds the user experience as design input, representing an innovative approach that goes beyond traditional resources such as personal experience and regulations.

Keywords –

Occupancy evaluation; Virtual reality; Crowd simulation; Immersive virtual environment; Building performance

1 Introduction

The use of Virtual Reality (VR) is becoming common in the Architecture, Engineering, Construction and Facility Management (AEC/FM) industry, closely linked to the implementation of Building Information Modelling (BIM) tools and processes. VR tools (e.g. game engine, immersive virtual environment, crowd simulation) can be used with different purposes, such as visualisation, communication, analysis, design optioneering and training [1] [2] [3]. For example, they can be implemented to analyse the eventual possibility of construction and operational issues in design proposals, simulating them into a virtual prototype since early design. A virtual prototype is, in fact, a digital representation of a design proposal that can be explored, tested and evaluated before being physically realised [4] [5]. Moreover, VR can be applied to evaluate if a design proposal satisfies a performance-based requirement. For example, considering operational outcomes, a pre-occupancy simulation can be applied as evaluation method in order to simulate how the space will be used by the end-users during their activities and, at the same time, improving the understanding of the client about the design proposal [6]; in this way, the human experience is added to the project before it is built [1] [7] [8]. For example, compliance of a design proposal with requirements that relate to access for people with disabilities could be demonstrated by simulating their movements within a virtual space [9]. In the case of an existing building, a virtual simulation can be developed based on Post Occupancy Evaluation (POE) data related to the current in-use condition to provide feedback about how the building is used and produce a benchmark for the possible need for renovation. Furthermore, several examples of immersive VR applied to the iterative design review and feedback process exist in literature. For example, immersive VR can be effectively applied as a communication tool in user-centred design processes based on the feedback of stakeholders [10]. Virtual prototypes developed in immersive environments can support collaborative design review sessions since early design stages, improving the communication among stakeholders [11] and allowing the evaluation of behaviours and preferences of end-users, given different design scenarios [12].

In the following paragraphs, a case study is described in which VR has been applied to the simulation of operational issues in an existing building with communication and analysis purposes. The implemented method and the obtained results are illustrated. Further considerations for future works are also introduced.

2 Case Study

A case study has been developed to test the implementation of two different types of VR technologies (i.e. crowd simulation and immersive virtual environment), regarding communication and analysis of access, space and use performance of the current in-use scenario of an existing hospital facility. The VR-aided analysis has been performed in collaboration with the contracting entity (CE), who wanted to evaluate the benefits of digital approaches to reconfigure spaces and services offered in the asset. In order to narrow the scope of the case study, a VR concept has been developed to communicate and analyse a specific critical in-use condition considering a pavilion where both medical (i.e. emergency entrance from the ambulance parking, elevators to the wards located at the upper floors) and food spaces (i.e. hospital canteen, cafeteria) are located (Figure 1). In critical time-slots (i.e. lunch time, 11:45 am – 2:45 pm) the access to the hospital canteen is likely to cause major queues (Figure 2). This increases the waiting time for the personnel, which has a limited amount of time to have lunch, and interferes with the access of internal and external users (e.g. personnel, patients, visitors), who head towards the elevator to go to the wards in the upper floors of the pavilion. The result of that current use scenario is a clash between flows of end-users.

The CE conducted a traditional POE to collect data for investigating such critical situations. Resulting data have been attached to a public call for feasibility studies to improve the current service response to the needs of end-users, while considering the possibility for a low-budget internal layout reconfiguration of the pavilion at ground-floor, among other solutions. The research group started from this specific case to experimentally evaluate (1) how VR could support the CE in communicating its needs, effectively considering the perspective of end-users and (2) how VR could support the CE in evaluating design proposals.

Figure 1 Ground-floor of the analysed hospital pavilion. Main entrances, wheeled-bed elevator and hospital canteen are highlighted

Figure 2 The queue in front of the elevators during the critical time-slot with people arriving from the emergency entrance

3 Crowd simulation of the existing building use scenario

A crowd simulation tool has been used to represent and simulate the existing building use scenario based on the POE integrated with additional data sources. The aim is to understand if such a simulation could support the CE to answer the following questions: how do the access, space and use scenarios perform in the existing hospital pavilion? Are the needs of end-users satisfied in using spaces and services?

3.1 Data collection regarding the current in-use condition

The case study integrates three data sources, which have been used to evaluate the current building use scenario:

1. existing surveys and building use data collected during the POE by the CE have been analysed
2. focus groups and thematic tables have been

organised with the CE, when critical issues have been discussed in detail, as well as the possibility of introducing a digital approach to the problem evaluation

3. further on-site surveys and walkthroughs have been carried out in order to (1) understand usual movement paths walked by the various profiles of end-users moving and using services in the pavilion (e.g. technical operators, healthcare personnel, administrative staff, medical staff, patients and external users); (2) have occupancy data on narrower time ranges than the ones provided by the CE with the POE. A mobile application was used to collect the number of end-users moving in the pavilion in the critical time-slot according to users profiles; these data, elaborated in percentages, was used as input for simulating the current building use scenario within a BIM-based crowd simulation tool.

Available as-built documents have been reviewed and translated into a BIModel in Autodesk Revit. The level of definition of the BIModel was established according to the model use defined for this case study, which is the translation of POE data into a dynamic simulation able to support the communication and analysis of existing occupancy conditions. Spaces, circulation paths, external and internal walls have been modelled to simulate the flows of end-users. Other elements (e.g. ceilings, windows, furniture) and attention to the lighting of the spaces guarantee a greater sense of presence during the immersive experience, which will be described in the next paragraphs.

The existing building use scenario of the pavilion, related to the critical time-slot (i.e. activities, end-users, circulation paths, spaces), has been formalised by the BPMN graphical modelling approach for processes [13] to be organised and used as a reference framework for the simulation.

3.2 Occupancy data as input for the crowd simulation

Occupancy data have been used as input to a crowd simulation tool (i.e. Oasys MassMotion), where the agents have been customised based on the profiles of end-users acting in the analysed pavilion. Various agents have been created to represent technical operators, healthcare personnel, administrative staff, medical staff, patients and external users (Figure 3). Their profiles have been parametrised considering geometrical data (e.g. range of action) and behavioural data (e.g. circulation paths, speed of movement). The number of agents for each type of profiles of end-users have been set according to the POE data integrated with on-site surveys and measurements organised in 15-minute time ranges during the critical slot.

The BIModel has been imported into MassMotion, which is able to parse the Industry Foundation Classes (IFC) data format and automatically recognise the elements that hinder the movement of people (e.g. doors, walls).

Finally, the simulation has been run according to the scenario described in the BPMN (i.e. critical time-slot), with the collected data used as simulation parameters and the geometrical constraints of the BIModel.

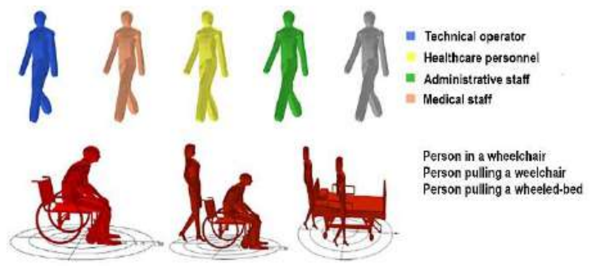

Figure 3 Agents set for the simulation

3.3 The BIM-based crowd simulation as communication tool

The result of the crowd simulation has been optimised by an iterative review process with additional on-site surveys and focus groups with the CE. Such an optimisation has allowed the simulation to be representative for the current in-use condition and related critical issues in the access of the end-users to the services offered in the analysed hospital pavilion. For example, the simulation has highlighted the problem of clashes between the two flows of end-users (i.e. users of the hospital canteen and users entering the building and going towards the elevator) in the hall of the pavilion in the critical time-slot (lunch time). Based on that, it has been possible to share with the CE and a representative group of stakeholders:

- a clear visualisation of the problem and communication of the issue to people that usually do not experience the critical time-slot in the pavilion, but that may be required to take decisions and develop strategies about it (e.g. define the available budget for the reconfiguration of the internal layout) (Figure 4);
- a definition of the profiles of end-users that access the services provided in the analysed pavilion (e.g. personnel, visitors, patients, disabled people using wheelchairs, patients transported on hospital beds) (Figure 5);
- a density map of the pavilion at the critical time-slot, useful to understand which services are the most used ones during the critical time-slot and support future design and decision processes regarding the

reconfiguration of the internal spatial layout (Figure 6).

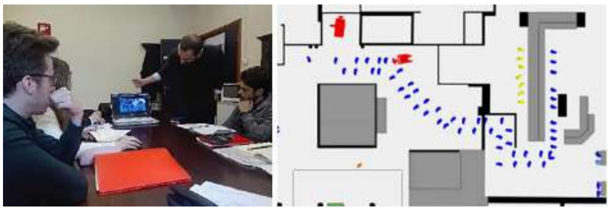

Figure 4 Results from the crowd simulation have been used to support focus groups with the client

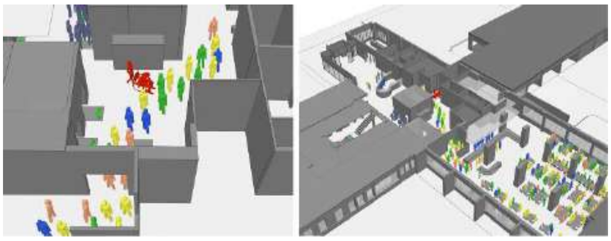

Figure 5 Crowd simulation of the current condition

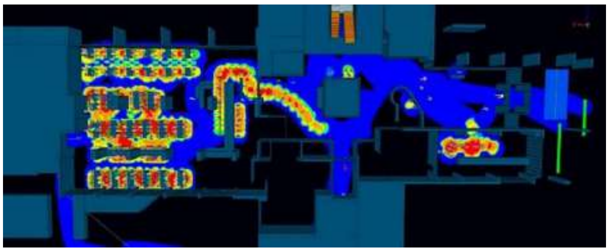

Figure 6 Density map of the pavilion at the critical time-slot

3.4 The BIM-based crowd simulation as Pre-Occupancy Evaluation tool

Occupancy data, collected during the POE and organised in traditional paper-based documents by the CE have been digitised. Once integrated with on-site surveys, they have been used as input for the simulation, becoming a dynamic representation of the current building use scenario and critical issues. The possibility to use the same simulation data and formalised building use scenario for evaluating design options for the layout reconfiguration of internal spaces has been discussed with the CE. In this way, the simulation would not be just the result of the Post Occupancy Evaluation and the picture of the current asset performance, but it would become the tool for an effective Pre Occupancy Evaluation of design proposals [14]. This hypothesis has been tested by proposing low-budget internal layout reconfigurations. The related BIModels have been imported in MassMotion, where the simulation, based on the same data as the existing in-use condition, has been executed again (Figure 7). In this way, it is possible to evaluate how, without changing the current building use scenario, it would be possible to (1) create a pre-occupancy simulation of access, space and use performance of the building according to various design proposals and (2) eventually select one of those options based on the results of this simulation.

Figure 7 Crowd simulation of the current in-use scenario applied to low-budget reconfigurations

4 Immersive Virtual Environment

Subsequently, both the BIModel and the crowd simulation have been imported into a game engine (i.e. Unity3D) to be visualised and experienced in an immersive VR headset (i.e. HTC Vive), with communication and analysis purposes in mind. The aim of this second part of the case study consists of the possibility to switch from the analysis of flows to the perspective of the end-users, who are part of those flows. Immersive VR has been used to evaluate the building spaces from various points of view, simulating four different scenarios:

- able-bodied users (scenario 0 and 1);
- person in a wheelchair (scenario 2);
- person pulling a wheelchair (scenario 3);
- visually-impaired person (scenario 4).

Unity3D was used to build the immersive environment with accurate lighting, a locomotion system and creation of various profiles of end-users to be simulated (e.g. viewpoint height), supporting the VR-headset natively. Moreover, the game engine was first used to import and visualise in the immersive VR both geometrical and non-geometrical attributes of BIM objects: this was necessary to be able to select and visualise information related to building objects while navigating the virtual scene. An interoperable data flow is not possible between Unity3D and a BIM authoring platform by default. The BIModel has been imported in Unity3D through the *.fbx data format and C# scripts have been used to import the non-geometric attributes embedded in BIM objects to be visualised when selecting them with one of the controllers. A teleporting system has been also integrated to navigate the BIModel.

In order to add the "occupancy" variable in the interaction with the building, while navigating in the virtual environment and experiencing the spaces as crowded as in the current building use scenario of the hospital pavilion, the crowd simulation developed in MassMotion has been also imported into Unity3D. This data flow has been managed by an Alembic (ABC) file exported from MassMotion to Autodesk 3ds Max, where an *.fbx file has been then created to be used in Unity3D (Figure 8). Once imported into the game engine, the crowd simulation maintains the number of agents and their speed of movement as defined in MassMotion and compliant to the POE data.

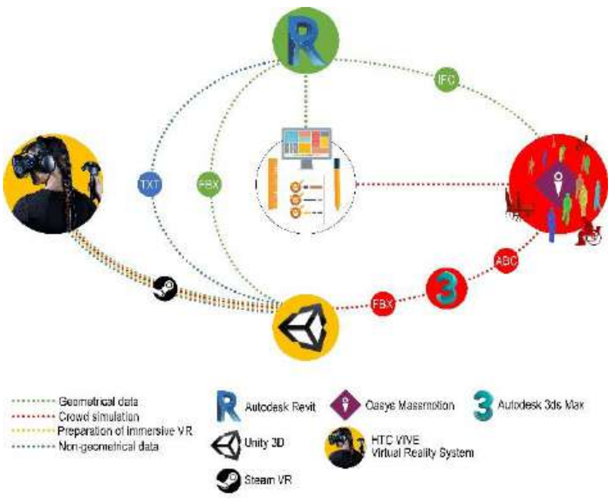

Figure 8 Data flow from the BIM authoring platform to crowd simulation and the immersive virtual environment

4.1 Simulation from the prospective of various end-users

Four scenarios have been created to experience the hospital pavilion and the crowd simulation from the perspective of as many profiles of end-users. The benefits of VR have been evaluated, highlighting its role as occupancy evaluation tool, its use for training purposes and to better understand how various profiles of end-users perceive the space. A modified first-person camera in Unity3D supports changing the perspective of the end-users according to the various scenarios.

4.1.1 Scenario 0: able-bodied users

Scenario 0 represents the point of view of an able-bodied user, a person of average height without disabilities and able to walk within the building spaces. The crowd simulation was not enabled in this scenario (Figure 9).

Figure 9 Internal spaces as visualised in the immersive virtual environment

4.1.2 Scenario 1: able-bodied users with the crowd simulation

Scenario 1 differs from the previous one because the crowd simulation has been imported in the immersive virtual environment and the user can evaluate how the feeling in using the building spaces changes when a crowded situation occurs (Figure 10).

Figure 10 Internal spaces as visualised by an able-bodied person, including the crowd simulation based on POE data

4.1.3 Scenario 2: person in a wheelchair

Scenario 2 represents the perspective of a person in a wheelchair: the movement of an electric wheelchair has been programmed in Unity3D to be controlled in VR by using the HTC Vive 3D-joysticks. The wheelchair user may represent either an employee on a wheelchair or an external visitor. A script has been created to visualise the walking (simulated) end-users via a red highlight when they are within the range of action of the wheelchair user. According to the CE, hospital employees with disabilities do not use the canteen service because of the current issue, optioning for other food services. This scenario aims to allow the CE to better understand the perspective of a person in a wheelchair using the building spaces and the problem that he/she must face in a day-to-day situation (Figure 11).

Figure 11 Simulation of a wheelchair user experiencing a crowded situation based on POE data. The accessibility of internal spaces can be tested and evaluated

4.1.4 Scenario 3: person pulling a wheelchair

Scenario 3 has been created to simulate an end-user pushing a wheelchair, which may be the case for medical staff that accompanies a patient from the ambulance parking to the hospital wards by the emergency entrance (Figure 12). In the current building use scenario, this situation is the one that causes major issues during the critical time-slot, because end-users entering from the emergency entrance and going to the elevator must cross the queue of end-users waiting to enter to the hospital canteen. The immersive simulation allows who usually do not experience that scenario to feel the actual discomfort of this implication.

Figure 12 Circulation path from the emergency entrance and the elevators is simulated from the perspective of a person pushing a wheelchair

4.1.5 Scenario 4: visually-impaired person

Scenario 4 simulates the viewpoint of a visually-impaired person. The rendered view in the HTC Vive has been partially obscured to reproduce the view of a visually impaired person (Figure 13). Sensitive paths have been modelled in the BIM authoring platform. A virtual cane, attached to the HTC Vive controller, enables users to follow the paths, while walking in the displayed building spaces. The cane/controller has been programmed to vibrate when touching sensitive paths during the navigation in VR. For example, such a scenario could be used (1) to validate the design of sensitive paths and internal spaces also in new design proposals acting as a Pre Occupancy Evaluation tool; (2) with training purposes; (3) to better understand how visually-impaired person perceive the space.

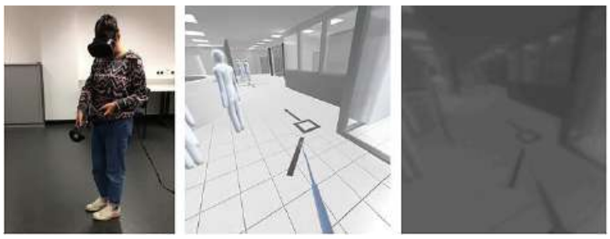

Figure 13 How a visually impaired user follows the sensitive paths with a simulated cane

4.2 Feedback collection

Feedbacks on the VR-aided scenarios previously described have been collected from people with various backgrounds and experience in the use of VR (i.e.

computer science, civil engineering, humanist disciplines, architecture, building accessibility, CEs). Fifteen users have been asked to navigate within the model, testing the proposed scenarios. It has been required for them to move through the spaces according to the actual circulation paths of employees, visitors and patients to experience the same crowded situation as detected during the POE and simulated in MassMotion. Despite the various backgrounds and experience in VR technology, users provided similar comments (excerpt):

- when switching from scenario 0 to scenario 1 it has been noted that spatial dimensions, even if compliant to building codes, may not be sufficient in a crowded situation as the experienced one
- the perception of the actual discomfort due to the occupancy simulation is realistic
- the crowd simulation, which is compliant with POE data, provides an added value to the implementation of immersive virtual environments as evaluation tools
- CEs have highlighted the possibility to experience building spaces from the perspective of the end-users as positive input in the decision-making process
- the possibility to support user-centred design processes and stakeholder engagement by immersive technology has been considered
- immersive VR could be an effective tool to analyse the accessibility of building spaces, going beyond codes, regulations and computable parameters and implementing the dynamic simulation of how the building is/will be used
- immersive VR could be used as a training tool to learn how a person with disabilities moves and acts within the space

5 Results

The paper describes the implementation of crowd simulation and immersive VR in the communication and analysis of access, space and use performance of an existing building. A case study has been developed testing VR implementation in an hospital pavilion where both medical and food spaces are located, causing a clash between flows of end-users in critical time-slots.

Crowd simulation has been used to integrate a multitude of paper-based POE data and translate them into a dynamic representation of the critical in-use condition; the case study has allowed the research team and the CE to understand which type of POE data are needed to create a reliable simulation of the in-use condition. Such a simulation allowed a clear visualisation and communication of current issues to people that usually do not experience them but who are involved in taking decisions related to the asset management. Moreover, POE data digitally simulated have been also applied to the pre-occupancy evaluation of design proposals for the low-budget reconfiguration of the internal layout.

Immersive VR shown the possibility to switch from the analysis of flows to the evaluation of the perspective of the end-users, simulating their point of view in a day-to-day situation. The combined use of crowd simulation and immersive VR, in fact, enables the users to perceive crowding in the occupancy evaluation and adds the user experience as a design input, representing an innovative approach that goes beyond traditional resources such as personal experience and regulations. This application may support the validation of design proposals, the evaluation of current in-use scenarios and a better understanding of how end-users perceive the space and its performance in meeting their needs.

A data flow has been proposed and tested to connect the BIM authoring platform, the crowd simulation tool and the immersive virtual environment. Moreover, the CE has started to consider the possibility to attach the outputs of a similar simulation (e.g. a video) to the traditional paper-based documents for better communicating needs and requirements to the suppliers.

6 Conclusion

The case study described in this paper aims to evaluate how VR technologies may be used to communicate and analyse the current in-use condition of an existing building as far as access, space and use performance are concerned. It conceptually connects the iterative review and feedback process (e.g. Post Occupancy Evaluation) to the briefing one (e.g. restate a need for action, evaluate lessons learnt, needs and expectations).

Some aspects should be further considered and researched about the implementation of VR in AEC/FM processes: technological, procedural and contractual aspects should be integrated into a single implementation framework. In particular:

- the suitability of various VR technologies should be considered according to different processes (e.g. collaborative design review, user involvement, building code checking) [11]
- process phases, users to be involved, related responsibilities and requirements to be analysed should be deeply evaluated before implementing VR
- contractual aspects related to the implementation of VR-aided simulations in AEC/FM processes should be investigated (e.g. consequences if a gap between simulated and actual performance occurs)

Moreover, the novelty effect of VR technologies in the AEC/FM industry should be considered: the case study described in this paper lasted for five months during which the CE has been iteratively involved to validate the simulation and evaluate the possible benefits of such an approach. The CE took a considerable amount of time before switching from considering the simulation as a fancy video to deeper understand its communication and analysis benefits. As a first attempt, this case study has been affected by the novelty effect, but final results suggest for a possible effective implementation of VR technologies, as well as BIM methodology, in future actions.

Acknowledgments

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Digitally Fabricated Innovative Concrete Structures

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Abstract –

This paper presents the general aim of the research at the Institute of Structural Design (ITE) at Braunschweig University of Technology to bring digital design and digital fabrication together to develop resource efficient construction elements, manufacturing processes and building systems.

Basis of research at ITE is the so-called Digital Building Fabrication Laboratory (DBFL). The paper gives an overview of machine design, the technical parameters and its basic abilities of subtractive and additive processes e.g. milling, printing and scanning.

Based on the combined use of these digital fabrication processes and in cooperation with high-performance materials such as ultra-high performance concrete (UHPC), different research projects are being performed at the ITE. To explain the possibilities of the DBFL, the paper will present the results of two different – additive and subtractive - research projects to develop fabrication techniques for the building industry.

The first project is dealing with the development of "digitally fabricated high precision Non-Waste-Wax-Formwork for innovative UHPC structures" and the second project is investigating "Additive manufacturing of free-form concrete elements using Shotcrete 3D Printing (SC3DP) technology".

Finally, the paper will highlight the possibilities of combining these technologies and transferring them to industry 4.0.

Keywords –

Digital Robotic Fabrication; Construction; Wax; Formwork; Shotcrete 3D Printing; Additive Manufacturing

1 Introduction

Concrete has been continuously developed in recent years into a high-performance material with a variety of different features. Nowadays we have the knowledge and the technology to cast self-compacting concrete, with the compressive strength similar to steel, into complex formwork or to modify the rheology of the concrete to the point where it is keeping its stability after pumping and spraying.

On the other hand, as the digitalization reached the building industry, it provided us with powerful calculation and planning tools, which liberated architects and engineers from restrictions concerning the geometric design of objects. This new freedom is still restricted by the available industrial standard of manufacturing technologies.

For example, the standardized, commercially available formwork systems for concrete components are optimized with regard to simple geometric shapes and joining principles. As a result, concrete structures are still composed of predominantly bending-stressed mass-intensive components. Although there are occasional attempts to realize free form, "non-standard" concrete architectures - such as the "Phaeno" in Wolfsburg by Zaha Hadid Architects - the challenge for the engineers is essentially to translate the architectural shape into reality. Nevertheless, light weighted and highly efficient structures, such as Heinz Isler's shell buildings, are barely to be found anymore [1].

Today, with the help of high-performance building materials, robotic automation and digital tools, we have all the instruments for fundamental developments in building construction. In 2002, Khoshnevis et al. [2] provided a concept how an automated approach to construction could look like, called "Contour Crafting" (CC). CC is extruding concrete and using trowels to create smooth and accurate planar surfaces. Another extrusion based process, called "Concrete Printing" (CP), was developed by Lim et al. [3] in 2011 at the Loughborough University. CP is not using trowels to achieve the surfaces quality needed, but a smaller resolution of deposition. Combining the advantages of all these technological developments, it is possible to build lightweight, efficient and therefore resource-saving structures.

With the research of the Institute of Structural Design (ITE) at TU Braunschweig, we want to develop digital fabrication methods to transfer innovative technology of computational design, automation and materials into building construction industry.

Application processes always depend on the materials used. In order to redefine the traditional manufacturing method, it is often necessary to rethink the entire fabrication process and adapt it to existing technologies and materials. Based on what the process offers the design space is stretched out. Our aim is to enlarge the architectural design space by providing new digitally controlled fabrication processes, see Figure 1.

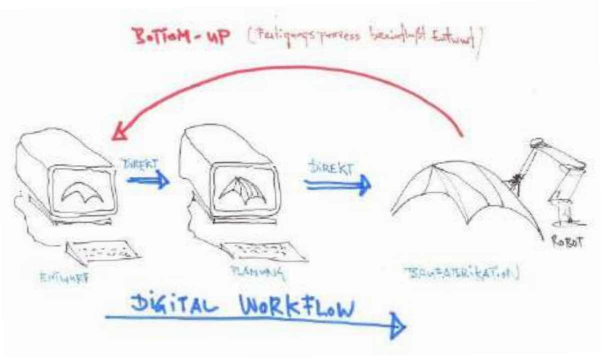

Figure 1. Design process turns into digital bottom-up workflow

2 Digital Building Fabrication Laboratory

The DBFL in its design and capabilities is unique and is the focus point of future research in the field of digital building manufacturing at the ITE. The focus is on combining latest technological developments from car and plane manufacturing with new high performance materials in order to fabricate material efficient structures for the building industry. By combining flexible robotic components with precise and robust machining systems, a huge bandwidth of applications will become available.

The DBFL operating range is almost 7 meter in width, 15 meter in length and more than 3 meter in height. A 6-axis Stäubli robot connected to a 3-axis portal is the core of the additive manufacturing unit in the DBFL (Figure 2). The robot can carry up to 200 kg and move freely in the entire working area. The end effector can be equipped with various attachments, depending on the examined process. The second portal is carrying a 5-axis CNC milling and sawing machine. It represents the subtractive part of the DBFL and has been designed for low tolerance and high precision milling jobs. It also has the ability to process high-density materials like granite and ultra-high performance concrete (UHPC).

Both units can operate individually or in a synchronized cycle. By combining the additive and subtractive abilities of both portals, complex process chains, in order to fabricate efficient and graduated building elements, can be established without moving the element.

As an example, the DBFL is capable of spraying and printing concrete, milling, scanning objects and connect these features. Its two portals can operate synchronously or simultaneously in order to investigate a majority of different manufacturing processes. Based on these possible digital fabrication processes and available high-performance materials like the ultra-high performance concrete (UHPC), different research projects are being performed at the ITE involving the DBFL.

Figure 2. Digital Building Fabrication Laboratory at ITE TU Braunschweig

3 Digitally subtractive fabricated high precision Non-Waste-Wax-Formwork for innovative UHPC structures

UHPC can generally be cast in any shape, assuming the right additives were used. Depending on the complexity of the required form, the main effort and cost is to build the formwork. The formwork systems, which are mainly used in the building industry today, can only produce geometrically simple basic forms and allow deviations within the range of centimeters.

To produce concrete parts that differ from these common straight and rectangular basic shapes, various 3D free-form formwork principles have been established in the construction industry. Primarily CNC-machined wooden formworks or epoxy resin coated foaming polystyrene (EPS) are used for these geometrically high complex free-form geometries. These CNC-milled formworks have high production costs and the disadvantage of not being recyclable due to the coating. In summary, it can be said that almost all 3D free-form formwork systems currently available on the market are usually expensive custom-made products, which cannot be reused for variable geometries. In addition, the currently permissible tolerance deviations of system formwork for high-precision precast UHPC elements are not acceptable. Precise and free-form shuttering is therefore a decisive factor in the production of UHPC constructions.

Due to this need and inspired by the research of Gramazio & Kohler [2] of ETH Zürich a research approach for free-form concrete formwork by CNC-milling industrial waxes was developed by the ITE.

In contrast, to the research approaches of Gramazio & Kohler, based on an adjustable formwork shell on which liquid wax is cast to preserve the form and the "FreeFAB ™" research approach of the Australian Dr. James B. Gardiner et. al. [4] using hot liquid wax to 3D printed free-form formworks, the ITE approach is based on the use of large cooled down wax blocks that are fast and precisely shaped into form by subtractive CNC-milling to robust Non-Waste-Wax-Formwork with nearly any geometrical shape.

Based on these developed approach, the technical applicability of industrial waxes for the fabrication of free-form formwork elements was investigate at the ITE within the joint research project: “Non-Waste-Wax-Formwork-technology: Innovative precision formwork on basis of CNC milled recyclable industrial waxes for the casting of geometrically complex concrete elements” [5] in the years 2014-2016. In addition to the prevention of waste, the complete recycling of the wax results in low formwork costs, as the material investment can be allocated to the number of applications. The industrial wax used has similar strength properties compared to polyurethanes with the same density, although the material costs per application are significantly lower than those of polyurethanes.

3.1 Material properties of the selected industrial waxes and production of large wax blocks

Since industrial waxes have not been used as concrete formwork material until now, a suitable wax had to be found. Therefore, a technical wax requirement profile for the application as formwork material regarding the technical properties was specified. Based on this profile different waxes were selected and tested regarding their general machinability (millability) and their different physically mechanical properties for example: compressive, bending and tensile strength, elastic modulus, temperature-dependant strain or volume change, Differential scanning calorimetry (DSC) and thermal conductivity.

As a result of the tests and investigations of the research project, an industrial wax titled “ConFormWax” with a melting point of around 60°C, a (elastic) compressive strength of around 2,5 N/mm² (at 20°C) and an elastic modulus of 1923 N/mm² was selected as most suitable wax for the developed Non-Waste-Wax-Formwork technology [6].

As Dr. Gardiner [7] also mentioned, wax is very difficult to melt and pour into large blocks. Big molten wax blocks contain a considerable amount of latent heat, due to their insulating thermal conductivity they only cool down slowly. Cooling results in thermal shrinkage, which leads to high internal stresses that cause deformations or cracks. If these internal stresses are too high, the wax blocks also deform during CNC milling, which leads to an insufficient dimensional accuracy and precision.

An important part of the investigations within the research project was therefore the development of a process for the production of large-format, low-tension wax blocks for CNC milling. The procedure which turned out to be the most suitable to minimize these effects was to use smaller, tension free, planed cold wax tablets as filler. These wax tablets can be placed in a rectangular shape at regular intervals and can be grouted together with hot liquid wax in almost any dimension of wax blocks, as seen in Figure 3.

Figure 3. Grouting of cold wax tablets with hot wax to wax blocks (left) Cooled off wax block (right)

3.2 Verification of selected wax and developed formwork process

To verify the selected wax, the wax block production and the wax milling process, wax formwork panels, with dimensions of 500 mm x 500 mm x 120 mm where produced. The wax formwork panels were digitally composed of different geometric elements as grousers and grooves, round and pyramidal stubs, uni- and multidirectional curved surfaces. After milling these geometries into the blocks, ultra-high performance concrete were then cast on the resulting wax formwork panels. The aim was to analyse the influence of the aspect ratio and structural refinement as well as the separating properties of the concrete (Figure 4).

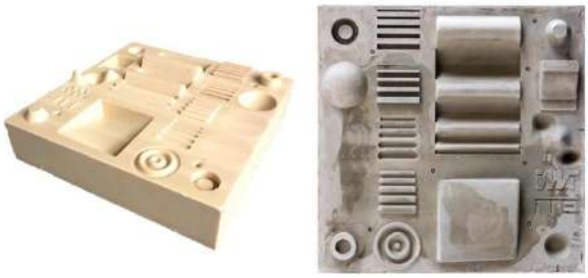

Figure 4. Wax formwork panel A after stripping of the UHPC (left); UHPC cast of panel A (right)

Hereafter the wax formwork panels and the UHPC casts were digitalised at GOM (company of industrial and automated 3D coordinate measuring technology) [8] with a standard 3D scanner (type ATOS). The digital 3D-scan data were used to conduct a volumetric form analysis in comparison to the original CAD data.

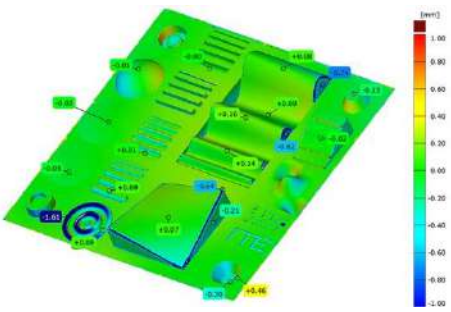

Figure 5. Comparison between the scan data of the UHPC cast (panel A) and the original CAD data

As shown in Figure 5, the UHPC casting of the wax formwork achieves very high precision over the entire area compared to the original CAD data.

The results of the research project have shown that the selected industrial waxes are suitable for the fabrication of precise formwork for complex, free-form concrete, and in particular UHPC, members. The technical properties of the used waxes, as the elastic modulus and compressive strength, are within a favourable range for concrete formwork construction rigid enough to withstand the fresh concrete pressure and soft enough for an efficient milling.

The volume analysis showed that not only the wax formwork, but also the cast concrete components have a high degree of precision for the construction industry. Apart from some production-related deviations, the measured tolerance is only in the tenth of a millimetre range. Due to the possibility of recycling the wax chips and wax formwork elements by re-melting, the Non-Waste-Wax-Formwork technology provides an ecologically and economically viable alternative to modern free-form formwork made of EPS and PU.

The technical foundations of the developed Non-Waste-Wax-Formwork therefore provide a technology and an industrial wax that enables the production of concrete and especially ultra-high performance concrete (UHPC) elements. The wax can be cast with adjustable surface qualities, with an accuracy in the tenth of a millimetre range and in almost any geometric form with sharp edges and very small curvature radii. A further advantage is the achieved sustainable closed loop recycling process, since the recycling (melting) of the wax chips and the disused wax formwork elements does not produce any waste in the process. This not only makes the wax formwork technology ecologically interesting, but also offers an economical alternative to modern free-form formwork made of epoxy resin-coated foam polystyrene (EPS) and polyurethane (PU). By reusing wax, material costs per application can be reduced to a comparable EPS level, while at the same time achieving better material properties - comparable to those of medium-density PU [5].

3.3 Transferring the Non-Waste-Wax-Formwork technology to the industry

Based on these good results and the industry's need for sustainable free-form formworks, the Non-Waste-Wax-Formwork technology was awarded with the German Innovation Prize of the Supplier Industry for Structural Concrete Products 2017 and is now being converted into industrial applications. The challenge of transferring the technology into an industrial process lies in the fulfilment of the respective user-specific requirements and the associated adaptation and optimization of the individual process steps, such as the production of the wax blocks.

To do so, two actual research projects are currently being carried out at the ITE together with industrial partners following different requirements and approaches.

The first project entitled "Development of a modular and fully automatic production process for free-form concrete formwork in building construction based on technical wax" is funded by the German Federal Ministry of Economics and Technology (BMWi). The focus of this research is the fast and fully automated production of modular expandable wax formwork, with a low demand on the achievable precision (Figure 6). The concept is to replace the disposable CNC milled eps formwork used today. In this project, the strategy of producing wax blocks by pressing cold wax chips into form is tracked. These pressed wax blocks have a four times lower compressive strength than cast blocks of wax (Figure 7) but their production is significantly faster and does not require any melting energy.

The second project entitled "Innovative Non-Waste-Wax-Formwork for the Fabrication of High-Precision Machine Frames made by UHPC", funded by the German

Research Foundation (DFG), focuses on the development of a precise and robust wax formwork (replacement of PU / Steel / timber "multiple formwork"). Therefore, wax blocks are made by casting filler-added wax. These wax blocks have shown a higher compressive strength (Figure 7) than compressed or cast wax blocks without filler. Their production is also less complicated, since the thermal shrinkage and the high melting energy are reduced.

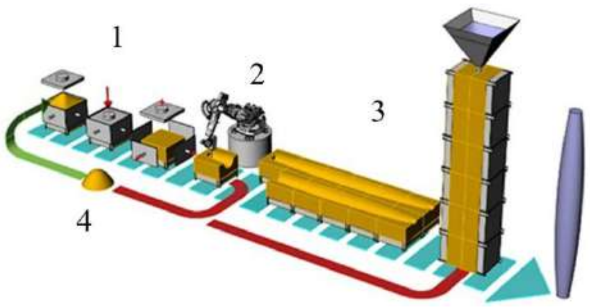

Figure 6. Principle of automated modular wax formwork: (1) compression of chips to blocks, (2) CNC-milling, (3) assembly of modular formwork, (4) closed loop recycling

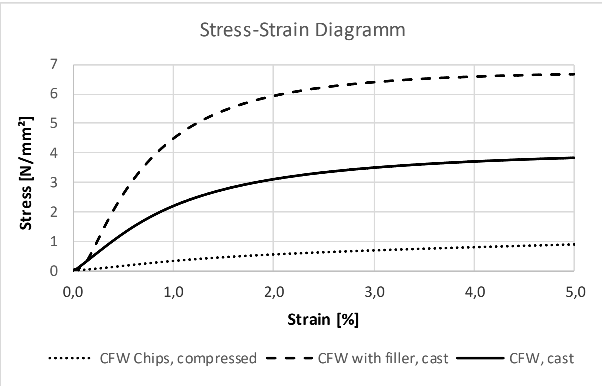

Figure 7. Stress-Strain Diagram of ConFormWax (CFW) samples produced by: cast (a), cast with 20% filler content (c) and compressed chips (b)

The aim of both projects is to make wax accessible for a variety of industrial applications. The fields, which both projects cover, makes it possible to use the wax, for example in precast factories, which then are able to react flexibly to requested free-forms.

4 Additive manufacturing of free-form concrete elements using Shotcrete 3D Printing (SC3DP)

For over 100 years, shotcrete has been used to spray reinforcement and produce lightweight and efficient structures. This technology is supposed to be transferred with the help of a robot into a digital, formwork-free and automated fabrication process. To achieve this goal a major collaborative research project of the Universities of Braunschweig, Hannover and Clausthal is carried out. Under the direction of the ITE, researchers from the fields of material science, mechanical engineering and computer science are developing a "robot-assisted shotcrete technology for generative manufacturing of complex concrete structures without formwork". The developed robot-controlled process is called "Shotcrete 3D printing" (SC3DP) see Figure 8. In addition to the development of a process technology, it is also necessary to develop a suitable shotcrete whose properties can be adapted to the respective components and the production process [9].

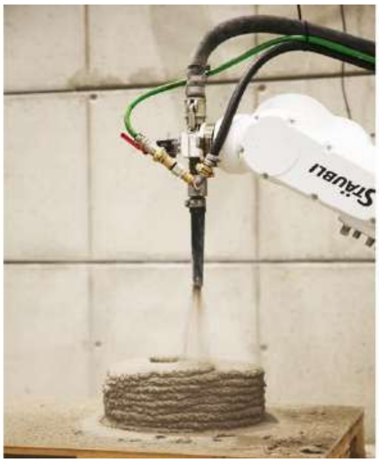

Figure 8. Application process of the new developed Shotcrete 3D Printing technology

Within the conventional Additive Manufacturing methods, the production of concrete elements is limited due to the layered application. Since no formwork is used for the 3D Printing process, the production process relies on self-supporting of the material. The material has to be applied on top of already printed material and overhangs as well as thin-walled elements are hard to realize. The use of the SCP3D method in additive manufacturing makes it possible to vary the application angle in contrast to the extrusion process. This opens up new possibilities in terms of geometric freedom. The material no longer simply has to be "deposited", but can be applied spatially to an already sprayed layer. In addition to a better surface bond, the resulting degrees of freedom can lead to a new surface quality and offer approaches for the integration of reinforcement in 3D printing with concrete. While the composite zone, according to Le T. T, et al [10], in extruded concrete components, from a mechanical point of view, is to be regarded as a weak point, this problem could not be observed using the shotcrete method [9]. In order to demonstrate the possibilities of robotic, generative manufacturing, it is planned to produce a single curved and a double curved wall without the use of formwork at the end of the project. In particular, curvature in two axes cannot be realized with current standard formwork systems.

4.1 Application parameters

One of the biggest disadvantages of the shotcrete process is also one of the biggest advantages. For example, the SCP3D process and the sprayed geometry depends on a many parameters, such as air pressure, concrete volume flow rate, robot speed and the distance of the nozzle to the target (see Figure 9). All these parameters must be controllable by the program in order to realize the desired application. Furthermore, the computer has to get real-time information about all parameters and the resulting geometry in order to control the shotcrete 3D printing. However, if you manage to regulate the parameters and adapt them to the application strategy, there are many possibilities for the shotcrete process.

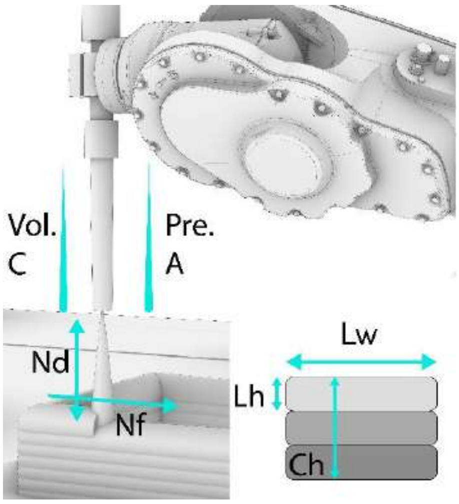

Figure 9. Overview of important parameters: Nd=Nozzle distance, Nf= Nozzle feedrate, Vol.C=Volume flow concrete, Pre.A=Pressure air, Lw=Layer width, Lh=Layer height, Ch=Concrete hardening

As the ITE has already been able to show, the control of these parameters is currently possible [11]. However, research is still in progress on the measurement technology for this complicated process. Currently, the focus of the integration is on a laser and a camera for in situ measurement of the sprayed geometry. This enables measurement of the width and height of the layer as well as the distance between the nozzle and the surface. This information is used to readjust the robots speed to either increase or decrease the thickness of the applied material.

4.2 Integrate reinforcement into the printing process

The manually spraying of steel and textile reinforcement was approved in different construction projects over the last years with great success.

The first studies at the DBFL to integrate reinforcement into the automated shotcrete process were performed in early 2018. It has been shown that it is possible to integrate textile and steel reinforcement without major problems. Although the reinforcement was still inserted manually, it can be assumed that a robot arm could perform this work even more precisely. Figure 11 shows a curved wall produced with the "Shotcrete 3D Printing" method. The wall is about 1.0 meters high and was reinforced at the backside with a textile (Figure 10, left). The smooth surface also on the backside was post processed manually by a trowel, based on Khoshnevis et al. [2]. Because the concrete hardens from the inside to the outside, it is already stable in the middle, but the outside is still soft enough to be processed. Therefore, the processing of the concrete with a trowel succeeds well. In preliminary tests with small robots [12], it could be shown that different surface qualities can be achieved in an automated process using trowels, rammers and scoops. However, the next experiments are intended to show that subsequent processing of the surface can also be carried out in real scale by a bigger robot.

On the frontside, a steel-reinforced console was added (Figure 10, right). To show the position of the reinforcement in the console, two reinforcement bars were not sprayed, as shown in Figure 11, left. The reinforcement is placed in the middle of the console and not in the upper part where it would statically belong, due to an easier integration process of the bars.

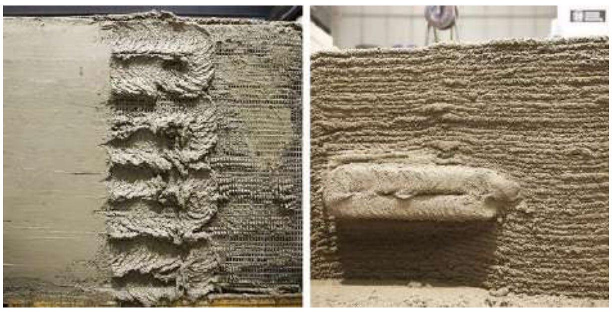

Figure 10. Wall produced with Shotcrete 3D Printing; backside smoothed and with implemented textile reinforcement (left); frontside with steel reinforced sprayed console (right)

Figure 11. Wall produced with Shotcrete 3D Printing; Detail of the console, with 2 reinforcement bars left blank (left); top view of the wall (right)

5 Summary and Outlook

In order to build concrete structures and elements more efficiently to save resources by making them lighter, alternative construction techniques to today's standard techniques are needed. With the development of the Non-Waste-Wax-Formwork technology, it is possible to realize a multitude of individual free-form concrete forms. Thereby the wax can be reused, which is not only ecologically but also economically reasonable. Further, the achieved surface quality can be utilized for high-precision components, which opens up new ways of use. But also low surface qualities and the associated rapid production of wax blocks is yet being applied in industry.

The next steps on the way to industrial use are the improvement of the wax by using fillers and the wax block production. This would reduce the energy absorption to melt the wax and increase its strength. Improving the material will always improve the process itself, which in return could reveal new fields of application.

In contrast, the Shotcrete 3D Printing requires no formwork at all, by assembling layers to bigger elements. This saves the intermediate step of producing a formwork and the time and cost associated with it. In this way, a complex curved shape could be produced without formwork. As the first tests showed, it is also possible to integrate reinforcement (textile or steel) without any major effort and to apply concrete horizontal up to a thickness of about 16 cm. As Hack and Lauer [12] stated it is possible to print a mesh-mould by a robot. This mesh could be sprayed with concrete, which would fully automate the building process. Upcoming experiments using meshes and more complex reinforcement structures will investigate the opportunities of the SC3DP to produce viable real scale structures.

Going along with these experiments, the integration of a closed control loop is prepared. This will push the method ahead by getting more control of the spraying process and the sprayed structures.

Strongly connected to the process is the used material. Just as with other additive manufacturing strategies, a high-performance concrete material, which meets the requirements, must be developed for this process. This is currently carried out at the Inst. of Building Materials, Concrete Construction and Fire protection (IBMB) of the TU Braunschweig in cooperation with the ITE. The objective is to create an adjustable concrete that can be adapted to the printing process in terms of rheology, mechanical properties and hardening [9].

In the future, the possibility of combining these two methods, described in this paper, will also be explored. This means that the concrete can be sprayed onto a single-face wax formwork and thus be graduated over its thickness. It would be possible to integrate reinforcement, other components or to leave out areas and have a precise and free-from single-side surface.

To produce load-bearing components for the use on construction sites it is necessary to implement reinforcement on an affordable level. This will be one of the next challenges for the 3D printing techniques. Using the DBFL, the ITE has the opportunity to address these challenges and enhance digital fabrication.

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Proposal for a discipline-specific open exchange framework

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Abstract –

Several data exchange standards support the open exchange of building data. Industry Foundation Classes (IFC) standard is the most widely implemented within software solutions and the most used in practice. This standard is developed by buildingSMART International and describes a schema defined with EXPRESS data modelling language also including the data validation rules.

Because of its richness and redundancy, inadequate support of specific disciplines, but also its variable application within software solutions, open data exchange has not achieved a satisfying level of reliability. To transfer building data, actors that exchange information turn to various alternative data exchange possibilities like other open exchange formats, software specific data exchange software solutions, and workarounds.

This paper aims at analysing the problem of data exchange among disciplines with varying exchange requirements. Depending on the discipline and its specific requirements, data exchange potentials with IFC differ largely. Overcoming the interoperability problems are often discipline-specific: providing new schemas, incorporating strict workflows (for native and receiving application), or using 2D drawing - based exchange, physically or digitally.

In this paper, two workflows that follow BIM modelling process are examined. The first step in both workflows is the creation of architectural BIM model. Consequently, two data transfers are considered: to structural analysis and to life cycle analysis (LCA) software tools. The actors' exchange requirements are identified, as well as their description through the data flow.

Thereby, the adequacy of a predefined set of exchange requirements in the construction industry is assessed. Results show that IFC schema, or any other schema defined in the same way, is not an optimal answer to the end user needs. An improved open exchange based framework is proposed with a data management concept that supports it. Finally, the implementation of the new concept aims to enhance the technological development of open standards and draw it towards the seamless exchange.

Keywords –

BIM; Data Exchange; Data Interpretation; Exchange Requirements; IFC schema; Structural Analysis; Life Cycle Analysis

1 Introduction

1.1 Current Modelling Framework

Construction industry practices differ worldwide. The role of an architect in Europe frequently overlaps or overtakes project manager roles, especially in small offices. An architect is the first actor in the planning process that defines geometrical and non-geometrical data of the object to be built. In BIM workflow, architect models a building using 3D objects representing the digital versions of building elements. These objects can be defined either within an architectural BIM modelling software or taken from the external sources. Besides that, architect produces drawings as planning documentation and provides other actors with the necessary information about building elements for further design, analysis, calculation, validation by authorities, etc.

Created geometric and non-geometric data is required by the other actors in the process, belonging to both design and non-design disciplines. The exchange processes in most cases are still performed using paper documents or 2D digital drawings. BIM workflow aims to change that. Open BIM initiative from software producers and buildingSMART [1] suggests the use of the same information by different disciplines. This workflow neglects the need for standardization of integrated model interpretation for different construction industry domains. However, exchange using the open exchange format is still the most promising way of exchanging information in the industry with numerous actors and disciplines involved, where each takes part in the planning process with their specific requirements.

1.2 IFC Open Exchange

Several standards define the open exchange. One of them is the IFC schema standard that specifies a building data model to be used for the data exchange. IFC schema describes the integrated building model representing some disciplines in the industry. The first actor providing data for an integrated model is most often an architect. Other actors who are part of the planning process use data that architects provide, and in the follow up enrich and change it. They contribute by introducing the new and modified information to the integrated model. Differences that exist in the disciplines are managed by different subschemas called Model View Definition (MVD). The latest version of IFC schema is IFC4. It includes two MVDs - Reference View and Design Transfer View. Software solution certification is only provided for Reference View. This MVD tends to provide the IFC building data model as a reference only [2]. It is not supposed to be used for further data editing. For Design Transfer View, that exists since July 2015 and should serve for further editing of the building model, the certification is still not launched. On the list of certified software solutions [3], there are currently no tools certified with IFC4 MVDs. Because of the inexistent formal practical implementation, a widely used IFC2x3 schema will be tested in this proposal. Software solutions that implement IFC 2x3 are officially certified only for MVD Coordination View version 2.0 (CV V2.0). CV V2.0 is used for three different disciplines: architecture, structural analysis, and building services. In this open exchange workflow, these three disciplines use the same subschema. However, implementation of MVD differs greatly between the software solutions. If open exchange workflow with IFC schema is used, all the involved construction industry disciplines must conform to the same schema and use specific parts of it with MVDs (Figure 1).

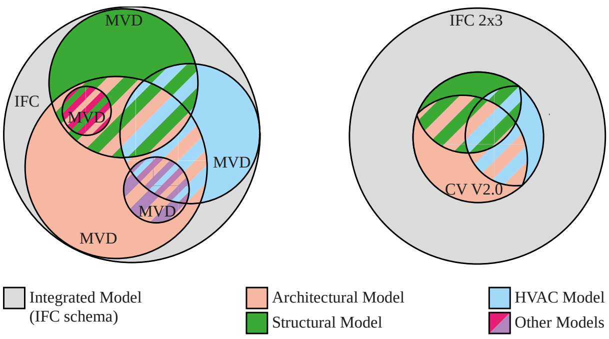

Figure 1 Concept of open data exchange with IFC schema and IFC2x3 with MVD CV V2.0

1.3 Asset Hierarchy

There is a strict asset hierarchy between geospatial industry, construction industry, and manufacturing industry. While the geospatial industry deals with the elements on the environmental scale and uses geographic information system (GIS) for its needs, manufacturing industry is on the product (or component) scale and uses product lifecycle management (PLM), construction industry deals with the products on the building scale [4]. There is an overlapping between the assets where GIS is interested in the data of a built facility as well as where the construction industry is interested in the components. Construction industry assets using BIM are represented through the IFC schema that defines the digital representation of building elements. However, the assets in the construction industry are getting evermore present within the other two industries. Architectural BIM software is mostly able to create product models as well (*.rvf files for Revit, *.gsm for Archicad or *.nmk for Allplan) and in that way, they are becoming part of the architectural model. Despite the fact that the product manufacturers are also interested in providing the digital content describing their product, its use within BIM workflow seems to be a gap in knowledge [5]. This field also lacks standards that relate it to open exchange. For instance, comparing to *.gsm and *.rvf files respectively, there are only 32% and 10% of digital objects provided in *.ifc format on one of the biggest online libraries for digital objects [6]. It is clear that product models are still generally exchanged with native software solution formats. These digital products are mainly developed to be used with software solutions in the construction industry. The new version of IFC5 [7] defines infrastructure elements which bring the schema closer to GIS. In other words, in the future, it will share more assets with geospatial industry. The schema provided by buildingSMART is in that way increasing its complexity and size, while the currently implemented MVD version is not sufficiently supported by software developers to achieve seamless exchange for most of the construction disciplines.

2 Background

2.1 STEP

Aspiration for standardisation of data for exchange purposes is present in all industries using digital models. STEP (Standard for the Exchange of Product Model Data) initially aimed to unify different national industry standards. It is widely implemented in the manufacturing industry, and it is the biggest standard of all ISO standards. It defines the way to exchange digital information about a product. Instead of defining an integrated model, its definition started by defining several part models called Application Protocols (APs) [8]. AP 225 called “Building elements using explicit shape representation” was a starting point for defining an IFC schema.

What construction industry lacks comparing to other industries is inter-firm adaptations. The construction industry represents loosely coupled system where every product is unique. For those reasons it is difficult, or maybe even inadequate to implement principles from other industries in the construction industry [9].

Actors involved in the planning process perform different actions that involve using different models of the same real-world product. Processes are complex and independent for each building in particular. Models of different domains differ from each other, where not only different data scope is used, but it also needs to be interpreted for a specific use (Figure 2).

If compared with the STEP standard, the whole range of disciplines that are used in the construction industry is reduced to a single Application Protocol that is later accepted as a starting point for the IFC standard. However, the construction industry with all its domains more resembles the STEP standard itself with multiple APs.

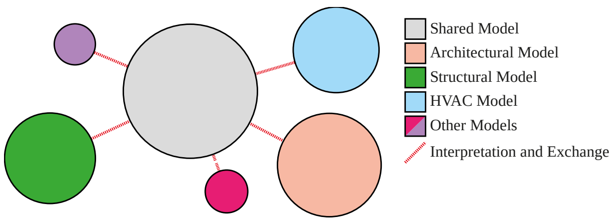

Figure 2 Concept of data exchange with domain specific models

2.2 Other work regarding structure

Two ISO standards are a base for the structure of building data model. Those are ISO 12006 "Building construction – an organization of information about construction works" Part 2 "Framework for classification" [10] and Part 3 "Framework for object-oriented information" [11]. IFC schema is based on 12006-3 addressing it as International Framework for Dictionaries (IFD). ISO 12006-2 is developed to standardise different national classification standards in construction and does not contain geometry information. Differences between IFC and 12006-2 are explained in [12]. IFC documentation does not state where the structure or model classes originate from.

Several works already described the necessity to expand the IFC schema to be able to support for instance structural analysis [13] or energy simulation [14]. buidlingSMART plans to involve several new disciplines in the future IFC editions [15]. The original plan is to create a steadily growing model that will eventually support all the involved disciplines. IFC2x3 covers eight domains including architecture and structural analysis. However, many problems are detected also in the domains supported by the schema [16]. A file-based data exchange is not a solution that has potential in the future [17]. Research by Lee et al. [18] states that schematic design is not enough for all the information needed for cost estimation. A necessity to bring the IFC schemas to an ontological level [19] describes transforming the IFC schema to ifcOWL, a terminology box definition using Web Ontology Language (OWL). For that reason, they propose to use semantic technology, where the IFC building data model is converted to RDF data.

The modularization of the ifcOWL ontology is suggested by Pauwels et al. [20] with the aim to use only the filtered model data. For that purpose, the particular modules need to be defined or the existing ones significantly redefined. Cost Estimation (CE) and Quantity Takeoff (QTO) framework by Aram et al. [21] suggests a knowledge-based system for using implicit besides explicit information in these two disciplines. Venugopal et al. [22] describe general schema structure reconsideration with MVD concepts to achieve a working modular exchange framework. The importing software needs to interpret the geometry and associate the meaning to the native objects for every discipline except simple geometry clash check. The mentioned research shows that the problems with the existing schema are detected in many disciplines. The focus is set on reaching the integrated model that will satisfy the requirements of more actors than the current open schema. On the other hand, the size of the current schema is also recognized as a problem, where data needs to be extracted, modularised and interpreted for specific applications.

3 Methodology

In this work, data transfers from architectural model to structural analysis and LCA using open exchange are reviewed. They both require specific geometric and non-geometric information about the building that is provided by the architect. Two workflows are depicted in Figure 3. The IFC data is considered for import into domain-specific software solutions. IFC2x3 with MVD CV V2.0 is used because of the lack of support for IFC4 in software tools, and because the certification of Design Transfer View MVD is still not taking place.

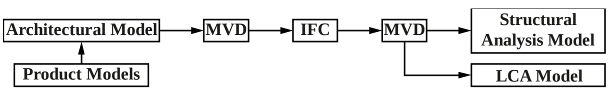

Figure 3 Two workflows considered in the study

Import exchange requirements are defined for each of the disciplines. These requirements are predefined with MVD concept list in the case of an open exchange. A simple case study model of door and wall is modelled in the architectural software [23]. Based on the previous research [16] [24], exports from the software solutions were generally using valid concepts of MVD, and therefore the exported model is considered valid.

Exchange requirements for two different imports that can be transferred from the native model to the exported model are identified and presented in Table 1. The structure of exchange requirements presented in the table is described from the end-user conception.

Table 1 Exchange requirements in the analysed case study model (SA = Structural Analysis)

Exchange Requirements			SA	LCA
wall	layer1	geometry	✓	✓
		material	✓	✓
		Load bearing	✓	×
	layer2	geometry	×	✓
		material	×	✓
		Load bearing	✓	×
door	handle		×	×
	panel	geometry	×	✓
		material	×	✓
	frame	geometry	×	✓
		material	×	✓
void		geometry	✓	×

The required data is allocated to the exported building data model and the structure of the export is analysed. Some special cases require additional information, but they are not considered in this work. The main aim is to describe various differences in exchange requirements, and how heterogeneity of disciplines and used software solutions require different ways of data exchange since it cannot be achieved with the current state of open exchange and MVD.

The presented case study questions if using an open exchange workflow with a predefined integrated schema answers the needs of actors in the construction industry. An open exchange framework allowing inclusion of more actors in the planning processes and bringing the digital building model closer to the real product is defined. With the results obtained from the case study and the related detected flaws, a new data managing structure is defined supporting the proposed framework.

4 Results

4.1 Geometrical Data

In this example (Figure 4) a wall consists of two layers, where one is load bearing. In IFC building data model it is represented as an entity IfcWallStandardCase. Its geometry definition is contained within the entity IfcProductDefinitionShape, where two different IfcShapeRepresentation entities are defined. First one is ‘Axis’ ‘Curve2D’ representation that is used for aligning material layer sets. Second is the ‘Body’ ‘Model’ representing the wall as a single homogeneous geometry, and not as a combination of two layers. Layer geometries are not specified separately. For structural analysis only the layer with load-bearing properties is relevant. That layer needs to be interpreted as a 2D element (with its axis and height). A common interpretation where a wall axis is placed in the central plane of the entire wall geometry creates an incorrect structural analysis element in this case.

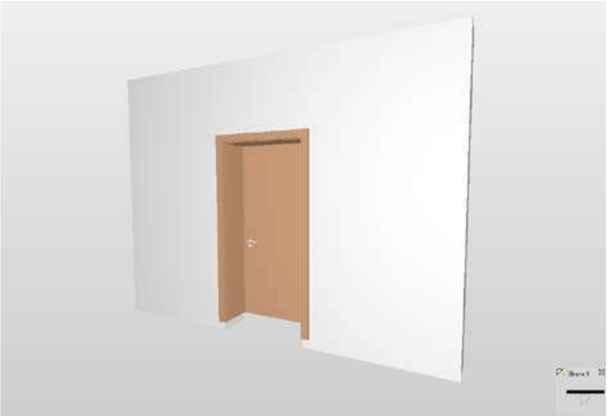

Figure 4 Screenshot from a viewer [25] of the

A door is represented by IfcDoor entity in IFC schema. There are two IfcShapeRepresentation that define its geometrical properties. This is ‘FootPrint’ ‘MappedRepresentation’ that defines an element representation in a 2D drawing, and ‘Body’ ‘MappedRepresentation’. Within the second one, geometry is represented using a boundary representation (‘Brep’) including all its parts. That means that a door handle, a door frame, and a door panel are creating a single geometry even though they are conceptually separate elements. For structural analysis the door does not represent an important element, only the void it creates in the wall. For LCA, a door panel and a door frame geometries are required. From these two geometries, the total width and height of the door information need to be extracted. In the IFC schema, the door total height and width are defined as attributes specific to the IfcDoor entity. In that way, it is easy to extract this information for LCA from individually defined attributes and not from its geometry, which makes redundant data.

The void is defined as IfcOpeningElement and its geometry is defined as ‘Body’ ‘SweptSolid’. It clearly specifies the cubic element that creates an opening in the wall.

Parameters that exist within the native model are generally lost during the mapping. This means that an ‘intelligent’ digital building model from the native software solution becomes a 'dumb' model [26]. For that reason, it is hard to interpret the future editing possibilities and constraints in the receiving applications. The details concerning the shape modelling aspects of the IFC models are not part of this work.

4.2 Non-geometrical Data

Non-geometrical data describing building element models, or attributes that represent them are mapped in three ways. They are declared as direct, inverse or derived attributes. In the study, all the analysed attributes are either direct or inverse ones. Direct attributes are attached to the model of interest, while the inverse ones are assigned through a relationship.

The structural analysis model requires the information about load-bearing properties for specific layers of the wall. The importing software tool only needs the load-bearing layers and to place the axis plane in the correct way. In the architectural software solution, the load-bearing properties of the layers are defined by an architect. In the IFC model, this is an inverse attribute defined through IfcRelDefinesByProperties. Property 'LoadBearing' is defined, but only for the wall as an entity, not for the specific layers within it. This property is not standardised and therefore not understandable by other software applications. Even if the load-bearing property can be successfully interpreted by an importing application, the specific layer cannot be extracted from the element. Another attribute necessary for proper interpretation is the information about the material. Materials are required by many disciplines and in this case both by LCA and structural analysis. For LCA materials of all layers are required. For structural analysis, it is necessary to import only the load bearing material information. Through IfcRelAssociateMaterial, IfcMaterialLayerSetUsage, and IfcMaterialLayerSet, materials are assigned to the wall. IfcMaterialLayer contains information about the layer thickness that could be used to extract information about the volume of a specific layer even if its geometry is not separately specified.

Data from the object IfcDoor is not required for structural analysis. For LCA calculation, it is necessary to have the total area of the door (including the frame) and materials of the door panel and the frame [27]. Materials are assigned with the relation IfcRel-AssociatesMaterial and IfcMaterialList to the door. There are three materials assigned to the whole element but without the details which specific parts of the geometry they describe. However, through IfcStyledItem, the geometry elements like the door panel, the handle, and the frame have different visual representation in IFC imports. These representations are defined using the inverse relations for geometry elements because objects like the door frame or the panel are not separately defined.

Most of the non-geometrical attributes are not standardised. In this case study, materials are mapped with the same names as in the native software solution. In the schema, there are some attempts to standardise attributes as IfcThermalTransmittanceMeasure, but that is not the case for any of the examined exchange requirements. In that way, the properties end up being machine unreadable and not relevant for future applications.

4.3 Data structure

The IFC schema structure, defined with the EXPRESS schema definition language, is rich and redundant. Attributes that can be optional or mandatory are inherited from the 'Supertype' of the entity or defined within it. In that way, entities are connected with the other types of entities. They can have simple or complex entities as attributes. That multiplies the possible definitions of the object. There are 812 optional and 625 mandatory attributes within IFC 2x3 schema. The mandatory attributes are often left as empty strings and not defined in the IFC building data model. Besides the hierarchically clear concepts, there are inverse relations that define inverse attributes. They act like containers of specific entities. This number of interrelated entities results with an extremely rich schema, which on the other side does not satisfy the needs of many actors involved in the industry. A simplified part of the case study model with the analysed exchange requirements is illustrated in Figure 5.

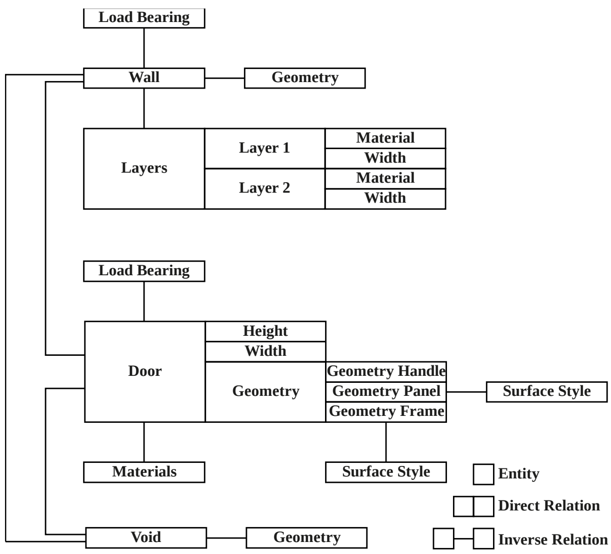

Figure 5 A simplified representation of the analysed case study building data model

A void element is connected to IfcWallStandardType with IfcRelVoidsElement which makes an opening in the wall and IfcRelFillsElement to IfcDoor that places the door in the opening element. The door and the wall are connected with IfcRelContainedInSpatialStructure to IfcBuildingStorey. For IfcDoor there are 7 different property sets connected with IfcRelDefinesByProperties, and 6 for IfcWall. Besides that, there are also IfcRelDefinesByType relations for defining IfcWallType and IfcDoorType for wall and door respectively. In total, for the door 45 IfcPropertySingleValue entities are defined, and for the wall 52, of which the majority is not standardised, machine-readable or required by the other software solutions.

5 Discussion

The intentions to use a single schema for a shared model in construction industry has not met user expectations yet. The history of IFC reaches back to 1994, but its main goal, achieving interoperability across the industry is still not achieved. In this paper, this schema is thoroughly analysed. The problems commonly occur due to three reasons: schema elements do not adequately represent the end user conceptions, some disciplines involved in the planning process and their requirements are not considered, and the schema implementation in software solutions is not trustworthy. To address these issues, a new concept for a schema is proposed followed by a framework that could result with an integrated building data schema definition.

A problem found in the case study is the lack of real-world object definitions that are required by the actors in the process. In the conducted analysis that problem is clearly presented with the door elements and wall layers. Upon the examined exchange requirements we propose a new structure from the end user perspective (Figure 6). The main property of the structure is to separate geometrical and non-geometrical data. Problems occurring within the geometry mapping are generally the problems of using different geometry kernels from the different software solution. The non-geometrical properties of objects belong rather to the standardisation category. Another advantage of this concept is that the end users can easily understand its structure. Thereby these two types of properties should be separated in the building data model (Figure 7).

The integrated data building model needs to support all the data exchanged in the planning process. The framework suggested in STEP standards, with different APs that would eventually form an integrated model, could deliver a functioning integrated schema. Due to numerous optional attributes that are left for users to define, the software solutions are already not able to follow with the support of the schema. Introducing new attributes and more possibilities to define the elements are not going to simplify its implementation and improve the interoperability without greater efforts by software developers. Mandatory attributes describing an entity are not necessarily a requirement for each discipline in practice. The planning processes differ between the countries and can be project-specific. Therefore the exact data exchange scenarios cannot always be predefined.

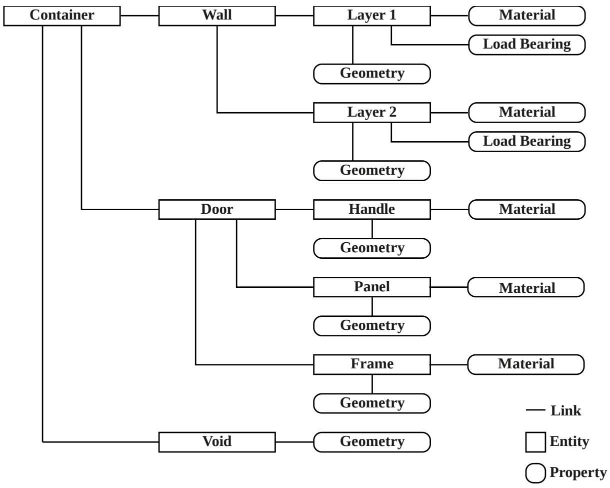

Figure 6 Schema proposal for easier implementation and validation

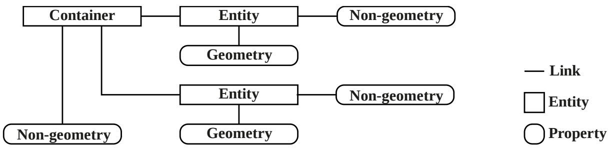

Figure 7 Basic part of the proposed structure

The attributes describing an object need to be defined as discipline-specific requirements, sometimes even software-specific requirements. Only after they are clearly stated, the schema definition can take place for the specific discipline. The limited integrated schema that cannot cover all the disciplines does not provide an answer. An integrated model can only exist with all the necessary requirements of every actor being supported. It can result from the coordinated unification of discipline-specific requirements across the industry. Following this concept, a base for an integrated schema would be a result of the specific disciplines' exchange requirements intersection. In this way, an extensive single schema is not avoided, but its definition is focused on the data exchange.

Implementation of the schema within software solutions, and especially software solution certification, is another obstacle for data exchange. This problem is extensively described in [24]. The idea of having different MVDs is still not implemented in practice since there is only one certified MVD used for data transfer between different disciplines (building service, structural planning, and architecture) that supports further planning tasks. Certification process of buildingSMART defines one concept list for import exchange requirements of all three disciplines. Software solutions certified without being able to support all the specified exchange requirements do not satisfy end-user expectations in practice. In order to achieve that, MVDs and the belonging concept lists need to reflect the discipline or software solution requirements.

When an integrated schema is defined as a product of discipline-specific schemas, a software solution does not need to support the integrated schema as a whole, or a single MVD, which is currently the case. Software solutions can in this way be tested for a specific purpose. Tools that are currently BIM capable would be BIM capable of a specific discipline, or more of them. It would be possible to measure which amount of relevant data a software solution is able to use based on the clearly defined end-user requirements. This concept can serve as a base for a metrics system for a discipline-specific certification process. The competitiveness of the software developers regarding the implementation of open exchange schema could improve the quality of its implementation. Defining a general metrics system and a certification that would provide end users with credible interoperability information can speed up a process of its implementation.

The analysis in this work is limited to three mentioned disciplines and a simple case study model. Analysis of a bigger example and its application in additional disciplines would surely address more issues regarding the schema. However, even this simple model demonstrates many problems that exist within an integrated schema currently used for open exchange. A more complex case study is avoided so the results could be presented as clearly as possible. Only one-way data exchange is considered.

The proposed structure concept is based on the end user conception of examined elements. The complete schema using the proposed structure would drastically increase in complexity, but comparing to the existing schema it would create a significant simplification of the integrated model. A software solution can only be certified for a domain specific or federative parts of an integrated schema, since there are no software solutions used for all the involved disciplines. The integrated model should support all actors involved in the process, without limitations and workarounds. Since there is a long way to achieve it, the focus can be set on the unification of federated models where the integrated model would be flexible enough and allow new concepts to become part of it. Its structure must, however, be clearly defined and validated. Another aspect of open exchange that needs to be standardised are interpretations for a specific domain and object properties. The uncertainties that occur during the mapping to the receiving application are one more thing that keeps the end users from using the schema. The same approach of filtering and interpretation must be applied in the other direction, federative or domain model to the integrated model. The future work regarding this topic is going to focus on the detailed structure development with a proof of concept to follow.

6 Conclusion

An integrated schema as a data managing concept in the construction industry was not able to provide satisfying results for many disciplines in the planning process. Processes like data filtering and interpretation are neglected in the general framework with the current IFC schema-based data exchange. Some disciplines can make use of the existing model only by filtering the information. However, the majority of actors involved find it easier not to use open exchange and to use other schemas, strict workflows that often include various workarounds and non-intuitive practices, and 2D drawing based exchange. Mapping processes are not standardised and clearly defined whereas many decisions are left to software producers. Viewers that are specifically made for the IFC schema are the most compliant with the integrated model. To solve the interoperability problems, schema has to cover the needs of all the software solutions involved in the exchange, and thereby consider all exchange requirements. Until then, all the disciplines that are not considered will turn to other options.

The required flexibility among the disciplines in the construction industry is not supported within the current open exchange schema. The taxonomy model defining exchange requirements could be a good start for the integrated schema. However, the schema that is limited does not satisfy the needs of the industry. The integrated schema must be complete and support all the product and project data from all the involved disciplines. For software solutions implementation, the focus needs to be set on filtering and interpretation processes. They need to support clearly defined subschemas similar to MVDs that are the answers for real end-user needs. Discipline-specific subschemas that represent exchange requirements are the key to achieving a working data exchange. The integrated schema unifying the discipline-specific requirements can offer answer to the interoperability problems in the construction industry.

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Modeling of Identifying Mediator Effects between Project Delivery Systems and Cost Performance

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Abstract–

This paper addresses the problem of explaining the reason for mixed assessment results in comparing cost performance of project delivery systems (PDS). In particular, we focus on mediator effects for the explanation that would traditionally not be handled by project performance evaluation disciplines. Previous studies revealed that two kinds of disciplines deal with change orders from different points of view. Evaluating PDS by project owners uses change order as a cost performance metric, whereas contractors consider it as a method to increase project cost for their own profit. A Path Analysis model was established by integrating these viewpoints to explain the discrepancy in assessment of PDS. It describes the process how PDS impact on change orders. For the path model, 234 public sector projects completed between 1998 and 2013 in Korea were collected and analyzed. The dataset consists of both Design-Build and Design-Bid-Build projects which are the most prevalent delivery systems. While examining the total effect of PDS on cost performance using the path analysis, mediator effects were significant in building construction project type. This study fills the gap between the successful performance result and the failed adoption of PDS using causal relationship as explanation. The intervention of procurement methods between PDS and their cost performance may provide the clue that project decision makers should consider mediator effects and project characteristics when they select and assess PDS.

Keywords–

Cost Management; Change Order; Cost Performance; Project Delivery System; Design-Build; Design-Bid-Build; Mediator Effect; Path Analysis

1 Introduction

1.1 Background

When project owners decide on a project delivery system (PDS) that will carry out their project within budget, it is important to consider related project and bidding characteristics. From the point of view of the project owner, the cost performance assessment of PDS is as important as the type of PDS used, because an inappropriate selection of PDS based on mistaken assessments may lead to considerable cost overruns and cause confusion throughout the project.

In order to assess PDS, most research compares the two prevalent methods, Design-Build (DB) and Design-Bid-Build (DBB) [1-5]. Research in this area mostly shows that the cost performance of the DB system is regarded as better than the DBB system [1-3, 6]. However, some studies have displayed negative results for the performance of DB against that of DBB depending on project characteristics and different datasets [4, 5, 7, 8]. These inconsistent results could stem from different measurement according to point of view. To measure the cost performance of PDS, various performance metrics such as unit cost, cost growth, intensity (cost/time) are used [1]. The cost growth from contract amount to completion amount is widely used as the cost performance metric. It mostly adopts change order as its operational definition of measurement index by owner's viewpoint [9-12] (Detailed explanation is provided in Section 2.3).

On the other hand, some studies consider change order as a method to preserve or increase contractor's profit during the construction phase [13]. Construction projects where there are significant differences between the selected bid price and the pre-bid estimate of the owner (hereinafter referred to as "bid to estimate ratio") have higher change orders [14-17]. Bid to estimate ratio and change orders are often influenced by the number of bidders depending on PDS in bidding stage [9, 10, 13, 18]. When the number of bidders is large, bid to estimate ratio is lower than a smaller number of bidders due to excessive competition. DB has usually small number of bidders than that of DBB, which can easily increase bid price. That is, DBB has lower bid price than DB, and in case that the bid to estimate ratio of DBB is significant lower than average, the contractors often try to increase change order during construction phase to preserve their profit. These bidding characteristics from contractors' viewpoint, bid to estimate ratio, and the number of bidders affect change orders during the construction phase. Those situations yield that DBB has generally higher change orders than DB. Higher change orders is welcomed by the contractor's viewpoint in those cases. However, from owner's point of view, fewer change order is known as superior in terms of assessment of PDS. From the point of view between owner and contractor, there two types of conflicting studies coexist for the purposes of using change orders.

Consequently, change orders should be understood with two different perspectives between owner and contractor (Figure 1). Owners use change orders to measure project cost performance, while contractors often consider it as a method to increase project cost for their own profit.

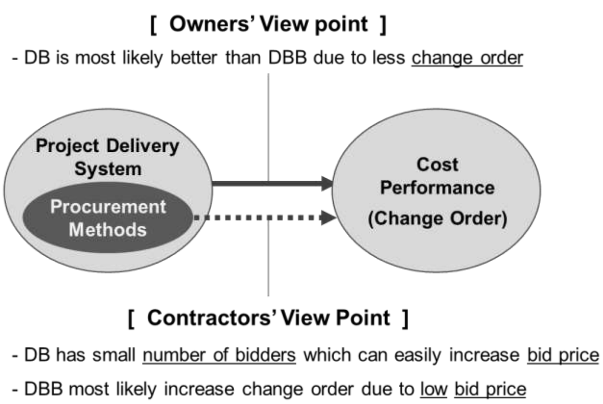

Figure1. Different perspectives between owner and contractor on change order

1.2 Problem Statements

As Figure 1 shows, this issue may lead to debates on cost performance between DB and DBB. Numerous studies have been conducted on each of these topics. However, the methodologies of both studies are limited to correlation or regression models, which can only analyze the dependent relationships of PDS, bid characteristics and change orders, respectively. Because, those methods analyze only direct effects between independent and dependent variables (Figure 2).

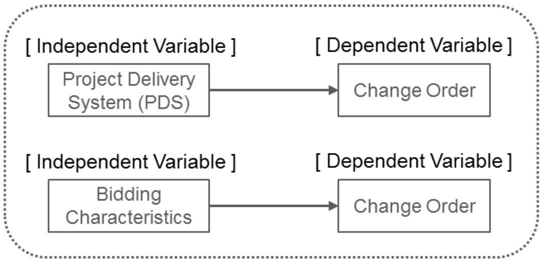

Figure 2. Different viewpoints of studies and their direct relationships

If other factors intervene between independent and dependent variables, they would act as mediator, which means indirect effects occur. Therefore, another method is needed to compare the size of the effects and to identify stronger factors that impact on change orders. To deal with this problem statement, we need to build a single model that combines the different purposes of both the owner's and contractor's viewpoints as influential factors (independent variables). Figure 3 shows the combined model, adopted a Path Analysis method.

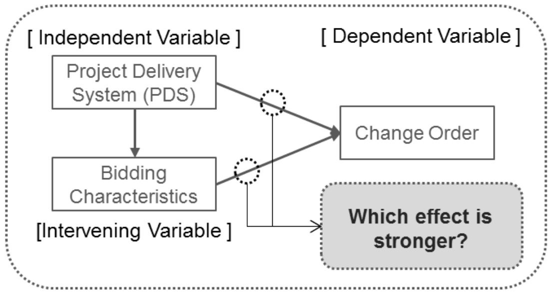

Figure 3. Integrated model of different view points

1.3 Adoption of Path Analysis Method

To deal with the aforementioned problem statements, we adopted a Path Analysis method. It performs causal analysis using a theoretically grounded model and covariance (or correlation) matrix. Compared to system dynamics models, it examines a hypothetical test using empirical data, while system dynamics build a more theoretical model that has difficulty validating the model. Path analysis makes it possible to identify both direct and indirect effects that are otherwise difficult to detect in multiple regression analysis. Path Analysis is a technique that can analyze not only the influence relationship between independent and dependent variables but also the influence relationship between independent variables at the same time [19, 20].

Let us compare path analysis models with multiple regression models. For instance, we can analyze the multiple regression model Y ~ X1 + X2. The regression coefficients are interpreted as how much Y would increase when we increase X1 by 1 and fix X2 at constant value. However, this assumption could be counterfactual if X1 has a causative influence on X2. If X1 increases X2 and X2 increases Y in succession, the regression coefficients of X1 underestimate the causal influence of X1 on Y. Path analysis incorporates the causal influence of X1 on X2 and successfully estimates the causal influence of X1 on Y.

In this paper, the Path Analysis model integrates the factors attributed to the two stakeholders. There is an influential relationship between PDS and bidding characteristics. Both are independent variables that affect change orders in a multiple regression model. The model will identify the relationships and estimate the effect of PDS on cost growth from change orders.

It combines the theory and the data to estimate the causal effects of variables. For the theory, we built a theoretical model through research hypothesis and literature survey, then the path model and real world data were combined and examined.

1.4 Research Objectives and Hypothesis

The objective of this study is to build a Path Analysis model that identifies mediator effects and describe the process of the causal relationship between PDS and cost performance. A database of 234 public sector construction projects completed between 1998~2013 in South Korea was examined for the path model. This study made an effort to explain the cost performance of PDS by illustrating the process of the contractor's impact on change orders by considering the different viewpoints of owners and contractors.

The research hypothesis is that the contractor's intention impacts on change orders that are measured for the cost performance of PDS by owners (Figure 4).

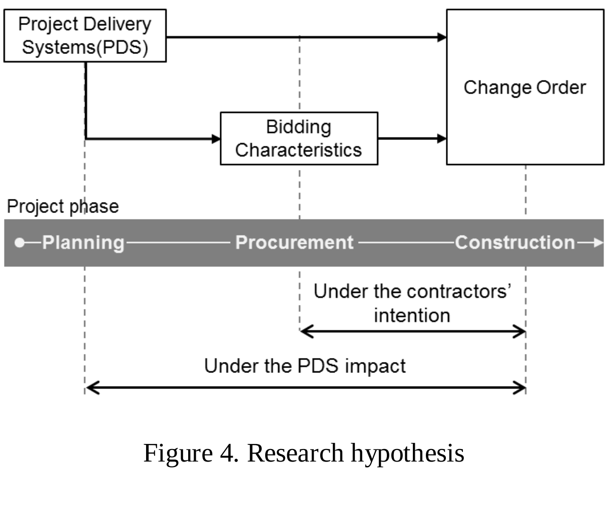

Figure 4. Research hypothesis

The intention will be identified as the mediator effect working between PDS and cost performance.

2 Methods

As described in section 1.3, we built a theoretical model. The data collected was analyzed to establish suitable Path Analysis models and the model that was supported by the data was examined.

2.1 Building a Theoretical Model

Moon [12] studied a mediator effect of bid price to estimate the ratio between PDS and change orders. However, more features can be uncovered and categorized as bidding characteristics that may be part of the contractor's intention. We examined the previous studies on which variables affect the change orders and hypothesized processes regarding how these variables affect the outcome (Figure 5).

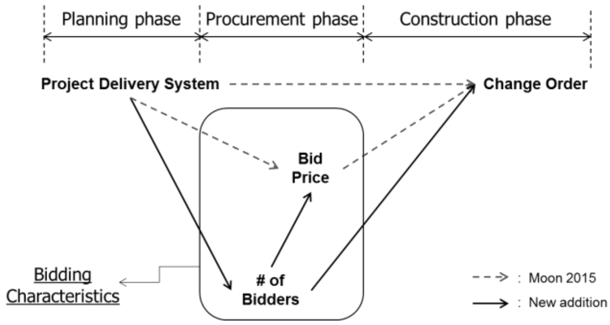

Figure 5. Theoretical path model

2.2 Data Collection and Analysis

This study utilized a database of 234 public sector projects that were completed in South Korea between 1998~2013. Each project awarded by the city of Seoul cost more than five million dollars. Nine project types were constructed and categorized to four types: civil, building, facilities, and landscaping. The sample size of DB and DBB projects are similarly distributed where DB is 97 samples (41.5%) and DBB accounts for 137 samples (58.5%). Figure 6 shows the sample size of each PDS according to project type. Building projects and civil projects were selected for the analysis as each project type has a similar distribution as well as sufficient number of samples for both DB and DBB. In addition, according to reports by the city of Seoul authorities, excessive change orders due to governmental policy and social conditions in four projects were assumed to be outliers and these were removed from the dataset.

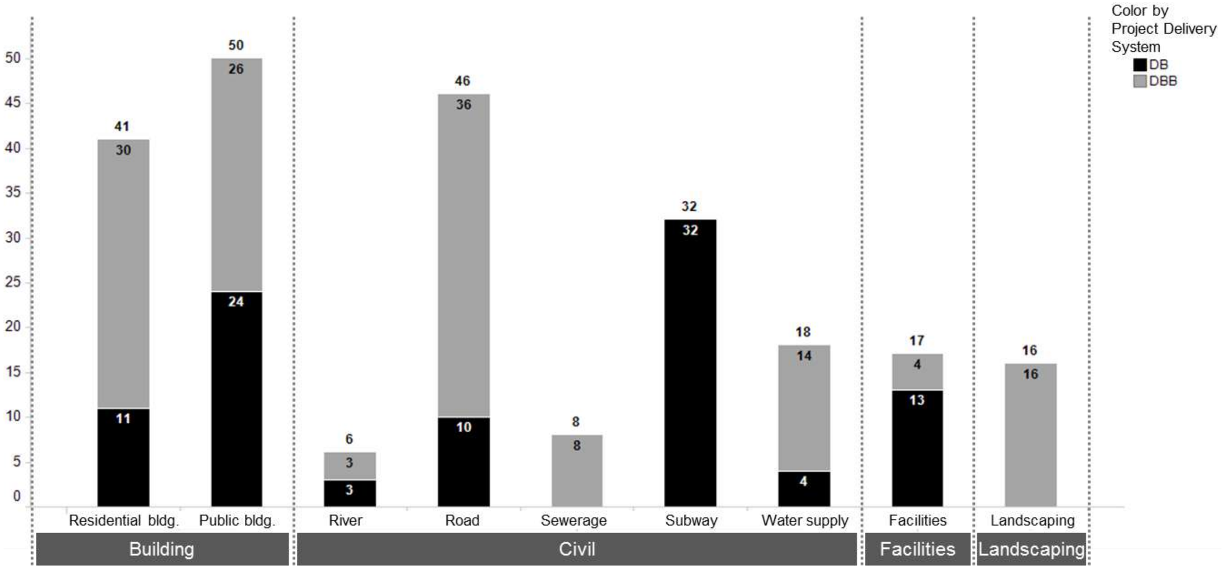

Figure 6. Sample size and project type

2.3 Cost Performance Metric

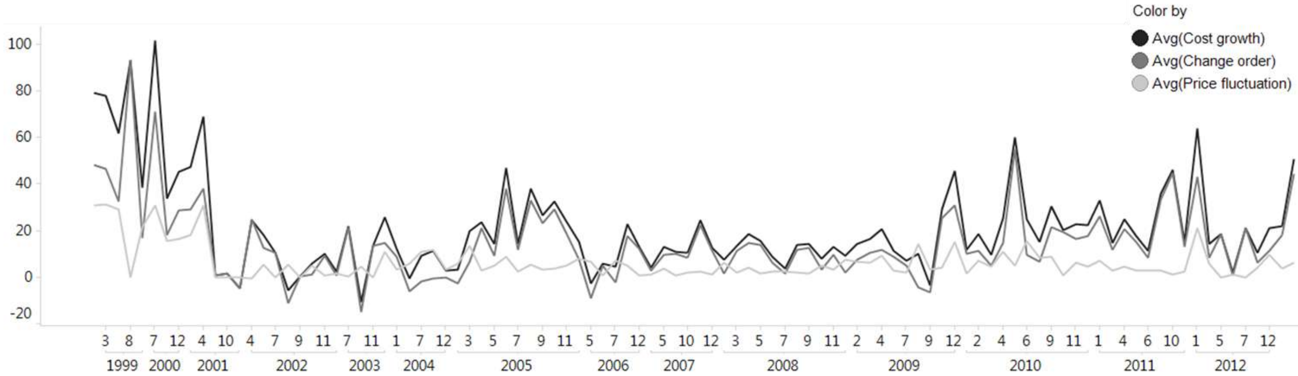

Figure 7. Change order as a cost performance metric

To address cost performance metrics, we analyzed the dataset. A line chart of cost growth rate was projected according to the actual date of project completions. Cost growth rate of the dataset consists of escalation (price fluctuation) and change order rate. Figure 7 shows that both cost growth and change order rates have similar rise and fall curves, but the price fluctuation rate is projected far from the both lines. The cost performance is dominated by change order rather than price fluctuation in the case of the present dataset. Finally, we adopted change order rate as the cost performance metric based on the metrics included in the previous studies [9-12] and data analysis. As operational definition, change order is represented in percentages by comparing the final construction costs which is subtracted fluctuation price to the initial contract cost.

2.4 Path Analysis Model

Unlike independent multiple regressions, path analysis simultaneously estimates the parameters and can estimate the indirect effects (mediator effects) of certain variables. Based on the theoretical model, we postulated the process model of how PDS affects the change order. Figure 8 shows two proposed path models. In the first (Figure 8(a)), PDS has a direct effect on change order and indirect effects through the number of bidders and bid price. In Figure 8(b), PDS has direct and indirect effects on change order, but the indirect effects have different paths. We assumed the number of bidders cannot have direct effects on change order but it has an indirect effect through the bid price. Some studies examined the effect of the number of bidders on change orders [10, 18]. However, we provide statistical evidence that these can be explained via the causal effect model.

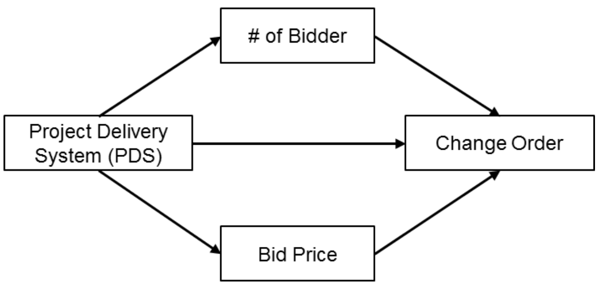

Figure 8(a). The path model-1

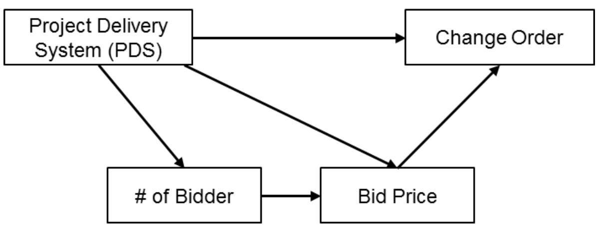

Figure 8(b). The path model-2

We analyzed the data using model described above and used multi-group analysis to incorporate the fact that the process of determining the change order might be different according to project type. We used Full Information Maximum Likelihood (FIML) to utilize the missing data fully. FIML is recommended by several methodologists since it is unbiased even when the missing mechanism is Missing at Random (MAR) rather than Missing Completely at Random (MCAR) [21, 22].

3 Results and Discussion

First of all, we examined the fit of both models to see how probable it is that the proposed models were true. It is advisable to check the fitness of a model before interpreting any coefficients from it [19, 20]. Since the proposed models are only one parameter short of being a saturated model per group, we used the chi-square test to see if the coefficient can be assumed to be 0. The scaled chi-square test [23] of the first model versus the saturated model resulted against the null hypothesis (chi-sq difference (df = 2) 17.56, p-value = 0.0002), meaning that the first model cannot adequately fit to the data. The scaled chi-square test of the second model resulted in a chi-squared difference of 3.4149 with a degree of freedom of 2. P-value was 0.1813 indicating that the second model has adequate fit. Therefore, we used the second model to estimate the effects of PDS.

Since we use multiple group analysis, the first thing to check was whether the coefficients were the same across the groups. We compared the multiple group model with the same coefficients between groups and the model with the different coefficients for each group. We used the chi-square test and the assumption of the same coefficients across groups that could not be justified by the data (chi-square difference = 19.513, df = 5, p-value = 0.002). We also tested if the error variance could be assumed to be the same across the group (allowing the coefficients to be the same for different group) and it was not supported (chi-square difference 46.305, df = 3, p-value = 0.000).

As a result of the aforementioned outcomes, we used models with the different coefficients and different error variance for each group. For powerful analysis, we used bootstrap method to estimate the direct and indirect effects and the standard error of these. We analyzed the data with path model-2.

The fit was adequate with chi-square p-value 0.352, RMSE 0.021(0, 00-0.20), CFI 0.99 and P-value for RMSEA being less than 0.05, 0.439 [24]. Estimated coefficients for building construction projects are in Table 2. In the building construction projects, the direct effect of PDS on change order was not significantly different from 0, but the indirect effect was found to be significant. Table 1 shows the two specific indirect effects of PDS on change order.

Table 1. Effects of PDS on change orders via different paths for building construction projects

Effect	Path	Estimate (Bootstrap confidence interval)	SE	P-value	Standardized
Specific indirect	PDS → # of bidders → bid price → change order	-0.97 (-2.13 ~ -0.12)	0.53	0.067	-0.079
Specific indirect	PDS → bid price → change order	8.65 (1.26 ~ 16.46)	3.94	0.028	0.705
Direct	PDS → change order	-2.91 (-13.93 ~ 6.49)	5.09	0.567	-0.238
Total	Sum of the above	4.76 (-0.86 ~ 10.24)	2.76	0.084	0.388

The results of Table 1 show that both of the specific indirect effects of PDS on change order are significant (Column Estimate shows the estimated coefficients and the .95 confidence interval from bootstrapping. Values in column SE and P-value are results from normal theory). But the sign of the effects is the opposite. Table 1 shows the complicated process of determining change order. Total effect of PDS on change order was insignificant but the indirect effect through the ratio of bid to estimate was significant and the estimate was quite large (8.65 with confidence interval from 1.26 to 16.46).

Table 2 shows all the estimated coefficients from the proposed model for building construction projects. In the results, PDS had significant effects on the number of bidders and bid price. Since the model is causative, we can analyze the causal relationship between variables. For instance, we can figure out what will happen when the number of bidders does not increase for PDS. The first specific indirect effect in Table 1 will be blocked and the effect will disappear so the change order will increase by 0.97 on average.

Table 2. Building construction projects

Antecedent	Consequent								
	M1(# of bidders)			M2(bid price)			Y(change orders)		
	Coefficient	SE	P-value	Coefficient	SE	P-value	Coefficient	SE	P-value
X(PDS)	70.38	13.2	0.00	-15.6	1.55	0.00	-2.91	5.09	0.57
M1(# of bidders)				0.03	0.01	0.00			
M2(bid price)							-0.55	0.26	0.03
Constant	-68.76	13.80	0.00	108.81	2.35	0.00	64.30	29.62	0.03
	R^2 = 0.191			R^2 = 0.562			R^2 = 0.119		

The model appears to be quite reasonable. In particular, the causal chain of PDS on number of bidders, the number of bidders on the ratio of bid to estimate, and the bid to estimate on the change order appears reasonable. As Hume [25] indicated, temporal priority is a necessary condition for causality.

Even though the model showed adequate fit, we could not be sure that the model is true of reality. As

Bollen [26] mentioned, researchers can only say their causal model is consistent with the data in hand and there may be other models that show adequate or better fit. For instance, causal relations can be nonlinear or there might be confounding variables in the causal relationships we hypothesized.

4 Conclusions

Based on previous studies, it is concluded that the DB system outperforms the DBB delivery system due to fewer change orders. This result is from the owner's perspectives in terms of assessment of PDS. However, according to different studies, the number of bidders and bid price during procurement phase also impact on change orders in construction phase. Change orders are often welcomed by contractors to preserve or increase their profit. These two types of research with mixed results were combined and the theoretical model that included PDS, the number of bidders, bid price, and change orders, was developed and tested statistically using Path Analysis method. In a specific project type, the mediator effects of bidding characteristics between PDS and cost performance were validated. In that case, we should not conclude that DB is superior to DBB only due to fewer changes.

This study made an effort to provide a better understanding of the mechanism of PDS impact on cost performance through intervening factors. This research is expected to help project decision makers in selecting a PDS by considering mediator effects of specific projects and bidding characteristics.

More data analysis techniques are needed to gain insight from real world data and for this data to be examined by the Path Analysis method.

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NLP and Deep Learning-based Analysis of Building Regulations to support Automated Rule Checking System

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Abstract –

This paper aims to describe a natural language processing (NLP) and deep learning-based approach for supporting automated rule checking system. Automated rule checking has been developed in various ways and enhanced the efficiency of building design review process. Converting human-readable building regulations to computer-readable format is, however, still time-consuming and error-prone due to the nature of human languages. Several domain-independent efforts have been made for NLP, and this paper focuses on how computers can be able to understand semantic meaning of building regulations to intelligently automate rule interpretation process. This paper proposes a semantic analysis process of regulatory sentences and its utilization for rule checking system. The proposed process is composed of following steps: 1) learning semantics of words and sentences, 2) utilization of semantic analysis. For semantic analysis, we use word embedding technique which converts meaning of words in numerical values. By using those values, computers can extract related words and classify the topic of sentences. The results of the semantic analysis can elaborate the interpretation with domain-specific knowledge. This paper also shows a demonstration of the proposed approach.

Keywords –

Automated rule checking; Natural language processing; Deep learning; Semantic analysis; Building information modeling (BIM)

1 Introduction

As BIM (Building information modeling) has increasingly used in architecture, engineering, construction (AEC) industry, there are many efforts to develop BIM applications to use rich building information. The role of automated rule checking has been recognized before the use of BIM [1]. As BIM provides computer interpretable building model, many researchers reported that BIM can improve efficiency and accuracy of design assessment [2]. The main components of rule checking consist of 1) rule interpretation and logical structuring, 2) building model preparation, 3) rule execution, and 4) reporting of the checking results [3]. Compared to other phases, rule interpretation task needs a lot of manual efforts. For automated rule checking, regulatory information must be expressed in an explicit format which computers can execute. Extracting and structuring required data from sentence is time-consuming and error-prone due to the vagueness of natural language. Therefore, to intelligently automate rule interpretation, computers should understand the semantics of the regulatory sentence.

Deep learning-based NLP (Natural language processing) enables the computers to learn the semantics of natural language from raw text data. Unlike conventional method, deep learning model extracts training features from raw text and adjusts the weight without human's intervention. It can alleviate the manual efforts to interpret regulation sentences which required for automated rule checking. In this regards, the objective of this research is to apply deep learning-based NLP for translating building regulations into a computer-readable format. As an early stage of research, this paper proposes a semantic analysis process to support rule checking, focusing on rule interpretation.

The scope of this paper is the approach to analyzing the semantic data of Korean building regulation sentences with NLP and deep learning. We analyzed 5 Korean building regulations: Building Act, Enforcement Decree of Building Act, Regulation of the building Structure criteria, Regulation of the building facility criteria, and Regulation of the evacuation and fireproof construction criteria. 3504 training sentences are derived from 5 building regulations. Steps of the proposed analysis are summarized as follows.

1. Learning step: Decompose training sentences in word-level and learn semantic of words and sentences by using NLP and deep learning model
2. Utilization step: Automatically inference the related word and topic of input sentence, utilizing trained learning model.

After dealing with proposed analysis process, this paper also presents a demonstration of utilization which is associated with domain database.

2 Background

2.1 Rule interpretation for automated rule checking

There have been many efforts to develop automated rule checking. Among the automated rule checking process, rule interpretation is a significant step for automating rule checking. The conventional methodology to translate the building code has been depended on hardcoding or logic rule-based mechanism. The CORENET (COnstruction and Real Estate NETwork) project in Singapore translated building code of Singapore into the programming language by hardcoding [4]. DesignCheck project formalized the building code of Australia and encoded it according to the EDM rule schema based on the EXPRESS language [5]. In GSA project, the courthouse design guide was parameterized and translated into computer-processible format [3]. In case of the Korean building permit research project, they used logic rules and intermediate code to translate Korean building act into the computer-readable format [6]. The conventional rule-based way guarantees the accuracy and reusability. However, establishing the logic rule for interpretation has been done by manual efforts due to ambiguity and vagueness of natural language.

In order to overcome the inefficiency of a manual process, some studies focused on analyzing the semantics of words in regulatory sentences and utilizing NLP. Zhang et al. proposed semantic NLP-based automated compliance checking (SNACC) system [7]. NLP and ontology were applied for extracting the regulatory information from documents. Through the NLP technique and other process, they automated the rule interpretation with semantic information extraction. E.Hjelseth applied RASE methodology to transform normative documents into a single well-defined rule which can be implemented into model checking software [8]. Uhm et al. translated request for proposal (RFP) for public building in South Korea [9]. Sentences in RFP were broken down into morphemes and categorized into four types (object, method, strictness, and others). Context-free grammar approach was deployed for parsing, and the sentences were translated into Semantic Web Rule Language (SWRL). SWRL is translated again into Python script language for implementation. Previous researchers have contributed to capturing the semantics of regulatory documents, but they still need manual effort to interpret patterns of sentences.

2.2 Natural language processing

NLP is a research field of artificial intelligence related to interactions between human and computer. The main research of NLP ranges from understanding human language to making proper responses. Due to the ambiguity of natural languages, it is a challenging process to understand the raw text data. Conventional NLP used logic rule-based or statistical methodology for analyzing natural language. In the rule-based method, the text is analyzed by rules defined with linguistic knowledge. However, the semantic meaning of words is hard to capture since it is hard to be defined by pattern or rules. WordNet is a lexical database for English, which provides sets of synonyms that are in turn linked through semantic relations [10]. This has been widely utilized to present semantic meaning of words but still needs a manual task to build and manage this database.

Development of machine learning and deep learning has changed the methodology of NLP and dramatically improved the accuracy of it [11]. Deploying an extensive amount of data and neural net algorithm, the computer can learn semantics in natural language by itself. As machine learning is processed with numerical vectors, words have to be converted into the computer-interpretable format. Distributed representation in vector space helps to represent words quantitatively. Rumelhart proposed this concept of analysis [12] and recently Mikolov implemented neural net based word embedding model called word2vec [13, 14]. After google opened the word2vec model to the public, many researchers make use of this model for sentiment analysis [15] and information extraction [16].

3 Learning semantic of words and sentences in building regulations

This section describes details of the semantic analysis for building regulations. As shown in Figure 1, proposed process is composed of 2 main steps: Learning semantics and Utilization. Learning step consists of 1) preprocessing, 2) semantic analysis of words and sentences and 3) sentence classification. The process and details about utilization are described in Section 4.

Preprocessing is focused on the grammatical analysis of documents, which is needed for semantic analysis. After the preprocessing, the meaning of words and the topic of sentences are learned by neural net-based word embedding technique. Sentence classification is conducted with deep learning model. In this paper, we used a Python package library KoNLPy [17] for preprocessing, Gensim [18] for word embedding and Tensorflow [19] for establishing classification model.

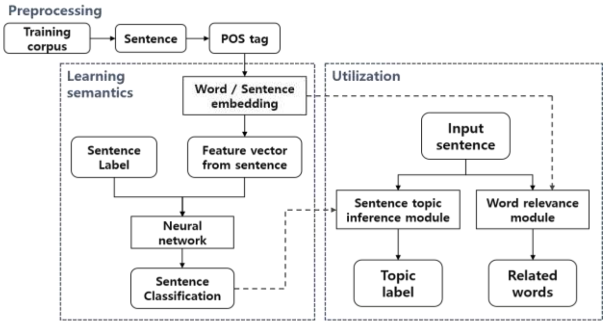

Figure 1. Proposed process of analysis and utilization of building regulations

3.1 Preprocessing

In order to proceed an accurate semantic analysis, raw text data have to be processed in a suitable format. In the Korean language, there are postposition particles which stand for grammatical use. They are attached behind to other words like nouns or adjectives. In the raw text, there are also stop words which disrupt semantic analysis (e.g. punctuation). The sentences should be analyzed in grammatically to exclude these unnecessary part. Preprocessing consists of morpheme analysis, Part-of-Speech (POS) tagging and excluding stop words. Morpheme is the smallest unit which has a specific meaning in a language. By decomposing words in atomic unit, morpheme analysis supports to separate the words from postposition particle. POS tagging assigned the label of grammatical function to each word, such as noun, verb, and adjectives. After POS tagging, we excluded Chinese character, punctuations, and numbers. Figure 2 presents a result of each step of preprocessing.

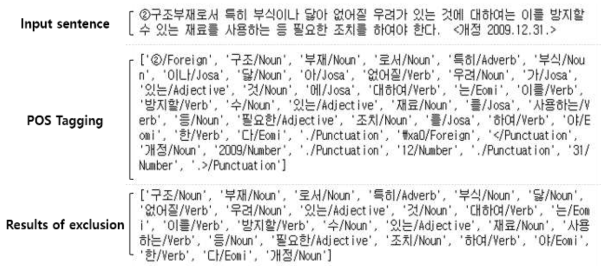

Figure 2. Example of preprocessing result (POS-tagging, Exclude stop words)

3.2 Semantic analysis of words and sentences

This paper uses word2vec model for the semantic analysis of words. Word2vec model is based on the word embedding technique and it learns the semantics of text from co-occurrence information. Some words which appear with target word in the same context are more related to target word than the others. Based on this concept, Mikolov et al. proposed 2 models to learn the word vector 1) CBOW (continuous Bag-of-Words) model and 2) Skip-gram model [14]. Skip-gram model predicts the current word with a certain range before and after the current word, CBOW model is the opposite. By predicting the current or context words, the computer can learn a co-occurrence data of words. Based on the co-occurrence data, the model assigns the high-dimensional vector values for each word. The numerical vector values enable for the computer to calculate a relevance of words. This learning process also can be applied to learning the meaning of sentence [20]. In this paper, the meaning of words and sentences are presented in 400-dimensional vector space, as shown in Figure 3. We set the maximum distance 5 and words with a frequency less than 3 were excluded from the training.

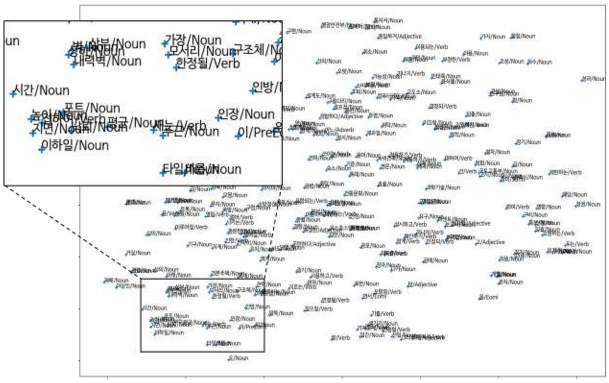

Figure 3. t-SNE Visualization of word distribution

3.3 Sentence classification

Korean building regulations contain not only requirements for building also other rules which are irrelevant to buildings (e.g. administrative procedures, Committees). BIM-based automated rule checking focuses on the requirements for buildings which can be expressed quantitatively. Therefore, computer should classify the sentences according to the content and extract the sentences related to buildings from the raw documents. Furthermore, classifying sentences supports identifying what information has to be extracted. The numerical vector values extracted from semantic analysis facilitate the classification of the sentences.

In this paper, we use deep learning model for classification of sentences. First, we tag the label to each sentence according to its contents. Table 1 shows a classification of content described in building regulations. In this paper, 6 categories are used for classification labels: 1) Non-AEC, 2) Site, 3) Building structure, 4) Facility, 5) Usage of building and 6) Evacuation & Fireproof. We just use Non-AEC category, as we don’t need more detailed for irrelevant sentences in terms of rule checking. Site category covers the regulations for a building site and roads. Facility category includes MEP facilities and Evacuation & Fireproof category is comprehensive of rules for evacuation plan and noncombustible material. For supervised classification learning, we use deep learning model which composed of 4 fully-connected layers and softmax function for multi-class classification. The graph of model and weights are saved for inference model.

Table 1. Classification of contents described in building regulations

Level-1	Level-2	Level-3
Non-AEC	Rule	Amendment
		Delegation, Reference
	Administrative	Procedure
		Committees
		participant
AEC	Site	Site
	Building	Structure
		Facility
		Usage
		Evacuation & Fireproof

4 Utilizing semantic analysis to support automated rule checking system

4.1 Extract related words from input sentence

Extracting related words to target word facilitates understanding of the semantics. Based on the numerical values, the computer can calculate the metric distance between words. The distance between words represent the relevance between them, so we can extract words related to the target word. This features could be used for extract semantic relations of words in a regulatory sentence.

This module extracts words related to a user-input word, using results of the semantic analysis. The given sentence which is selected by users is decomposed to word-level. After decomposition, the relevance of input word and each word from the given sentence is calculated. Through those steps, the computer can get a list of related words, but it has no idea which words are building object or their property. This gap can be decreased by domain knowledge which deals with rule checking data. This paper used the KBimCode database made up of previous work of this research [6]. KBimCode database provides the computer-executable code data and corresponding Korean words. It can be used as a dictionary for translating Korean words into object, property and method data, as shown in Figure 4.

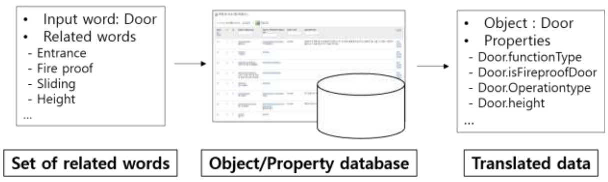

Figure 4. Translating words to corresponding object/property data

4.2 Inference the topic of input sentence

Topic inference module is based on a result of classification learning. The input sentence is also decomposed in a set of words. After preprocessing, inference module infers the vector values of input sentence based on other sentences vector values. In this paper, we assigned the meaning of the sentence in 400-dimensional space, so the inference module also returns the same shape of value. Then, the inferred vector is given as an input for the classification model. It uses a same graph and weights for predicting the topic.

5 Demonstration

The proposed modules described in the previous section are implemented in GUI applications for supporting rule checking process. This section demonstrates the results of implementation. With this application, users can get related words, corresponding KBim data and a predicted topic of the input sentence.

Table 2. An example of word extraction for Korean building regulation

Input Sentence	[Enforcement Decree of Building Act, article 35] Direct stairs installed on the fifth or upper floor or the second or lower underground floor pursuant to Article 49 (1) of the Act, shall be installed as fire escape stairs or special escape stairs in accordance with the standards prescribed by Ordinance of the Ministry of Land, Infrastructure and Transport: Provided, That the same shall not apply where main structural parts are made of a fireproof structure or non-combustible materials and either of the following is applicable
Input word	Stair

Top 5 related word	Direct / Noun Escape / Noun Floor / Noun Underground / Noun Special / Noun
Extracted word	Direct stairs, escape stairs, Special escape stairs, underground floor, fifth floor, second floor
KBim data	-Object: Stair, Floor -Properties : Stair.isDirect, Stair.isEscape, Stair.isSpecialEscape -Method : getFloorNumber()

Table 2 shows a result of extracting related word when "stair" is given as an input word. The result is presented in GUI application as shown in Figure 5. The properties of the stair are also easily found in a lexical level search. However, in the lexical level, floors where stairs are installed or related objects are not searched. The demonstration shows that not only the properties of the stair are suggested, also the related object (Floor) and its properties (Underground), from the semantic analysis.

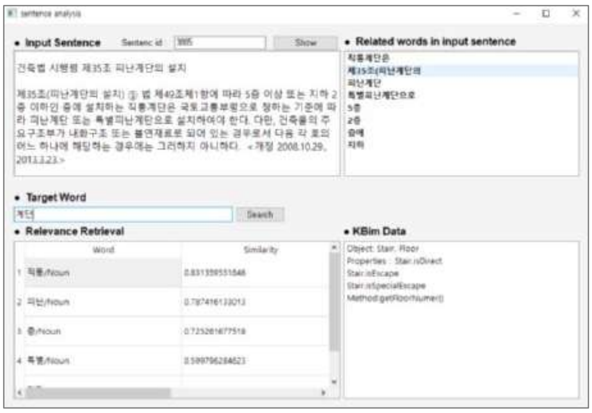

Figure 5. Screenshot of the application for extracting related words in sentence

The topic inference module suggests predicted topic of an input sentence and also similar sentences based on their content. Suggested similar sentences are extracted based on vector representation, calculating the metric distance of each sentence, same process with the word extraction. In terms of extending the scope of rule checking to RFP or other new regulations, this topic prediction makes it easier to classify the sentence whether it deals with content related to BIM-based rule checking. Table 3 shows the examples of topic prediction results. The inference module makes an accurate output in case 1. However, in case 2 and 3 the module make a wrong prediction, as the correct label is predicted in second. The results of prediction are demonstrated in GUI application, as shown in Figure 6.

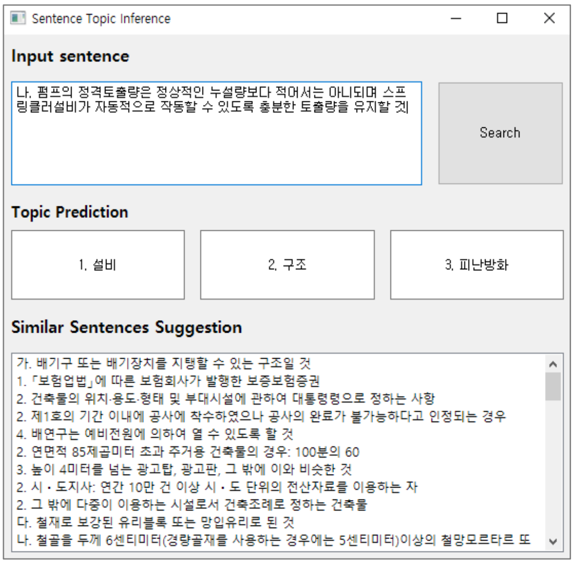

Figure 6. Screenshot of the application for Topic inference module

Table 3. Examples of topic prediction for input sentence

Case	Input Sentence	Output Topic
1	[Fire safety standard for sprinkler (NFSC 103)] Article 5. The rated discharge rate of the pump should not be less than the normal leakage and maintain sufficient discharge volume for the sprinkler system to operate automatically	1. Facility 2. Structure 3. Evacuation &Fire-proof 4. Non-AEC 5. Site 6. Usage
2	[Seoul bylaw for construction] Article 33 Buildings whose floor surface of 1st floor is over 0.5 meters above the ground surface and whose height added to height between 1st floor and ground floor by 8 meters is less than 12 meters.	1. Usage 2. Structure 3. Evacuation & Fire-proof 4. Facility 5. Site 6. Non-AEC
3	[Special law on disaster management of complex buildings and coordination of high-rise and underground] Article 19 Supervisors for high-rise buildings should install and operate shelter safety zone where workers, residents and users can evacuate in the event of a disaster	1. Facility 2. Evacuation & Fire-proof 3. Site 4. Structure 5. Non-AEC 6. Usage

6 Conclusion

This paper proposes a semantic analysis process and its utilization to support rule interpretation. In this paper, Word embedding model is used for learning the semantics of text. Through the training, the semantic of word and sentences are represented in vector values. The results of the semantic analysis are utilized for extracting related words and classifying the topic of sentences. Sentence classification based on deep learning model enables the computer to classify the regulatory sentence according to its content. Extracting related words helps both human and computer to find semantic information from raw text. Demonstrated implementation shows the possibility of utilizing deep learning and NLP to support rule interpretation process. Leveraging this process can decrease the manual efforts and time for interpreting rules.

This paper also has some limitations. In preprocessing process, there are some errors in morpheme analysis which are done by NLP framework. This causes critical problems for information extraction task and interpretation. And this paper mainly deals with the semantic relation of words. To entirely automate rule interpretation, it needs to be developed to the logical relation. For the future work, it can make a breakthrough to deploy the syntax parsing for capture the logical relations of words. Furthermore, to enhance the accuracy of morpheme analysis and sentence inference, other deep learning models could be applied (e.g. RNN or CNN for sentence classification [21]).

Acknowledgement

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Transfer Learning-Based Crack Detection by Autonomous UAVs

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Abstract – Unmanned Aerial Vehicles (UAVs) have recently shown great performance collecting visual data through autonomous exploration and mapping in building inspection. Yet, the number of studies is limited considering the post processing of the data and its integration with autonomous UAVs. These will enable huge steps onward into full automation of building inspection. In this regard, this work presents a decision making tool for revisiting tasks in visual building inspection by autonomous UAVs. The tool is an implementation of fine-tuning a pretrained Convolutional Neural Network (CNN) for surface crack detection. It offers an optional mechanism for task planning of revisiting pinpoint locations during inspection. It is integrated to a quadrotor UAV system that can autonomously navigate in GPS-denied environments. The UAV is equipped with onboard sensors and computers for autonomous localization, mapping and motion planning. The integrated system is tested through simulations and real-world experiments. The results show that the system achieves crack detection and autonomous navigation in GPS-denied environments for building inspection.

Keywords –

Unmanned Aerial Vehicle; Building Inspection; Crack Detection; Transfer Learning; Autonomous Navigation

1 Introduction

Inspection of buildings throughout their lifecycle is vital in terms of human safety as the number of structures increases expeditiously. In line with this objective, periodic inspections are essential for residents' safety. For instance, systematic bridge inspections are done periodically in six years to detect structural cracks [1].

In this context, Unmanned Aerial Vehicles (UAVs) have been widely used in inspection operations in the last decade since their workspace is superior than that of ground vehicles. Today, UAVs are employed especially in visual building inspections by utilizing onboard cameras.

Moreover, the robotics community has increased the automated capabilities of the UAVs in terms of data acquisition and processing for inspection. In [1], a micro helicopter using computer vision approaches to be able to inspect bridges is presented. In [2], authors introduced a UAV system for inspecting culverts utilizing GPS, LIDAR and IMU. The data acquired from these sensors are fused to estimate the state enabling autonomous outdoor navigation.

A methodology to monitor the changes due to corrosion damages on industrial plants by using UAV is presented [3]. Images acquired at different instances are aligned through geometric transformation to highlight the changes above a threshold which is automatically determined by assuming damages that have usually different aspects with respect to the surrounding structures. In [4], researchers demonstrated a quadrotor MAV integrated with a stereo camera configuration that can explore GPS-denied indoor environments. They validated the system by autonomous flights inside an industrial boiler.

Recently, a lot of effort is put on crack detection using UAVs. A hybrid image processing technique that estimates crack width while decreasing the loss in crack length information is reported [5]. Another approach for crack detection and mapping using UAVs is presented in [6]. However, the previous works mainly focus on either autonomous navigation or post-processing of the acquired data (i.e. defect detection) by mostly using traditional image processing techniques (as in [7] & [8]) that may fail in different lighting conditions and/or materials.

In this context, the aim of this research is to achieve autonomous navigation and revisit motion planning of UAVs to surface crack locations in order to perform automated building inspection operations since the inspections are generally periodic and requires revisiting for close examination. This revisit task planning strategy enables UAVs to autonomously navigate in different environments while proposing a decision making tool by crack detection. The major contribution of this dissertation can be stated as an implementation of autonomous building inspection considering not only the

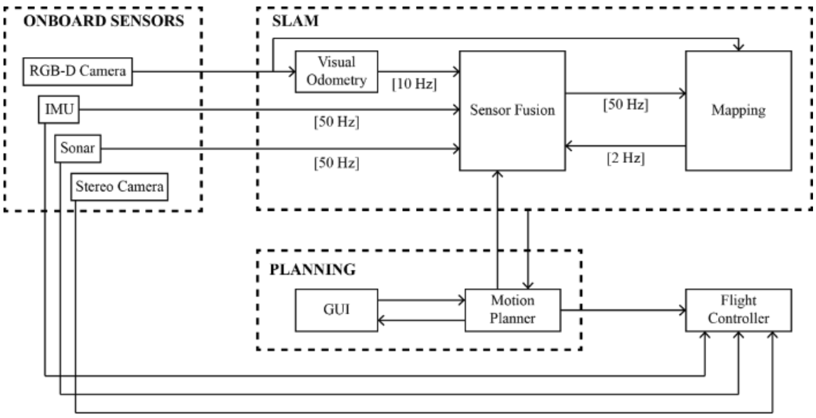

Figure 1. Schematic of the high-level system architecture

data acquisition phase but also revisiting crack locations by transfer learning.

In this regard, an autonomously navigating quadrotor UAV is developed to be able to revisit pinpoint locations. For this purpose, SLAM using onboard visual-inertial localization and mapping to explore the environment in which the UAV is located and motion planning with obstacle avoidance are applied. Transfer learning approach is used to identify surface cracks from images so that possible revisiting locations can be determined for high-level decision making during inspections. Finally, a commercial quadrotor UAV is integrated with onboard sensors and computers in order to validate and verify the methods by testing.

2 System Overview

The necessary software for autonomous navigation and crack detection is both developed and implemented from open source libraries and packages supported by the community in the scope of this study. Figure 1 presents the schema of the software architecture for the overall system. all the computations are done onboard except from GUI and image classifier which runs on a ground station computer. The developed software components for this research is open-source and available online [9].

The flight controller of the quadrotor platform [10] ensures the low-level (attitude and velocity) control of the vehicle. Modified open-source software is implemented for SLAM and motion planning strategies. RGB-D camera is the source for the visual odometry and mapping processes, and it is fused with onboard IMU and ultrasonic sensor for state estimations by an Extended Kalman Filter. Also, a CNN is employed as the image classifier for surface crack detection. It presents an optional support mechanism for task planning of revisiting locations during inspection. It is built on top of autonomous navigation capability of the UAV with a user interface.

A graphical user interface that runs on a ground station computer is developed for high-level planning of the revisiting tasks. The interface wraps the capabilities of the system and enables users to utilize it without a prior knowledge of robotics. Functional callbacks for planning, motion control and other features for visualization purposes such as live video stream are other aspects derived from this interface.

The integrated system aims autonomous navigation with onboard computations. The objectives of autonomous navigation of the UAV in GPS-denied environments are determined as follows:

1. Real-time state estimation of the UAV during flight,
2. Mapping of the environment in which the UAV operates for global localization and motion planning,
3. Motion planning with obstacle avoidance to target locations of revisiting.

In order to achieve these objectives, software is developed and implemented on top of open source software packages and algorithms presented by the robotics community through Robot Operating System (ROS) so that the software can be modular and extendable. Implementation of the software throughout this work is achieved by using ROS framework.

Attitude control is achieved by using velocity control mode of the onboard flight controller in the employed UAV. A graph-based RTAB-MAP [11] ROS node is used both for visual odometry and mapping. A RGB-D camera is integrated with the UAV for visual odometry and onboard IMU is fused with visual odometry with an Extended Kalman Filter [12] at 50 Hz.

Motion planning is achieved with an implementation of MoveIt! [13] ROS node with OMPL [14] backend. A

Universal Robot Description Format (URDF) of the UAV is constructed for collision checking. An algorithm is developed for interoperability of the motion planner and the revisit planner.

3 Revisit Planning

The proposed revisit planning workflow in Figure 3 is demonstrated step-by-step as follow:

1. Images acquired during flight are shown in the GUI for users to pick a revisiting location. Each image corresponds a location (position and orientation) in the algorithm since these images are previously linked with locations.
2. (Optional) A crack detector can step in to process images if a user aims to use the crack detection approach as a support for decision making of locations to revisit.
3. If Step-2 is fulfilled, the GUI visualizes the new cracks on a new set of images.
4. By the corresponding image, a location for revisiting is found. Then, the GUI delivers this goal to the motion planner.
5. The GUI receives an obstacle-free optimal trajectory as the form of waypoints if available.
6. For UAV to cover the path, the required velocities between the waypoints are calculated by an algorithm. In case of being successful or having no feasible motion plan, the GUI reports feedback.

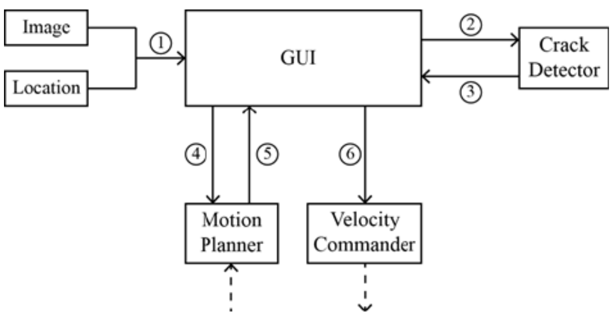

Figure 3. Workflow of the revisit planning strategy

For the step 1, Matching the images with their corresponding locations is essential for this strategy. A ROS node is developed in order to match images with poses (position and orientation) where the UAV had been visited during inspection for possible revisiting in future missions. This algorithm subscribes to both visual-inertial odometry and RGB images. Then, it matches them using Approximate Time Synchronizer message filter of ROS in a predefined period (2 Hz in this implementation). The images saved with their corresponding poses in favor of the revisit planner.

In order to provide the step 4&5, an algorithm is developed using Python interface of MoveIt!. It sends the goal to the motion planner and computes the velocities from the corresponding trajectory. It runs at the backend of the GUI.

4 Crack Detection

Crack detection is one of the most common objectives in building inspection. Increasing efficiency of visual inspection can be achieved by decreasing the time spent for post-processing on captured images during flight.

In this context, Convolutional Neural Networks (CNN) are one of the most commonly used architectures since they can overcome most of the contemporary challenges in crack detection [15]. They are getting more accurate and robust for image classification in recent years.

On the one hand, CNNs are easy to train and can be applied from open source libraries. On the other hand, training an entire CNN from scratch is not preferable for the majority because it is comparatively difficult to have a sufficient amount of data. Transfer Learning has eventually emerged. It uses a pretrained network on a large dataset (e.g. ImageNet which contains 1.2 million images with 1000 categories) as an initialization or a fixed feature extractor for the newly created network. Fine-tuning is one of the methods in Transfer Learning which is used as a complementary of CNN in this study. For working efficiently with small datasets and using a pretrained networks that assures time effectiveness, this approach becomes appropriate in the scope of this research.

4.1 Training the CNN

In this work, InceptionV3 [16] network model with ImageNet weights is fine-tuned since it has relatively high performance in top-1 validation accuracy than most of the top scoring single-model architectures (Figure 4). Keras with TensorFlow backend is used for the implementation. Graphics Processing Units are utilized in training sessions. For this purpose, a modified version of [17] is used.

In the fine-tuning of the CNN, ‘Crack’ and ‘NonCrack’ classes are designated for the image classifier. The training dataset is collected from Middle East Technical University campus buildings. It includes 582 images with cracks, and 458 images without cracks (Figure 5). Since a poor performance was observed on brick wall images in the first implementation, a group of brick wall images are added to the ‘NonCrack’ dataset in order to detect cracks on brick materials. Additionally, data augmentation function is applied to increase the number of the data for greater performance.

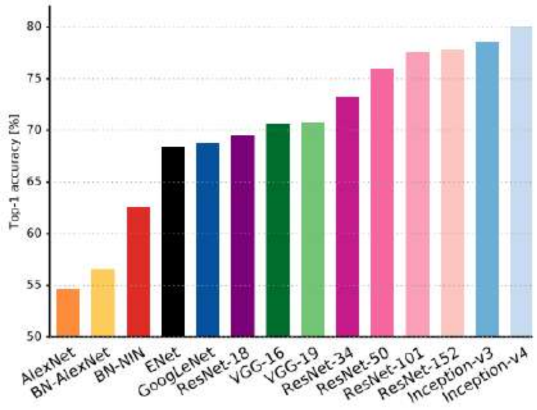

Figure 4. 13 Single-crop top-1 validation accuracies for top scoring single-model architectures [18]

The training and validation accuracies over each epoch are shown in Figure 6. After 5 epochs, the model's training accuracy jumps over 90%. After 20 epochs, the training and validation accuracies attain to approximately 98%. The training and validation losses over each epoch are shown in Figure 7. The losses converge to 0.05 after 20 epochs.

Figure 5. Sample of images used in the training ('Crack' images at left, 'NonCrack' images at right)

4.2 Cross-validation

After the training session, cross validation is done by using a different dataset in terms of image variation. The cross validation dataset consists of 64095 images. 19368 of these have surface cracks while there are no cracks in the rest. The fine-tuned model accurately predicts 62417 from the 64095 image. The accuracy is 97.382% in the cross validation. These results clearly demonstrate the convenience of using an InceptionV3 model as the backbone for transfer learning for such a crack detection application.

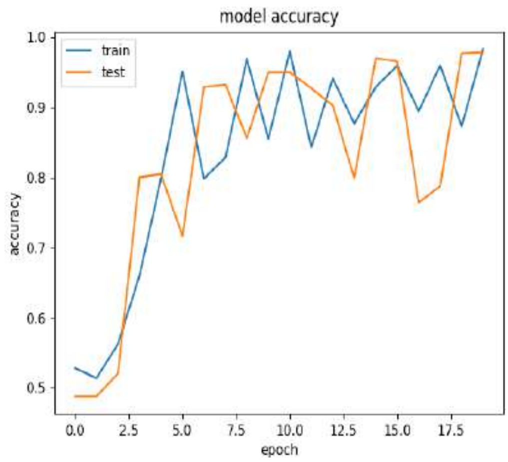

Figure 6. Accuracy vs. epoch number in the training and the validation sets

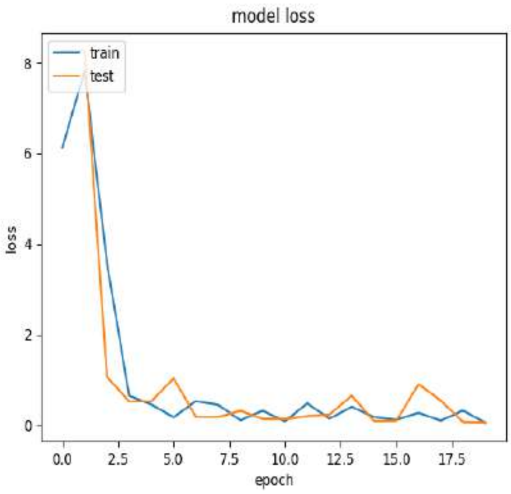

Figure 7. Loss vs. epoch number in the training and the validation sets

5 Experiments

In order to validate the system, autonomous navigation and crack detection capabilities are tested through computer simulations and real-world experiments.

5.1 Simulations

The simulations are performed in order to verify the state estimation performance of the system. For this purpose, a simulated environment is created inside Gazebo simulator. The environment is constructed to mimic an indoor space to be able to verify the performance of visual-inertial navigation of the system in GPS-denied environments. Figure 8 shows the environment used in simulations. Two connected spaces in the environment is enclosed by 3x1x3 m (height x width x length) brick walls. Another wall with relatively monotonous texture is located because identifying loop-closures is harder when repetitive patterns are present in the environment. In this way, the performance of loop closure detection is more indicative since it is a more challenging case.

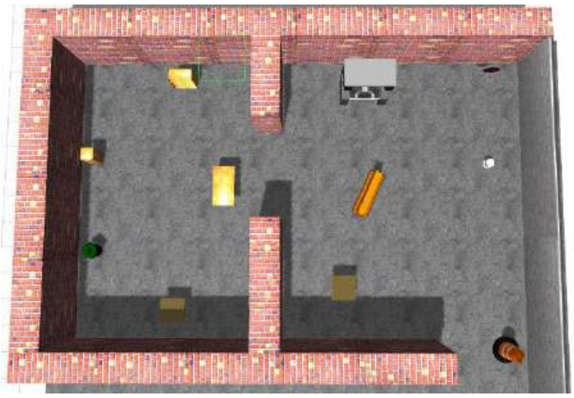

Figure 8. Indoor test environment used in the simulations

5.1.1 Mapping

After the simulation environment is established, the tests are performed to evaluate the performance of the mapping, the state estimation, and planning approaches. First, an exploration (of the environment) session is conducted by manually operating the quadrotor UAV, a 3D voxel grid map is constructed Figure 9. The performance of the mapping is assessed by comparing it with the original environment in the simulations.

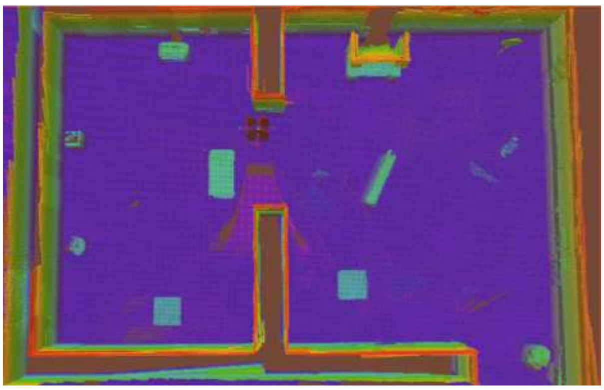

Figure 9. Reconstructed 3D voxel grid map of the environment

5.1.2 State Estimation

In order to evaluate the state estimation performance of the system, the position (global x-y-z) and orientation (yaw) estimates are compared with the corresponding ground truth values. The ground truth values are obtained from the simulation environment. Visual odometry and visual-inertial odometry results are plotted along with ground truth values (Figure 10). The estimates are closely tracking the actual measurements of the trajectory.

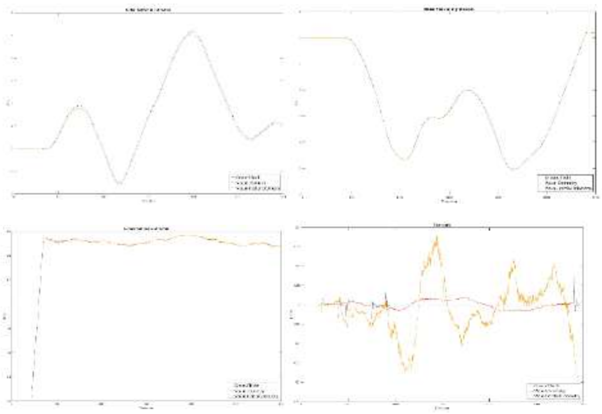

Figure 10. Ground truth vs. Visual-inertial estimations (x-direction at top-left, y-direction at top-right, z-direction at bottom-left, yaw degree at bottom-right)

The maximum deviations (errors) in state estimates are presented in Table 1 in order to comprehend the results in a clearer way. It can be observed that visual-inertial odometry has superior performance than visual odometry as expected. Although the maximum deviations in the x, y and z direction are close to each other, the errors in the yaw angle are slightly dramatic compared to them. This expected behavior shows the importance of fusing inertial measurements with visual odometry since yaw angle of IMUs are generally prone to have error due to the fact that the gravity measured by accelerometers cannot be used to help to estimate it [19]. The values in the table show that the maximum error along the estimated trajectory is in the order of 0.1 m. This value is negligible relative to the building scale so, the performance of the state estimation can be evaluated as sufficient in terms of building inspection.

Table 1. Maximum deviations in the state estimation

	Visual Odometry Max. Deviation	**Visual-Inertial Odometry Max. Deviation**
Global x-direction	0.146157219 m	0.145886557 m
Global y-direction	0.064824391 m	0.052191800 m
Global z-direction	0.058057038 m	0.054663238 m
Yaw Angle	0.23723990 rad	0.02274868 rad

5.2 Indoor Experiment

The second test case is conducted indoor to be able to verify the fully integrated system. After verifying the state estimation and mapping performances in simulations, experiments are performed in a GPS-denied environment for evaluation of the integrated system. The experiments are conducted in the workshop of Design Factory in Middle East Technical University that can be seen in Figure 10.

Figure 11. Indoor experimentation environment

5.2.1 Hardware

In real-world tests, hardware of the system is composed of five components which are an aerial platform, an onboard visual sensing system, a RGB-D camera and an onboard computer. As the aerial platform, DJI Matrice 100 [10] is employed. It is a vertical take-off and landing (VTOL) quadrotor vehicle with reconfigurable hardware installation capability. Matrice 100 is used since it meets the requirements of this research by having onboard low-level flight controller that handles attitude control.

For the onboard visual sensing system, five units of low resolution stereo camera and one processor named Guidance [20] are implemented. Guidance is compatible with the flight controller of the aerial platform, and it fuses stereo camera data for real-time obstacle avoidance in this work.

As the onboard RGB-D sensor, a widely used and open sourced hardware, Microsoft Kinect v1 is used. Having served for the purpose of mapping and localization, it has an RGB camera and infrared depth camera with 43° vertical by 57° horizontal field of view at 30 frames per second.

As the onboard computer of the system, DJI Manifold that has a quad-core, 4-plus-1 ARM processor, NVIDIA Kepler-based GeForce graphics processor, 2GB memory with customized version of Ubuntu 14.04LTS is preferred. Besides, it has a wireless connection chips and antennas for communication purposes.

Figure 12. Integrated quadrotor UAV used in this work

5.2.2 Revisiting a Defected Location

The first phase of this test case is the mapping phase. A low resolution point cloud representation is presented in Figure 13. The environment is partially mapped since it is sufficient for the evaluation of the system. For mapping of the environment, the UAV is covered a trajectory (blue marker in Figure 13). The trajectory contains overlapping positions so that loop closures can be detected.

The test case is demonstration of a revisiting task. For this purpose, the images acquired during the mapping phase are processed with the image classifier developed to detect cracks on walls of the environment.

The algorithm that is developed for matching the images with their corresponding locations acquires 20 images (Figure 14) in the mapping phase. 13 of these images are replaced with images that contain cracks (Figure 15) since there are no surface cracks available in the test environment. The registered locations (positions) are kept same as in mapping but only the images are changed. In this way, the developed task planning pipeline as well as the crack detection approach can be tested.

Then, these 20 images are fed into the CNN in order to identify the cracks. After processing, the CNN classifies 16 of the images as cracks although it should be 13. Several other elements such as windows and radiator mislead the CNN as in the extra 3 images. The other 13 images are those which have cracks. Thus, it can be stated that the crack detection application gives sufficient performance as a decision support tool.

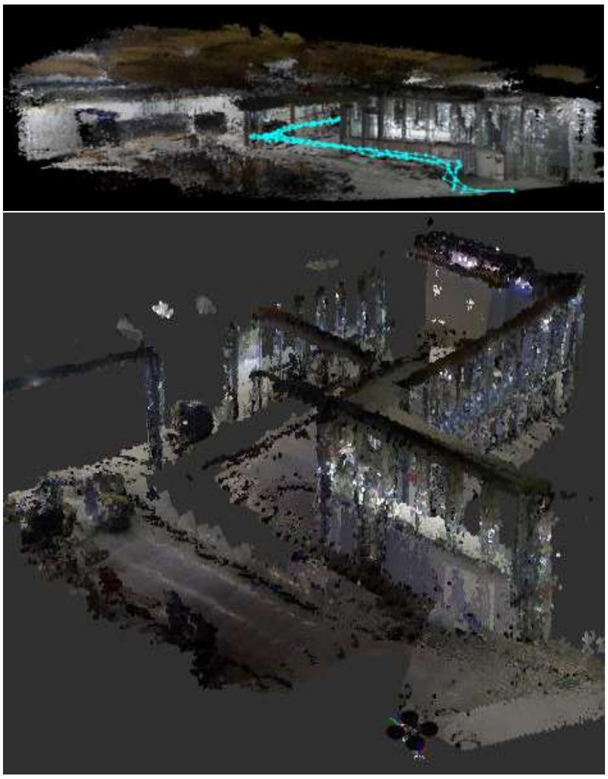

Figure 13. Reconstructed maps of the environment

Figure 14. Sample images acquired during the mapping session

Figure 15. Sample crack images that are replaced with the acquired images

5.2.3 Motion Planning

After the crack detection, one of these crack images that corresponds to a specified location that is selected as the goal position for revisiting. The goal position is selected so that the most complicated motion plan should be achieved in the environment. Thus, the distance between the start and the goal positions is set to be as long as possible in the map. Moreover, the walls and the windows exist between them as obstacles so that the UAV should takeoff and move around the junction of the two walls for obstacle avoidance during motion.

Path planning algorithms that are available in MoveIt! are tested for the motion planning problem between start and goal positions. PRM*, RRT and RRT* algorithms compute solutions while EST, SPL, LBKPIECE, PRM, BKPIECE algorithms are not able to solve the problem. The reason is possibly the sampling strategies of these algorithms. They might not be able to sample the workspace such that the start and the goal positions are covered for a complete solution. The solution of the PRM* algorithm (Figure 16) is not acceptable in terms of both the optimality and the motion constraints since it requires large roll degrees in the motion that may cause overturn. The trajectory planned by RRT (Figure 16) has a sudden jump in the motion which is not possible for the UAV to execute. On the other hand, RRT* computes a trajectory (Figure 16) that satisfies criteria for motion planning. The trajectory is collision-free and smooth as well as optimal in terms of length. Therefore, the motion planner is set to use RRT* as the main algorithm in the motion plans. After the motion is planned, the UAV can be sent to the goal location for revisiting the crack location.

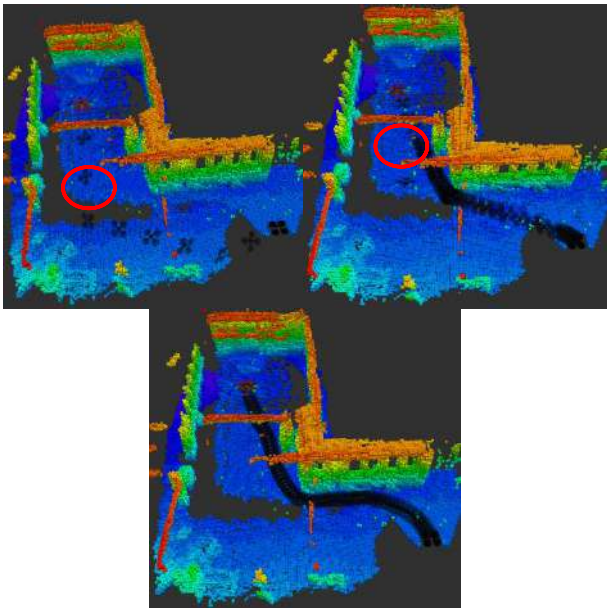

Figure 16. Motion plans (PRM* at top-left, RRT at top-right, RRT* at bottom) Red circles show the motions that violate the planning objectives

6 Conclusion

In this work, an integrated system that enables revisiting crack locations during building inspections by means of a quadrotor UAV is presented. Autonomous navigation of the UAV in GPS-denied environments is achieved by integrating and developing open source software. A task planning strategy is developed in order to revisit defected locations. Transfer learning is used for surface crack detection. Simulations and indoor experiments are conducted for the system verification.

The major contribution of this work can be stated as a application for building inspection by autonomous UAVs considering not only the data acquisition (mapping) phase but also the subsequent close examination (revisiting) of crack locations that are identified by a CNN. Future work will focus on improvements of crack detection on different materials and of crack properties.

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A Study of Field Condition Feedback to a Remote Controlled Underwater Heavy Machine Operator

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Abstract –

Construction in the water is currently under way using an underwater excavator. The underwater excavator is operated by a diver. To reduce the burden on the diver, remote controlled system of underwater excavator is developed, but the current system has poor operability to use. The purpose of this study is to improve operability of remote controlled underwater heavy machine. We considered and proposed the working field condition feedback methods to the remote controlled underwater excavator operator for improving the operability. The methods were evaluated through simulation experiments.

Keywords –

Underwater excavator; Unmanned construction; Teleoperation; Operating Support; Instructions; Input Device

1 Introduction

An underwater excavator is used for constructions in harbors and dams. The underwater excavator is shown in Figure 1. It is remodeled from the land one by reloading the diesel engine to the underwater motor and hydraulic pump, and it can work underwater environment. In the underwater constructions, the excavator is operated by divers riding on it like Figure 2. So, the divers must operate it in the water for a long time. Therefore, remote controlled construction machines are needed for underwater constructions to reduce their burden, and remote controlled underwater excavators and their control systems were developed.

Figure 1. An underwater excavator [1]

Figure 2. An excavator operated by a diver [1]

In the underwater construction using current remote controlled excavator, the operator can get working field conditions only from camera images. The visibility is poor and it is insufficient for the operator to operate the excavator smoothly.

Therefore, operability of the remote control system for underwater excavators should be improved and some improvement methods were proposed [1]. However, the previously proposed remote control system has complex interfaces for showing the environment around the underwater excavator, and its operability improvement is still insufficient.

Then in this study, we propose a simple but efficient method for improving the operability of remote control system for underwater construction machines using vibration of operation lever.

In chapter 2, we analyze the cause of the insufficient operability in the underwater excavator operation. In chapter 3, we propose the simple but efficient working field condition feedback methods to the remote controlled underwater excavator operator. In chapter 4, we evaluated the operability of the proposed methods described in chapter 3 by using our developed simple simulator. In chapter 5, we conclude our study described up to chapter 4.

2 Considering about insufficient operability of underwater excavator

When the diver riding on the underwater excavator operates it, the diver relies on his seeing view, feeling shake of the excavator and hearing sounds. In the water, the diver sometimes cannot see his working field situation because of the rising clouds of dust by the excavator. In this case, the diver must operate the excavator only relying the shake and sounds. This state is shown in Figure 3.

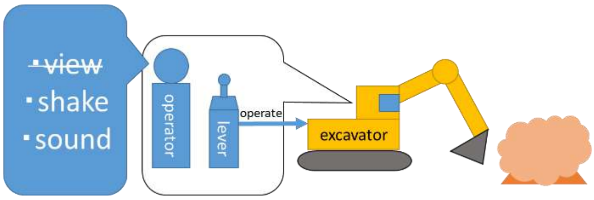

Figure 3. Excavator operated by a diver in the water

Current remote control system has some cameras on the excavator and the working field images are displayed to the operator. But, the operator cannot feel the vibration and sound of the excavator. Additionally, in the underwater work, operators cannot see the field condition when the clouds of dust soar by the operation of the excavator. Then, in the current system, operators cannot rely on not only the vibration and sounds of the excavator but also displayed images of the working field. Therefore, operators cannot operate excavators until the clouds of dust disappear. This state is shown in Figure 4.

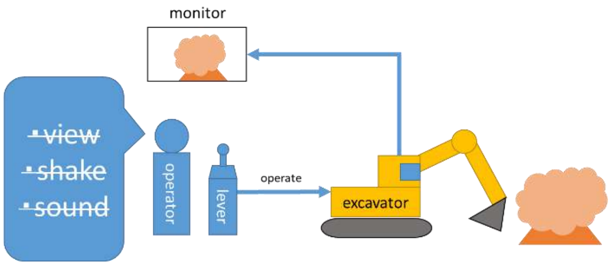

Figure 4. Excavator operated by remote control system from the operation room

3 Considering and proposal of the field condition feedback methods

This study proposes working field condition feedback methods to improve the operability for the remote controlled underwater excavator operators. Necessary information for the excavator remote control was revealed by the interview to the operators who often operate underwater excavators using remote control system. The necessary information is:

- The moment when the excavator starts moving
- The moment when the excavator hits some obstacles
- Whether the excavator reached its moving limits

In the current remote control system, some sensors are attached to the excavator, and their sensor values are sent to the operation monitors and displayed. We considered more intuitive methods are necessary to inform the working field conditions to the operators than using a display monitor. Then, we considered 3 different methods for informing the excavator conditions to the operator based on the sensor values. The methods are as follows:

- Make sounds of different types and patterns for expressing sensor values of the excavator and inform them to the operator
- Move the seat of the operator depend on the sensor values of the excavator
- Apply reaction force or vibration to the control lever of the excavator controller depend on the sensor values of the excavator.

About the first method, some current systems have a function which presents the sounds of working field picked up by a microphone on the excavator. However, further information like presenting many sounds during excavator operation may confuse the operator. About the second method, the already developed system exists [2]. It is shown in Figure 5. Although this system is effective for informing working conditions to the operator directly, it may increase the operator’s burden. Therefore, we considered that the third method, moving control lever depend on sensor values, is the most suitable for informing working conditions to the operator, then we adopted it for our study.

Figure 5. Moving operation seat for the remote control system [2]

We considered 3 methods to move control lever of the excavator controller for showing the sensor values of the excavator and informing working conditions to the operator. The methods are as follows:

- Applying reaction force to the control lever of the excavator controller depend on the sensor values.
- Applying breaking force to the control lever of the excavator controller depend on the sensor values.
- Vibrating the control lever of the excavator controller depend on the sensor values.

The first method was applied to the tele-operated support system of underwater excavator and confirmed that this method is good for tele-operated system when the operator cannot see the surroundings of the excavator [3]. The developed system is shown in Figure 6. Although this method is effective for informing working conditions to the operator when the operator cannot see the surroundings of the excavator, sometimes the operation may become unstable due to the delay of the feedback signal. The second method also seems effective for informing working conditions of the excavator to the operator. But, this is a passive method because breaking force acts only when the operator moves the control lever. Furthermore, the first and second methods may interfere when they are applied to the control lever at the same time. Then, we decided to adopt the third method which is vibrating the control lever depend on the sensor values.

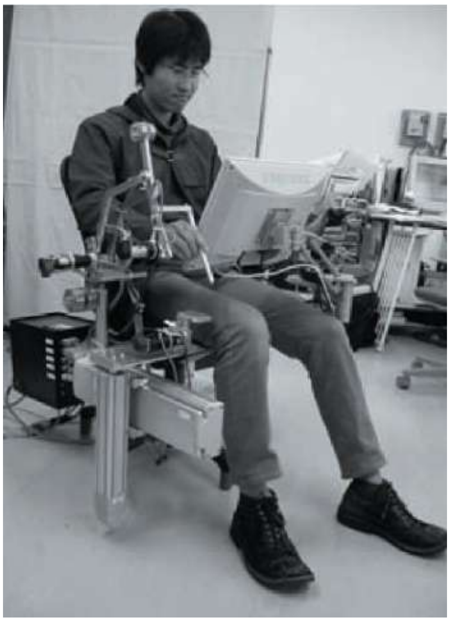

Figure 6. The operation system with force feedback controller [3]

We considered what kinds of vibration patterns of the control lever are good for operators to inform the condition of the excavator, and we proposed some vibration patterns shown in Table 1, Table 2 and Table 3. The proposed vibration patterns shown in Table 1 are for the information to the operator when the excavator starts moving. The vibration patterns in Table 2 are for the information when the excavator hits some obstacles. The vibration patterns in Table 3 are for the information whether the excavator reached its moving limits.

Table 1. Proposed vibration patterns which inform to the operator when the excavator starts moving

Method	Good point	Output
Vibrate only when the excavator starts moving	Can understand the moment when the excavator starts moving	Binary value
Vibrate while the excavator is moving	Can understand the excavator is moving or not	Binary value
Vibrate variably based on the moving speed of the excavator	Can understand the moving speed of the excavator	Analog value

Table 2. Proposed vibration patterns which inform to the operator when the excavator hits some obstacles

Method	Good point	Output
Vibrate while the excavator is loaded	Can understand the excavator is contacting something or not	Binary value
Vibrate variably based on the load of the excavator	Can understand the exerted load to the excavator	Analog value

Table 3. Proposed vibration patterns which inform to the operator whether the excavator reached its moving limits

Method	Good point	Output
Vibrate when the operator tries to move the excavator beyond moving limit	Can understand when the operator tries to move the excavator beyond the moving limit	Binary value
Vibrate variably based on the distance to the moving limit of the excavator	Can understand the distance to the moving limit of the excavator	Analog value

For informing the change of above three excavator conditions to the operator for the excavator remote control, we proposed two types of control lever vibration patterns. One is a constant vibration pattern, and another is a variably vibration pattern. The constant vibration pattern is proposed to detect the moment of condition change when the excavator starts moving or contacts something, etc. And, the variably vibration pattern is proposed to recognize the continuous condition change while the excavator is moving or receiving loads, etc. We evaluated these two types of patters through experiments using a simulator in the next chapter.

4 Evaluation of the proposed condition feedback methods

4.1 Evaluation system and method

We revealed three necessary information for the excavator remote control from the interview of skilled underwater excavator operators, and we proposed 7 vibration patterns of the control lever for informing the condition of the excavator to the operators.

To evaluate the proposed vibration patterns shown in the previous chapter, we developed a simple simulator system and made some experiments.

From the constraints of our experimental system, we evaluated the selected 4 vibration patterns of the control lever for informing the change of excavator conditions to the operator based on the sensor values shown in Table 4.

Table 4. Evaluated vibration patterns by our simple simulator system

Pattern number	Vibration pattern
1	The control lever vibrates while the excavator is moving. *The strength of the vibration changes according to the moving speed.
2	The control lever vibrates only when the excavator starts moving. *The vibration time is 0.2 sec.
3	The control lever vibrates while the excavator is loaded due to the contact of bucket and soil. *The strength of the vibration changes according to the exerted load.
4	The control lever vibrates when the operator tries to move the excavator beyond moving limit. *The vibration continues while the operator tries to move.

We made experiments to evaluate the above proposed 4 vibration patterns of the control lever. A joystick controller with vibration function and our developed simple simulator were used for the experiments. Figure 7 shows the joystick controller and its specifications are shown in Table 5. Our developed simulator is shown in Figure 8.

Figure 7. Joystick controller “PXN Thunder PRO”

Table 5. Specifications of the joystick controller [4]

Product name	PXN Thunder PRO
Model	PXN-2113
Connection	USB cable
Working current	100mA
Dimensions	22.5 x 18.5 x 18.5cm
Product Weight	About 495g

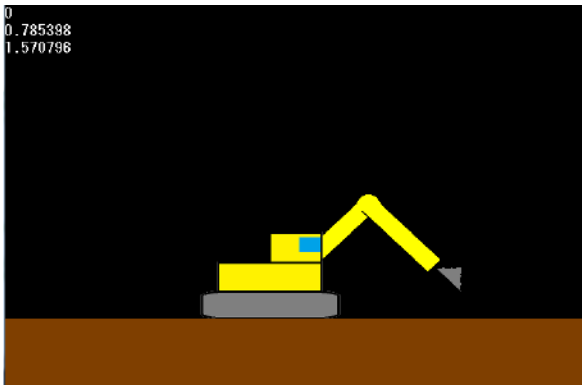

Figure 8. Simulator for the experiments

The simulator was composed of the joystick controller, a computer and a monitor. The connection of these equipment is shown in Figure 9. The computer receives a signal of tilt angle of the joystick controller and sends a signal of strength of the vibration. The monitor displays an image of the excavator like Figure 8. In the simulator, a boom of the excavator moves when the joystick controller is tilted to back or forth, and a bucket of the excavator moves when the joystick controller is tilted to left or right.

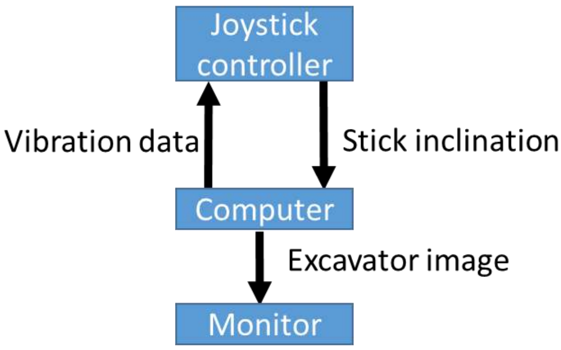

Figure 9. Equipment connection of the simulator

About the vibration pattern 1 in Table 4, the excavator in the simulator moves by tilting the joystick controller, and the moving speed of the excavator changes according to the tilt angle of the joystick controller. The joystick controller vibrates while the excavator is moving, and its vibration strength changes according to the excavator's moving speed. About the vibration pattern 2 in Table 4, the joystick controller vibrates for 0.2 sec. when the excavator starts moving by tilting the joystick controller. About the vibration pattern 3 in Table 4, when the contact of bucket and soil occurs in the simulator while the excavator is moving, the joystick controller vibrates for informing it. The strength of the joystick controller vibration shows the strength of the load exerted to the excavator bucket. About the vibration pattern 4 in Table 4, when the operator tries to move the bucket and the boom of the excavator beyond moving limit in the simulator, the joystick controller vibrates for informing it. The vibration continues until the operator stops moving the excavator to that direction.

Some subjects experienced all vibration patterns by using the simulator. After that, the subjects answered the questions about the impressions of each pattern. The questions are as follows:

- Which vibration pattern was good for operating the excavator?
- How did you feel about using these patterns?

4.2 Evaluation Results by subjects who have no experience operating excavators

Two subjects who don't have experiences operating excavators participated in the experiments. Both subjects answered that the vibration of the joystick controller to inform the collision of the excavator bucket to some obstacles is most useful for recognizing the working field conditions. And, one subject answered that the vibration of the joystick controller during excavator's moving is useful too. The answers of all subjects are shown in Table 6.

Table 6. Evaluation results by the subjects who don't have experiences operating excavators

Vibration pattern number	Evaluation
3	Easy to understand the collision of the excavator bucket to some obstacles, intuitively.
1 and 3	Good for recognizing the excavator and its working field conditions

4.3 Evaluation Results by subjects who have experiences operating excavators

Four subjects who have experiences operating excavators participated in the experiments. All subjects answered that the vibration of the joystick controller to inform the excavator's moving condition is more useful than the vibration which informs the start of moving of the excavator. The answers of all subjects are shown in Table 7.

Table 7. Evaluation results by the subjects who have experiences operating excavators

Vibration pattern number	Evaluation
1 and 3	Good for recognizing the excavator and its working field conditions
1	Vibration pattern 1: Vibration during the movement of the excavator is OK. Vibration pattern 2: It is difficult to understand the excavator's condition only from the vibration which informs the movement start of the excavator. Vibration pattern 3: It is difficult to understand the vibration's differences.
1 and 3	The system should have two different strength of vibration patterns which are strong and weak.
1, 3 and 4	Combining the vibration pattern 1 and 4 will inform us the posture of the excavator. The system should have different types of vibration patterns for presenting different information at the same time.

5 Conclusion

A remote controlled underwater construction machine was developed to reduce the operator's burden. However, current developed system has insufficient operability. This paper revealed the cause of operator's burdens for the operation of the excavator. Furthermore, more intuitive methods to inform the working field conditions to the operators than using a display monitor are considered. And, we proposed the simple but efficient working field condition feedback methods which uses the vibration of the control lever of the excavator for the remote controlled underwater excavator operator.

We considered three necessary information for the excavator remote control, and proposed 7 vibration patterns of the control lever for informing the change of excavator conditions to the operator based on the sensor values. Four different vibration patterns of the control lever were implemented to the simulator and they were evaluated through experiments.

From the results of evaluation experiments, we found that the vibration of the control lever to inform the excavator's moving condition is more useful than the vibration which informs the start of moving of the excavator for all operators. And, the vibration of the control lever to inform the collision of the excavator bucket to some obstacles is useful for recognizing the working field conditions around the excavator for non-skilled operators.

Our study will improve the operability of remote control system for construction machines. In future work, we will evaluate more vibration patterns and some combined vibration patterns using different types of vibration patterns through simulator and actual system experiments. In addition, further study about applying other kinds of feedback methods to the construction machines will be evaluated for the improvement of the system operability.

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Shape Control of Variable Guide Frame for Tunnel Wall Inspection to Avoid Obstacles by Laser Range Finder

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Abstract

To progress the automated inspection and maintenance of inner wall of tunnel, the advanced inspection system with restricting the traffic regulation was developed. In this inspection system, the guide frame along tunnel wall was installed on the protection unit stepped over the road like gantry crane. The inspection device moved with stability by adopting the guide frame, and the inspection accuracy could be improved. However, when this unit moved along the tunnel, this guide frame should avoid the convex obstacles such as duct fan, lamp and several road traffic sign in the tunnel. Therefore, by composing the entire frame of VGT (Variable geometry Truss), the shape of guide frame was changed flexibly and it could be passed in the tunnel. As a shape control of the guide frame, the inverse analysis method and mathematical interpolation method were applied. The angle of each frame was reversely analysed according to the shape of the obstacle measured with the LMS (Laser Range Finder), and the actuator of the frame was controlled simultaneously. We investigated the construction of a system that can perform a series of tasks such as searching for obstacles and positioning, frame shape simulation, frame shape change, inspection device movement. In this paper, the outline of tunnel wall inspection applied variable guide frame, the structure principle of the guide frame, basic method of shape analysis, the finding of convex obstacles by LMS and the whole inspection system are explained in detail.

Keywords –

Automated Inspection system; Variable Guide Frame; Shape Control; Obstacle Detection; Tunnel Inspection, ;

1 Introduction

Most of infrastructures for civil engineering structures such as highway roads, bridges, tunnels constructed around the urban region in high-growth era of 1970-1990 begun to reach the life, and it has been the time when large-scale repair and renewal, rebuilding were demanded. Since these structures are difficult to renovate after completion, it is necessary to grasp the progress of deterioration by periodic inspection and to maintain and manage such as repair and renewal on future prediction. Especially, with the collapse accident of the high way tunnel generated some time ago in Japan, the inspection of the superannuated tunnel was requested.

Generally, in the periodic inspection of the road tunnel, by restricting the traffic regulation and the engineers detected the deteriorated wall parts by sighting and hammering sound. To progress the automated inspection and maintenance of inner wall of tunnel, some advanced methods were adopted in the SIP program in Japan of the theme of "Maintenance and management robot". In our proposal of this theme, the inspection system was developed applying the variable guide frame to evade the obstacle in the tunnel without restriction of the traffic regulation as indicating in Fig. 1. In this inspection system, this guide frame was installed on the protection frame with travelling unit. When this unit moved along the tunnel, the guide frame should avoid the obstacles such as traffic plate and lamp in the tunnel. The shape of this frame changing flexibly, the frame was able to pass these obstacles in the tunnel easily [1], [2].

However, since the shape and position of the obstacle on the inner wall of the tunnel are different, it is necessary to change the shape of the guide frame according to each obstacle. In this study, we show the measurement method of the obstacle by the laser sensor and the result and specified the position and shape of the obstacle. As a method of measuring obstacles using laser, we can refer to automatic measurement technology [3], [4], 3-D scanning system [5], [6], [7], tunnel surveying system [8], [9]. On the other hand, as the determination of the guide frame shape, inverse kinematics of the robot mechanism, Spline interpolation which is a mathematical method were applied, assuming that both ends of the guide frame are fixed. By integrating such a series of measurement, analysis and control, it is possible to operate an efficient guide frame.

In this paper, the outline of tunnel wall inspection applied variable guide frame, basic method of shape analysis, the finding of convex obstacles and the whole inspection system are explained in detail.

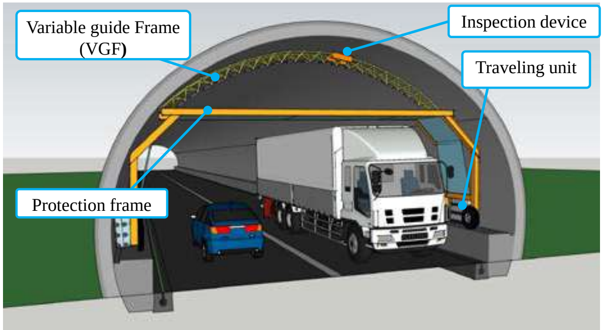


Fig. 1 Variable Guide Frame Vehicle for Inspection of Tunnel

2 Obstacles Detection in Tunnel

Since the positions and shapes of the various obstacles existing in the tunnel are described on the construction drawing of the tunnel, it is possible to change the shape of the frame so as to avoid obstacles. However, the guide frame being on the based truck, it is necessary to accurately measure the relative distance between the based truck and the obstacle. Also, because the movement error of the based truck is actually included, the obstacle search was carried out on the based truck at the site. In this chapter, Stereo measurement system, analysis method of the shape and position of the obstacle, and its measurement results were verified.

2.1 Stereo Measurement System Using Laser Rang Finder

As the base truck on which the guide frame is installed moves along the inner wall of the tunnel, obstacles protruding from the inner wall near the ceiling may come into contact with the guide frame. Here, as shown in Fig.2, two kind of the LRF was installed at the center of the truck beam surface part. LMS-1 is used to measure obstacles of short distance (6 m or less) with high accuracy, and LMS-2 is used to measure the whole area including obstacles at long distances (30 m or less), as shown in Fig. 3. The specification of LRF-1 and LRF-2 are indicated in Table 1.

We connected the LRF to the pan unit and constructed the stereo measurement system giving its inclination angle θ_2 to the plane measurement area angle θ_1 of LRF as indicated in Fig. 4-(a). In this case, if the distance to an obstacle measured by the reflection time of the laser is l, its coordinates (x, y, z) can be expressed by Eq. (1) - (3).

$$x = l \cdot \cos\theta_2 \cdot \cos\theta_1 \quad (1)$$

$$y = l \cdot \cos\theta_2 \cdot \sin\theta_1 \quad (2)$$

$$z = l \cdot \sin\theta_2 \quad (3)$$

The range of measurement is 30[m], the scan time rate is 25[ms] and the resolution angle of rotating laser is 0.25

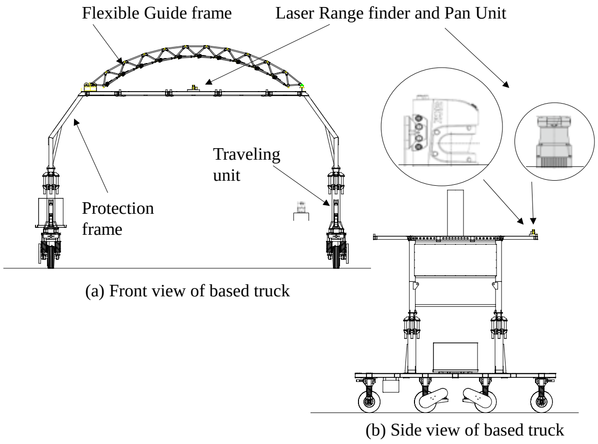
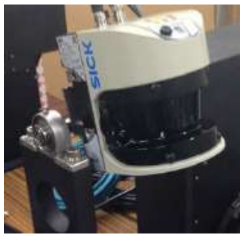


Fig.2 Structure of based truck and install of LRF on the truck

(a) LRF-1 and Pan Unit

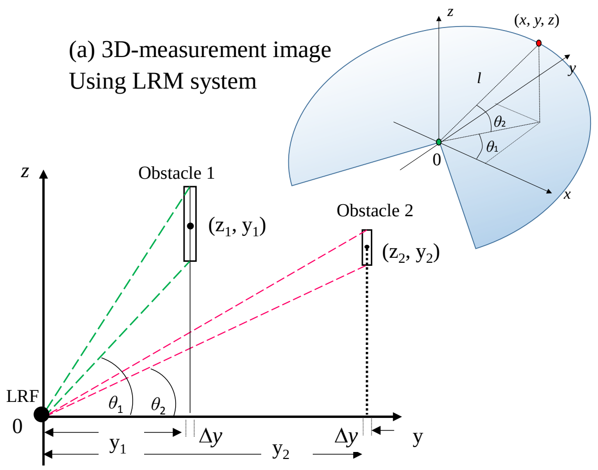


(b) LRF-2 and Pan Unit

Fig.3 Structure of based truck and install of LRF on the truck

Table 1 Specification of LRF

Type	LMS-1	LMS-2
Model Number	UTM-30LX	SICK-LMS511
Light Source	l=870 nm	l=870 nm
Measureable Area	270 deg	190 deg
Accuracy	10-30 mm	25-50 mm
Angular Resolution	0.25 deg	0.166 or 0.25 deg
Scantime	25 ms	10-11.3 ms
Pan unit resolution	0.5 deg	0.5 deg



(b) Objects analysis in x-z coordinate by LRF

Fig.4 Structure of based truck and install of LRF on the truck

[deg]. The angular resolution of pan unit was 1.0 deg. at $\theta_2 \leqslant$ 10 deg. and was 0.5 deg at θ_2 > 10 deg, the measurement precision was increased as it approached the tunnel inner wall. In an actual measurement, the laser irradiated from LRF is reflected to the outer side of the object, and the distances on each object surface were measured from the principle of TOF (Time of flight).

As shown in Fig. 4-(b), to ascertain the cross-sectional shape of the obstacle ahead from the based truck, the laser reflection points existing at the interval of ⊿y (= about 100 mm) with respect to the distance y from the based truck are counted. Then, it estimated that there is an obstacle in a certain y portion where the reflection points are strongly concentrated.

2.2 Position Analysis Method of Obstacles

In order to determine the position of the obstacle in the cross-sectional of tunnel, the center position of the obstacle was analyzed assuming that the shape of the obstacle was a circle from the contour of the point group. By assuming that the obstacle was circular even if it was rectangular, the contour of the obstacle was estimated on the safe side.

Fig. 5 shows the analysis flow for estimating the position and shape of the obstacle.

①: First of all, scanned the inside of the tunnel with LRF and derived and recorded the laser reflection point. However, since the laser reflection points from the inner wall of the tunnel were geometrically known, their reflection points were deleted. As a result, the shape of the obstacle ahead of the truck was extracted.

②: We classified the start position and the end position where the laser reflection point of the obstacle was recorded and extracted the edge of the obstacle.

③: The center position of the circle was estimated using the Constant Distance Method (CDM) [10] and the Least Squares Method (LSM) [11], assuming that the point group constituting the edge was an arc of a circle.

④: Finally, we confirmed the range that the shape change of the guide frame avoids with an extra margin against obstacles.

By repeating the above process, the shape and forward position of the obstacle to be avoided by the guide frame are determined [12].

2.3 Measurement Result of Obstacle

2.3.1 Short Distance Measurement by LRF-1

In short distance measurement using LRF-1, it is necessary to determine the position with an obstacle with high accuracy. Using the real simulated tunnel constructed for the experiment, the obstacles attached to the inner wall of tunnel was measured by LRF-1. Fig. 6 shows the state of the obstacle measured. In the x - y

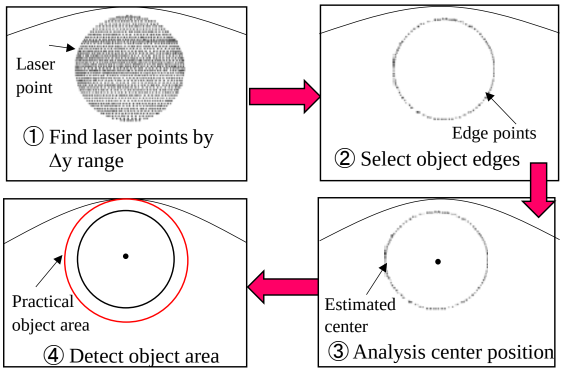


Fig.5 Analysis flow for estimating the position and shape of the obstacle by 3-D Laser Range Finder

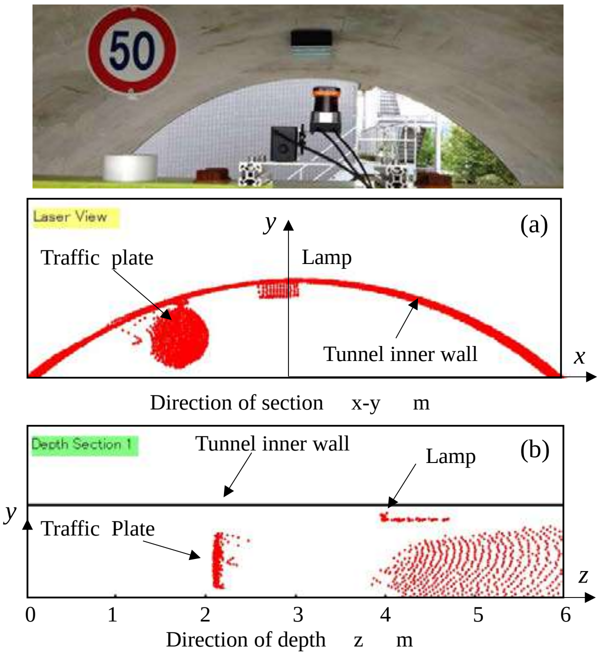


Fig.6 Obstacles state and positions measured by LRF

plane (Fig. 6- (a)), the shape including the traffic signs and the contours of the ceiling lamp in the tunnel is better captured by comparing to the actual picture. In the depth direction z-y plane (Fig.6- (b)), the position of traffic plate and the lamp could be estimated from the portion where the reflection points of the laser are densely concentrated, and it was confirmed that the position was also nearly accurate. In the calculated center position based on the obstacle data in the x - y plane was described in reference [13].

2.3.2 Long Distance Measurement by LRF-2

In order to confirm the long distance measurement using LMS-2, the obstacle was searched using actual tunnel. The radius of the tunnel was about 6 m, and the measuring instrument (LRF-2) was installed at a point of 90 degrees from the horizontal plane was performed at a resolution angle of 0.5 degrees, and the laser reflection distance in the tunnel was acquired. Fig. 7 shows the measurement situation in the tunnel. The lamp protrudes at regular intervals on the side of the ceiling surface of the tunnel, which is expected to become an obstacle when passing through the guide frame. Fig. 8 shows the measurement situation of the obstacle on the x-y plane seen in the entire cross section of the tunnel. When observing on the x-y plane, the obstacles overlap, so it is difficult to determine the exact shape of each obstacle.

On the other hand, the position of the obstacle was analyzed in the depth direction (z axis direction) of the tunnel. Fig.9 shows the shape (y axis direction) of the obstacle with respect to the depth position. Also, it shows the shape of the obstacle in the tunnel cross section with respect to positions ① to ④ where the obstacle was detected. It was confirmed that the lighting at the tunnel ceiling (①, ③, ④was located at regular intervals. As the depth distance became longer, the reflection point spacing of the laser expanded, and the shape of the obstacle became unclear. However, the existence of rough obstacles could each be confirmed. Also, as can be seen in the cross section of ②, obstacles (duct pipe) of a

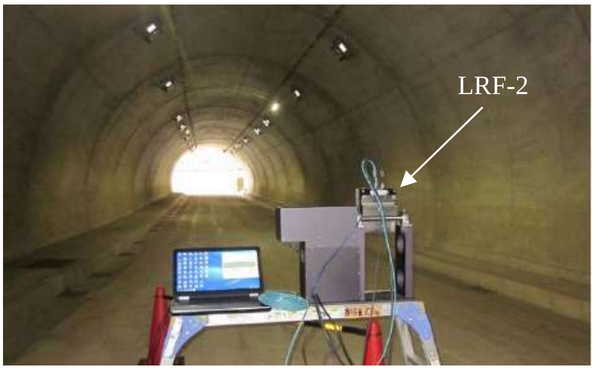


Fig.7 Measurement situation by LRF-2 in the tunnel

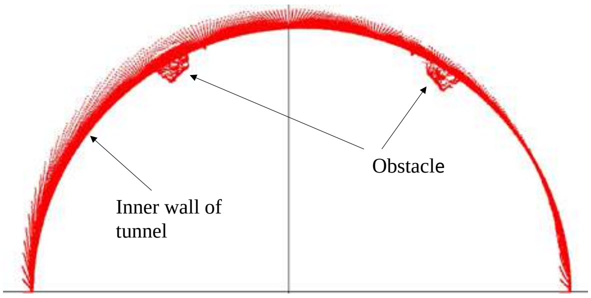


Fig.8 Measurement and shape of obstacles on x-y plane seen in all cross section

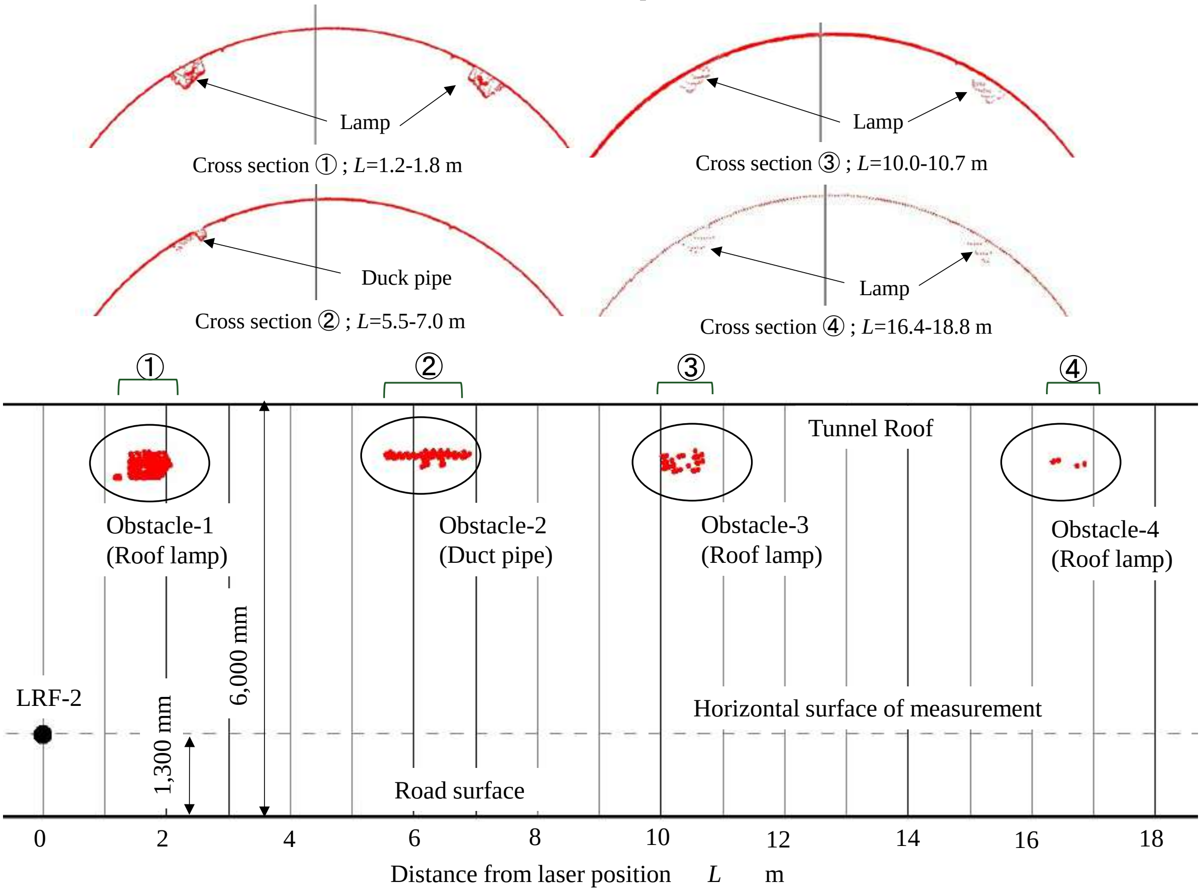


Fig.9 Shape (y axis direction) of the obstacle with respect to the depth position (z axis direction)

shape could be sufficiently confirmed

As described above, by combining the two LRFs methods, it was possible to detect the approximate position and shape of the obstacle at a long distance, and the accurate position and shape at short distance.

3 . Shape Control of Variable Guide Frame

In chapter 3, in order to create a complicated frame shape avoiding any obstacle on the ceiling surface of the tunnel, we simulated the shape of the guide frame by mathematical method and verified the possibility using real guide frame.

3.1 Frame Analysis by Kinematics

As analysing the arch structure composed of VGT, the whole of guide frame was assumed to be a cantilever structure as indicated in Fig.10-(a). The frame can replace a robot manipulator combining two fixed-length members in series. When the supported edge of frame was $q(x_0, y_0)$, the top $q(x, y)$ of the x, y co-ordinates of the frame combined with n (n≧2) VGT sets was given by Eq. (4) and Eq.(5) using each hinge angle θ_j.(j=1, 2, 3, · ·n),

$$q(x,n) = l_0 \cdot \sum_{k=1}^{n} \cos\left\{\sum_{j=1}^{k} \theta_j\right\} \quad (4)$$

$$q(y,n) = l_0 \cdot \sum_{k=1}^{n} \sin\left\{\sum_{j=1}^{k} \theta_j\right\} \quad (5)$$

Where, l_0 was the length of diagonal member of the frame. To transform the shape of arch frame, some hinge positions on the frame only had to change in proportion to target shape. However, for an intended frame shape fixed by equations (4) and (5), it was quite difficult to solve these equations analytically and to decide the angle because the frame was a very highly redundant. In this case, inverse kinematics analysis was applied [14], [15].

Introducing an inverse analysis to avoid the obstacle, first of all, a virtual obstacle was positioned on the perpendicular line of the obstacle as shown in Fig10-(a). The position of a virtual obstacle was gradually lowered, and the frame shape was changed so that surroundings of the obstacle should not come in contact with the frame. As showing the Fig.10-(b) and (c), the arch frame was indicated to change like avoiding the obstacle. Finally, a virtual obstacle came in succession at the position of a real obstacle, and the shape of a final arch frame was decided.

Fig.11 shows the result of experiment in actual model tunnel using variable guide frame. With the real arch frame of 6 m in length, similar shape was able to be also achieved by referring to the simulation result.

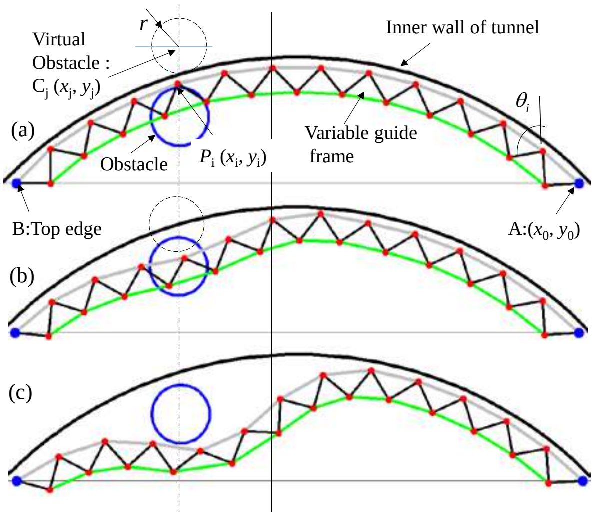


Fig. 10 Shape simulation of VGF to avoid obstacle

Fig11 Shape control of guide frame for traffic plate

3.2 Frame Analysis by Spline Function

In order for the guide frame to avoid obstacles, it is necessary to predict the final shape of the guide frame avoiding obstacles. In this section, the shape of the guide frame was analyzed using a Spline interpolation method and its effectiveness of the method was considered.

3.2.1 Shape Analysis by Spline Interpolation

To the initial guide frame shape, the overall shapes for avoiding obstacles were mathematically combined by the spline interpolation function.

Spline interpolation is a method of combining arbitrary shapes with polynomials to form a continuous shape. Assuming a function that interpolates the section (x_j, x_{j+1}), the piecewise polynomial $S_j(x)$ is expressed by the Equation (6).

$$S_j(x) = a_j(x-x_j)^3 + b_j(x-x_j)^2 + c_j(x-x_j) + d_j \quad (j = 0,1,2\cdots) \quad (6)$$

In order for this cubic equation to be a smooth curve, it is assumed that the value of the first derivative and the second derivative of $S_j(x)$ are equal, and the value of the second derivative at the start point x_0 and the end point x_n is 0. By applying the above conditions to each equation for several interpolation points, the coefficient of function a_j, b_j, c_j, d_j was calculated, and the function

by the spline interpolation was determined.
Here, each coefficient was determined as follows;

$$a_j = \frac{S_j''(x_{j+1}) - S_j''(x_j)}{6(x_{j+1} - x_j)} \quad (7) \qquad b_j = S_j''(x_j)/2 \quad (8)$$

$$c_j = \frac{y_{j+1} - y_j}{(x_{j+1} - x_j)} - \frac{(x_{j+1} - x_j)(2S''(x_j) + S''(x_{j+1}))}{6} \quad (9)$$

$$d_j = y_j \quad (10)$$

3.2.2 Estimation of Guide Frame Shape Avoiding Obstacles

Using the method in the previous section, several interpolation points (x_j, y_j) were determined so as to avoid obstacles, and the constants of the piecewise function were calculated using equation (6). Here, arbitrary six points (including both end points) that avoid obstacles are selected for the shape of the upper chord of the guide frame, and the shape of the new guide frame is analyzed. By constructing a system that can select representative points by touching the tablet screen, we were able to visually show the position to avoid obstacles. Several analysis examples are shown below.

(1) Example of side obstacle

The shape of a circular obstacle suspended from the left side of the tunnel ceiling overlapped the guide frame as shown in Fig.12-(a). We selected 6 optimum interpolation points to avoid obstacles and analyzed the shape of the upper chord by spline interpolation (Fig.12-(b)). A new guide frame was reproduced by configuring the guide frame to conform to the shape of the obtained upper chord member as shown in Fig.12-(c). Based on the above analysis results, the shape of the actual guide frame was observed in Fig.11. It was verified experimentally that the shape of the guide frame analyzed by spline interpolation was a shape that could smoothly obstruct obstacles.

(2) Example of center obstacle

In this case, the shape of the guide frame was analysed assuming an obstacle such as a discharge fan at the center of the tunnel as shown in Fig.13-(a). The interpolation points placing symmetrically at the bottom arc of a circular obstacle, it was possible to determine the shape of the guide frame for avoiding any obstacle (Fig.13-(b)). The shape of the actual guide frame was transformed using data analyzed. The experimental situation is shown in Fig.14. The guide frame was shaped to avoid obstacles, and it was confirmed that there was sufficient margin for structural mechanics.

From the above results, by using Spline interpolation method, it was possible to determine the shape of the guide frame for avoiding any obstacle

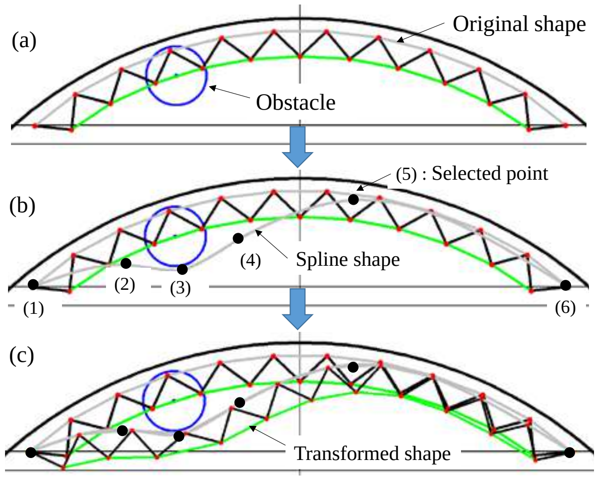


Fig.12 Shape decision of spline function for obstacle

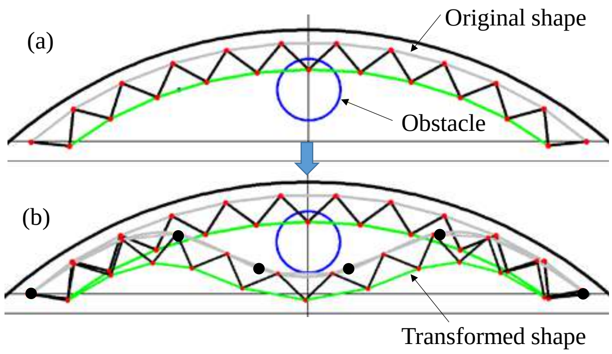


Fig.13 Shape decision of spline function for obstacle

Fig14 Shape control of guide frame for traffic plate

4. Conclusion

The tunnel ceiling area which was an obstacle of the guide frame was searched using two kind of LRF. LMS-1 is used to measure obstacles of short distance with high accuracy, and LMS-2 is used to measure the whole area including obstacles at long distances. By combining the two LRFs methods, it was possible to detect the approximate position and shape of the obstacle at a long distance, and the accurate position and shape at short distance. And also it was expected that it could be applied sufficiently to the actual measurement.

Next, we propose a method to analyzed the shape of the guide frame by inverse analysis and spline interpolation in order to create complicated frame shape avoiding arbitrary obstacles on the tunnel ceiling surface.

When using the inversed analysis, the shape change was created smoothly, however, since each frame undergoes a subordinate change, it is not very effective for complicated shapes. On the other hand, in the case of using spline interpolation method, since the function classification can be divided according to the shape of the obstacle, complicated obstacles can be dealt with.

In the future, we will establish a control method to continuously change the shape of the guide frame from the obstacle search in the tunnel, and to apply it to the actual inspection system.

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Evaluation Framework for Korean Traditional Wooden Building (Hanok) through analyzing Historical Data

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Abstract

A comprehensive research has been initiated by Korean government in order to disseminate modernized traditional Korean building (Hanok). Major objectives of this project include reducing construction cost and enhancing performance by developing construction materials and method for modernizing traditional Korean architecture. For example, modern construction methods such as glulam, steel joint, and truss are modified in order to keep the representations of Korean traditional esthetics. As part of this project, seven test-bed projects have been actually built in order to validate the performance of the modernized Hanok, and each project has somewhat different applications depending on its own design requirements.

In order to systematically compare and analyze the different applications of newly developed construction methods, this study proposes an evaluation framework with influencing variables. Firstly, the influencing variables such as different types of floor plan, roof structure and long-span beam of Korean traditional buildings were explored and defined. Historical database of these seven test-bed projects were then organized with standard classifications and numbering system. Finally, the historical database was analyzed based on the influencing variables in order to find patterns and compositions in applying new materials and methods for modernized Hanok. The findings of this study would provide a guide to selecting effective alternatives for new building types in terms of cost and performance.

Keywords –

Traditional housing, Information, Historical data, Evaluation framework

1 Introduction

1.1 Background and Objectives

There are active efforts to develop timber construction technologies around the world, such as large-scale and high-rise wood buildings. With this trend, researches in Korea are also being carried out to develop the technology of wooden buildings. One of them is to inherit the context of Korean traditional wooden building technology and modernize it [1].

In Korea, wood had been actively used in construction over the several centuries. Traditional architecture style of 'Hanok' had been widely used, and it was a typical housing type of Korea. However, due to the rapid industrialization, overseas technology such as masonry and concrete spreads rapidly, and the domestic wooden technology had relatively underdeveloped in Korea. As a result, 'Hanok' which was the traditional wooden structure of Korea now only exists as a traditional style, but it is hard to recognize it as a general urban building style [2].

Therefore, from 2010, Korean Ministry of Land, Infrastructure and Transport has conducted research on "Hanok Technology Development", which aims to develop Korean wooden technology by carrying on the legacy of Hanok. It has developed 'modernized Hanok' technology accommodating modern architecture technology [3]. 'Modernized Hanok' has been designed from the traditional Hanok to fit modern people's life, using modern methods and materials. This has resulted in improved durability and reduced construction costs. Currently, efforts are continuously being made to diffuse these technologies [4].

Moreover, using wood for high-rise and large-scale buildings is a world-wide trend. In line with this trend, researcher and practitioners are trying to develop large space and high rise [5] wooden buildings for modernized Korean traditional buildings.

The diversity of technology is largely divided into the user diversity and the technical diversity. The user diversity includes the requirements of the user such as the purpose of the facility, the size, etc., and the technical diversity includes the conditions applicable to the designer and the constructor such as the construction method and materials. Therefore, in the early stage of the project, it is required to technical diversity such as construction methods, materials and materials that can be applied to user diversity such as the use of buildings, size and budget. Especially, it is necessary to provide evaluation methods to solve this problem in boosting the architectural style of 'Hanok'.

Therefore, the purpose of this study is to propose an evaluation structure for examining various applicability of Korean wooden structure inheriting the traditional context of Hanok. For the purpose of developing the evaluation method, this study analysed seven test-bed projects those are actually constructed as part of this research. The evolving patterns of these seven test-bed projects are also analyzed in order to find implications

1.2 Hanok

Figure 1 Hanok - Ojukheon House
(Source: 'Korea Tourism Organization' Website)

Hanok is Korea's representative architectural style with more than 2000 years history. It is an eco-friendly building using wood as its main material and using natural materials such as stone and soil [7].

Traditional Hanok methods have only been connected by mortise and tenon joints [7]. This required considerable skill and effort, and it was disadvantageous for mass production. Further, it was difficult to have a large space due to the problems such as scarcity of large size wood materials. The inside space was formed by the column spacing of 2.4 ~ 2.6m [8], based on the unit space (칸, 間) consisting of four columns.

Traditional Hanok is a wooden building which has the advantages of eco-friendly and aseismicity, but it is difficult to reflect it in the modern age due to the structural limitations on durability and space enlargement.

Nevertheless, due to its traditional beauty, Hanok is still regarded as a type of housing that Koreans want to live in (As of 2008, 42% of Korean people want to live in Hanok) [9]. Today, although the appearance of the building seems to be a traditional Hanok style, its interior of the building is being developed using modern construction methods such as concrete. However, the discussion on how to define 'Hanok' in architectural style is controversial.

The purpose of this study is to provide a basis for the evaluation criteria of the applicability of modern construction methods to propose the continuous development direction of the Hanok applying various construction methods.

1.3 Hanok Scope of development

Before proceeding with research, 'Hanok' should be defined first. The reason is to propose a standard to judge to what extent Hanok can be defined as 'Hanok' when the Hanok evolved into various technologies.

"Hanok" in "Act on Value Enhancement of Hanok and Other Architectural Assets" is legally defined as follows. "the main structure of which consists of wooden columns, beams and Korean style roof frames and which reflects the traditional style of Korea, and any building annexed thereto [6]." According to the Seoul Metropolitan Government Ordinance of the Republic of Korea, "Hanok" is defined as follows. "The main structure is made of wood, and it means the buildings or their attached facilities that have traditional beauty among the buildings using Korean style tiles [7]". Table 1 summarized the definitions about Hanok in the literatures and the laws in Korea.

Table 1 Requirements of Hanok

Original Hanok[8]	・Main structure and all visible elements : traditional techniques, ・Indoor space: Modernized kitchens and bathrooms, applying modern technology for heating and air-conditioning equipment, electrical equipment, insulation, sanitary facilities
Traditional Hanok[9]	Hanok with traditional technology and space
Modern Hanok[8]	・Main structure: Wood ・Roof, Stylobate, Wall : traditional
Traditional Urban Hanok[10]	・Korean style tile, wooden column, ・Buildings that maintain the traditional style of the wooden structure
Hanok style House[11]	・Main structure: Wooden structure or Traditional hanok style using other materials, ・Korean style tile

As a result of examining related laws, ordinances and research literature defining Hanok, it could be summarized as follows.

1. The exposed main structural part should be wooden. (External columns must be exposed)
2. Korean style Tiles should be used on the roof.
3. Do not expose the metal connector to joints.
4. It should be finished with natural material.

According to these requirements, the material other than wood (e.g. steel, concrete) can be used for main structure of Hanok if it is finishing with wood.

In this way, it is very important to analyse quantitatively the process of the various materials and the construction method according to various demands in the historical and industrial aspects of Korean architecture.

It is also very valuable to set standards for analysing the changes in materials and construction methods and accumulating information.

2 Case Study

In the modernization of traditional Hanok, it is important to predict the range of applicable technology for various needs and apply the optimal combination through it. Therefore, this study aimed to classify the applicable technologies to Hanok through Hanok test-bed projects as a step to derive the optimal technology combination.

2.1 Analysis of the Hanok cases

'Modernized Hanok', which was constructed in the research process of modernizing traditional Hanok, was attempted as far as possible in the application of various modern new building methods and materials, without hindering the traditional aesthetic appearance. During the period of about 6 years, there were efforts of the research team to establish a total of seven different test-bed buildings. In addition, various as-built databases of test-bed projects such as construction cost, construction period, and productivity from the construction process were standardized and accumulated. Especially, intensive efforts to lower the high cost of construction, which was one of the characteristics of traditional Hanok, and to improve the quality had been concentrated.

The entire study was carried out in two stages. The first stage was residential facilities, and the second stage was extended from residential to public facilities for various applications of technology. In addition, the third stage of research is started in 2018, and the technology is being developed for large-scale Hanok.

In order to propose the evaluation structure, seven case studies were carried out except for the case of a village test-bed project. Case 1 used traditional Hanok construction methods for comparison purpose, Case 2 and Case 3 were built by using modernized methods for residential housing. Finally, Case 4, Case 5, Case 6 and Case 7 are modernized Hanok for public buildings.

Table 2 summarized the general outlines of the seven cases. Carpentry construction accounted for about 30% of the total construction cost. But the fact that proportion of construction cost is decreasing didn't mean the decreased use of wood materials. It was caused by increased cost of concrete in the foundation.

Though the total costs including carpentry, finishing, equipment, mechanical, and electrical works were analysed, this paper focuses on carpentry works cost per unit area, a large amount of construction cost was used without any major change in the absolute amount of

Carpentry is the main structural part of the Hanok and occupied a large portion in terms of total costs and quantities.

Table 2 Table 2 General outlines of 7 actual modernized Hanok cases

	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7
							
Total construction cost ($)	240,000	260,000	275,000	2,406,000	1,002,000	708,000	541,000
Total floor area (㎡)	70	130	140	950	450	260	250
Building area (㎡)	70	80	70	570	340	275	110
Characteristics	Traditional	Wet+Dry	Glulam	Curved Beam	Truss	Arch Frame	Steel Frame, Concrete Slab
Construction period (day)	-	-	154	337	237	167	199
Roof form	3	3	5	5	5	5	3
Carpentry Cost ($) per area	1,144	439	676	702	468	684	252
Carpentry ratio (%)	33%	21%	34%	28%	21%	25%	12%

2.2 Needs for Standard Classification for Hanok Construction

As mentioned above, the aim of this study is to develop an evaluation methods for selecting appropriate methods for different type of Hanok projects. The evaluation structure should reflect user diversity and their technical diversity. In order to explain this, it is necessary to classify the technical standard of the Hanok wooden structure and the following suggestions was drawn to define it.

First, the structure of Hanok should be based on wood columns and beams.

From the past, Hanok has emphasized the characteristics of each element of the building. Various terms were used depending on the details of the design used, the shape of the member, the size, and so on. It was also possible to estimate the era of Hanok construction through these characteristics. Therefore, a very complicated terminology has been used, and the problem has arisen that the standard classifications are not clear when modern architects try to describe modernized Hanok elements. However, this is one of the most representative features of Hanok. So it is difficult to apply modern classifications, while completely ignoring it. Therefore, in order to know the applicable technology range of the modernized Hanok, it is necessary to define the terms of the absence of the classification according to the element, and to organize the applicable techniques such as the construction methods and materials.

Second, in order to utilize the best combination of technologies for each span and scale at the time of building a Hanok, including large size and high-rise buildings, it is necessary to review the structural safety evaluation standards.

Third, it should be able to support the analysis of economic efficiency in the construction method and material selection in the state where the original design of the Hanok is fully reflected.

Fourth, it should be able to support the industrialization of materials. Industrialization of each member is essential for the spread of Modernized Hanok. Through the standard classification of Hanok technology, it is possible to derive efficient member dimensions for each technology according to the span and scale of the building, and these dimensions should be standardized to support establishment of industrialization base.

3 Standard Classifications for Hanok

Standard classifications for Hanok technique are defined as element classification, method classification, and material classification reflecting the characteristics of Hanok discussed above.

3.1 Element Classification

Element classification should be the first since Hanok has different characteristics and methods. The element classification was divided into five categories: roof, roof structural system, beam, column, and floor through previous studies [16]. Complex and various traditional terms were re-defined with simple descriptions.

Roof included timber used for roof parts such as rafters [*Seo-ka-re*] and wood board. Roof Structural system was located between the columns and the roof, and represent the overall structure of the roof and the building. This is one of the distinct characteristics of Hanok, and includes purlin [*Dori]*, etc. Beam in the highest floor was categorized as one of the roof structural systems. However, it was classified in order to perform detailed analysis for each applied method. When comparing quantities by element in this paper, they were combined and analysed together. The columns included inner columns [*Go-ju]* and outer columns [*Pyeong-ju]*. The slabs include joists [*Jang-sun*], floor boards [*Ma-ru*] and the like.

3.2 Method Classification

The classification criteria of methods based on literature reviews as well as domestic and foreign wooden building case studies (including 7 modernized Hanok test-beds) are summarized as follows. It was classified into one column system, one slab, four roof structural systems, four beams, and two roof systems. Table 3 below summarizes the applicable methods for each elements. The column method is divided into one vertical column, which supports vertical load, and the slab is divided into one, horizontal slab method. The roof structural system is divided into four types: Korean Traditional, truss, arch, and tension cable. Among them, the beam part which is one of the members of roof structural system is divided into four parts: straight beam, curved beam, truss beam, and Tension Supported Bending structure. The roof is divided into two types, wet type and dry type.

Of course, it is difficult to see the all applicable method for each element, but it was based on the possibility in the category of Hanok which is now recognized, and it can be added later

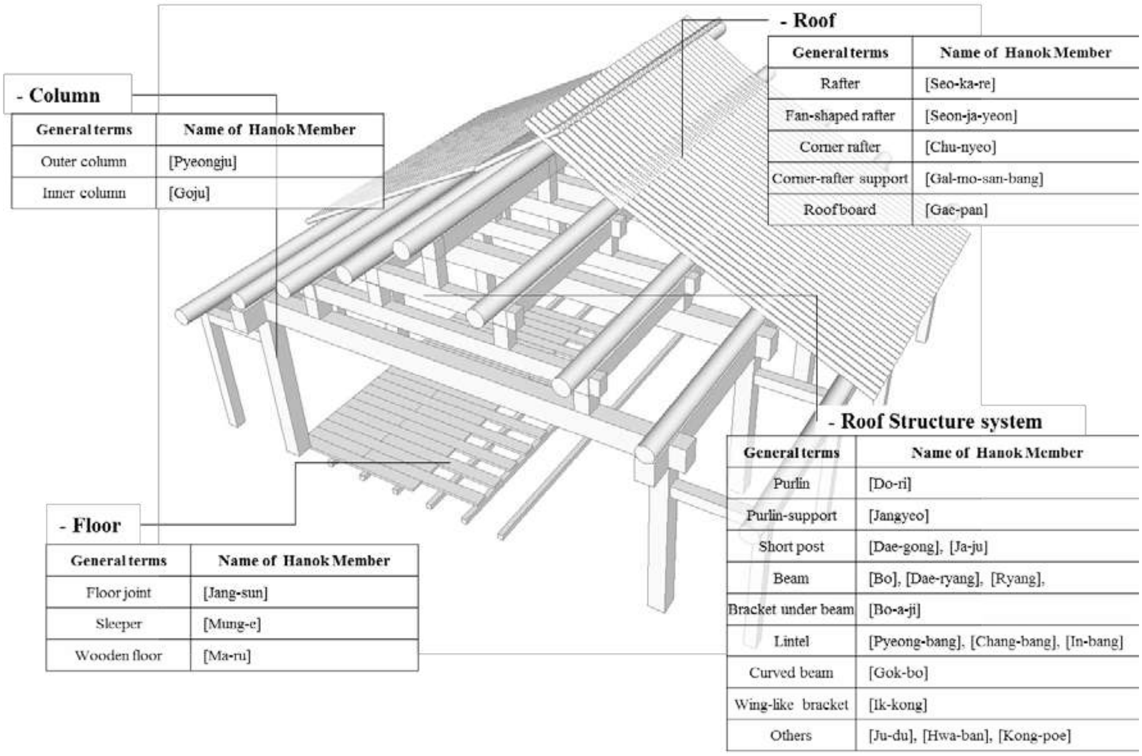

Figure 2 Element classification of Hanok (Preceding study) [16]

Table 3 Elements Classifications and Methods Classifications in each part

Elements		Methods	
C	Column	C01	Upright Column
S	Slab	S01	Floor Slab
F	Roof structure system	F01	Korean Traditional
		F02	Truss
		F03	Arch
		F04	Cable
B	Beam	B01	Straight Beam
		B02	Curved Beam
		B03	Truss Beam
		B04	Tension Supported Bending Structure
R	Roof	R01	Wet (Traditional Method)
		R02	Dry

3.3 Material Classification

Next, materials that can be used in each method should be selected. The classification of materials was summarized by using literature data and classified into five categories: wood, glulam, steel, reinforced concrete and composite. (Table 4)

Clearly Hanok architecture is a wooden building, so it is required to pay attention to use other materials other than the wood for the main structural parts. However, as the different requirements (size, use) of the main structural parts of the Hanok have been increased, other materials including steel and concrete have been applied to the standards so as able to be reflect the possibility of various applications.

Table 4 Classification of Materials

Materials	
W	Wood
G	Glulam
S	Steel
R	Reinforced Concrete
C	Composite

Among the standard classification of Hanok technology, the top three categories were summarized as elements, methods, and materials. When it has shown as matrix, the total range of its combinations was about 80,000 cases.

In future studies, the most unlikely combinations should be excluded through the quantitative evaluation to find a more optimal combination.

4 Utilization of SC Matrix

Hanok can be applied in various ways beyond the traditional style of the past by applying modern technology and it can be developed into a large scale and a high rise.

Therefore, in modernization of Hanok which has the potential of development, it is required to quantitatively analyze and systematize the variables.

4.1 Concept of Evaluation Framework

Hanok can be developed variously through application of modern technology.

Figure 3 shows the concept of the evaluation framework that draws the optimal combination of technologies according to the diversity of users by using the standard classification matrix of the Hanok technology. Variables according to user diversity, such as the size, use, and budget of the facility, are entered as input variables in the standard classification matrix of Hanok technology, and the matrix is used to evaluate the practical, productive, and economic combinations. In this way, optimized combinations of method and material are drew about each element, and optimal combinations of type1, type2, type3, etc. can be selected as output.

In conclusion, the purpose of the evaluation framework is to find out the optimal value required by the user more efficiently and to consider the correlation, quantity ratio, economical efficiency, productivity, etc. in the total number of possible cases of Hanok technology. In addition, it is to evaluate the combination of classification elements by analyzed quantitatively.

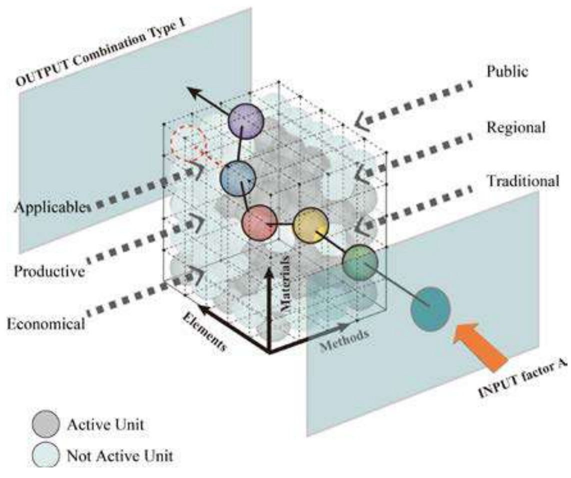

Figure 3 Evaluation Framework Structure using SC Matrix

The evaluation framework using the standard classification of Hanok technology can support to select the optimal technology combination, and it can be used in various ranges.

First, it can be used to estimate the appropriate construction cost. It is possible to analyze the correlation between each combination technique using the actual Hanok data and use it to predict each construction cost, and estimate it more accurately.

Second, it is possible to find the optimal combination according to various variables such as the size and the floor of the Hanok that users want to build. The combination of appropriate technologies based on span, number of floors, type of building, etc. is quantified and evaluate. And ultimately it makes it possible to select the optimum combination of high evaluation values.

Third, it is possible to consider the design which preserved the traditional Hanok. Proportion and harmony are important when designing considering the traditional Hanok. It can be evaluated in consideration of the dimensions and proportions of members, and it can be utilized in the design of traditional Hanok.

In the following chapters its utilization was explained with more specific examples.

4.2 Case-study using Evaluation Framework

In order to propose a combination of Hanok wood structure using the evaluation framework, it is necessary to draw elements through analysis of many accumulated actual cases.

Among the seven test-bed projects of the modernized Hanok introduced in the previous chapter, five cases were selected for this case-evaluation except case 1 and 3. Because case 1 and case 3 were too difficult for comparing with the others (Case 1 used traditional method and case 3 wasn't classified by the same classification).

Table 5 compared the main structures by case for technical classification of wooden structures. Case 1, Case 2, and Case 3 were residential buildings and had similar wooden structure characteristics. And these public buildings of cases 4, 5, 6 and 7 in which various requirements were changed from the residential were used for the analysis of the wooden structure.

As shown in Table 5, the evaluation framework could be effectively used to compare the wood structures by element, material and construction method. There were many cases where materials other than wood materials were used in the floor part when dividing the quantity of wood, so it was difficult to compare and it seems that it will become more serious in the modernization of Hanok.

Table 5 shows the share of wood per square meter. The wood quantity of the columns, the roof structural system part, and the roof part were examined by each case. When the wood quantities in the cases are compared (except for the quantities of wood flooring), the proportion of each part of total wood use is as follows. Case 2 showed 7% of columns, 44% of roof structural system, and 49% of roofs. Case 4 showed 12% of columns, 40% of roof structural system, and 48% of roofs. In Case 5, 11% of columns, 48% of roof structural system and 43% of roofs were used. In

Table 5 Comparison of materials and methods by elements, Qty Unit : ㎥ (Slab : ㎡)

	Case 2		Case 4		Case 5		Case 6		Case 7	
	Technique	Qty	Technique	Qty	Technique	Qty	Technique	Qty	Technique	Qty
Roof (㎥)	R01G	9.3			R02G	1.1			R02G	0.5
	R01W	6.1	R02W	122.6	R02W	33.7	R02W	37.3	R02W	48.0
R Total		**15**		**123**		**34.8**		**37.3**		**48.5**
Roof wooden structure (㎥)	F01G	0.2	F01G							
			F01W		F01W	13.39	F01W	12.0	F01W	37.6
					F02W	15.4				
							F03G	1.1		
F Total		**0.2**		**0**		**28.79**		**13.1**		**37.6**
Beam (㎥)			B01G	35.0						
	B01W	14	B01W	59.5	B01W	10.2	B01W	18.05	B01W	3.2
			B02G	8.1						
B Total		**14.2**		**102.6**		**10.2**		**18.05**		**3.2**
Column (㎥)	C01G	2.1	C01G	26						
			C01W	4	C01W	8.9	C01W	5.0	C01W	2.3
									C01C	
C Total		**2.1**		**30**		**8.9**		**5.0**		**2.3**
Slab (㎡)	S01G									
	S01W	290			S01W	1141.6	S01W	163.8		
			S01R	467			S01R		S01R	
S Total		**290**		**467**		**1141.6**		**163.8**		**0.0**
Total floor area (㎡)	130		950		450		260		250	
Wood Qty (㎥) per Total floor area – **R ㎥/㎡**	**0.12**		**0.13**		**0.08**		**0.14**		**0.20**	
F ㎥/㎡	**0.11**		**0.11**		**0.09**		**0.12**		**0.16**	
C ㎥/㎡	**0.02**		**0.03**		**0.02**		**0.02**		**0.01**	
S ㎡/㎡	**2.30**		**0.49**		**2.56**		**0.62**		**0.00**	

Case 6, 7% of columns, 42% of roof structural system, 51% of roofs, 3% of cases 7, 44% of roof structural system and 53% of roofs were used.

By comparing the cases, the similar distributions of the wood quantity were found except for Case 7, where the first floor was constructed with a steel frame and then finished with wood. In this way, it can be inferred that the cross section and the number of columns are maintained at a constant ratio with the amount of wood in the roof structural system part and the roof part. In addition, other materials can be used through the ceiling finish, which can reduce construction costs by replacing traditional methods of exposing wood to roofs without ceiling finishes.

It can be seen that most wood structures use raw woods. This can be considered in relation to the emotional part of Koreans, and it means that the use of natural wood, which has been used from the past, has been recognized as a representative material of Hanok until now. However, the use of glulam is expected to increase in modern Korean Hanok, and it is expected that the use of this will become even higher due to safety reasons in the modernized Hanok, which is growing in size.

Most of the beams and roofs are similar, but the change of the partial construction method can be confirmed because of the increase of the space area or the installation of the attic room.

Although it is only the result of analyzing with few cases, it was possible to analyze the change of the structure of Hanok wood structure through the Hanok technique classification more accurately. It will analyze these more in detail in the future and incorporate it into the main component of the evaluation framework. In particular, it will be finally necessary to elucidate factors such as economic analysis, design proportion, regional characteristics, and structural safety of the evaluation structure proposed.

5 Conclusion

The purpose of this study is to suggest a framework for evaluating the application of various methods available in Hanok construction and for deriving optimal technology combinations.

For this purpose, this study defined a standard classification of Hanok wooden structure, which accounts for the highest construction cost in Hanok construction. Based on a literature review and seven test-bed projects, the concept of evaluation framework was proposed to develop a classification matrix.

Furthermore, a detailed and systematic evaluation will be developed in near future by building more test-bed projects.

Future study will include the relationship of wood quantities between the column and the roof structural system, the relationship between the area (or span length) of the space and the wood quantity, and the relationship between the sectional area of the member and building (or roof) area, and so on.

It is expected that this evaluation structure will be used as a research that would systematically suggests the combination of modernized Hanok technology that encompasses future large-scale Hanok and future Hanok.

6 Acknowledgments

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Development of automated mobile marking robot system for free access floor

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Abstract –

Improvement of productivity in construction work is strongly required because a shortage of construction workers has become a major social issue in Japan. Marking work for installing building materials is indispensable. This work is currently carried out manually. If this work can be automated, construction workers can concentrate on installing the building materials. Therefore we intend to improve productivity by automating this work with a mobile marking robot system.

For the first step, we developed the marking robot system for a free access floor. To build this, grid-pattern lines should be drawn on the floor. Our system can automatically mark the intersections of the lines which are the positions for installing pedestal bases of the free access floor. Our system consists of a mobile marking robot and a laser positioning unit. The former is a mobile robot which has the marking device at its center. Cross marks are drawn on the floor by controlling the marking device. The laser unit accurately directs the point and line laser in the target direction and measures the distance to the object on which the laser spot is projected. The marking robot tracks the line laser and arrives at the target area. The deviation between the target position and the robot center is calculated, and the cross mark is drawn exactly on the target position.

This paper describes the mechanism of our system. It also shows the satisfactory tracking performance and marking accuracy in several experiments.

Keywords –

Marking; Mobile robot; Omnidirectional vehicle; Tracking; Free access floor

1 Introduction

A shortage of construction workers has become a major social issue in Japan. In 2015, the number of construction workers was about 73% of what it had been at its peak in 1997. In the construction process, marking work is indispensable. Construction workers need to draw marks and lines on the floors, walls, ceilings, and so on in the construction site in order to install building materials. In recent years, survey technology has progressed remarkably. Instruments such as laser scanners and total stations have been used in construction fields. Some 3D measuring and marking systems using a total station have been reported [1-3]. These systems are not aimed at automating marking work but at increasing the efficiency of manual marking work. By automating this work with mobile marking robots, construction workers will be able to concentrate on installing building materials and productivity will increase. There have been some studies on automated mobile marking robots. The system reported by Tanaka et al. draws specified figures on the ceiling board [4]. This robot needs to detect the edges of three existing pillars in the construction site by using a laser range finder (LRF). If the distance from the robot to pillar is far or the pillar is covered with fire resistant material, this system cannot mark with high accuracy. In the system reported by Zulkifli et al. [5], a camera needs to be installed on the ceiling and calibrated depending on the installation position, which is very laborious and costly work. Moreover, the area in which a robot can mark is limited by the visual field of the camera. Inoue et al. reported a system using a total station and LRF to measure the robot position [6,7]. In this system, the attitude angle of the mobile robot cannot be measured while moving. Therefore, in our viewpoint, it is difficult to stably navigate the mobile robot to the target position. The navigation method from a mark point to another mark point has not been reported in detail. "Laybot" developed by DPR construction [8] can mark lines on slabs for drywall layout. Since it draws lines while running, it is difficult to draw highly precise straight lines.

As a first step, we intended to automate the marking work for installing a free access floor. In order to build the free access floor correctly, grid-pattern lines should be drawn on the floor before they are installed. The intersections of the lines are the positions for installing the pedestal base of the free access floor. This paper deals with the development of the marking robot for automatically drawing cross marks on the floor which indicate the positions for installing the pedestal bases.

The marking robot is guided to the target position by the laser marker. The three dimensional measuring instrument measures the robot position accurately. Based on the actual robot position, the marking pen installed on the robot is controlled and draws the cross mark at the target position. After that, the robot moves to the next target position and continues this cycle. Since this process is fully automated, just giving all the target positions coordinates in advance to this system allows, all the cross marks corresponding to the positions for installing the pedestal bases to be drawn.

2 Outline of the marking robot system

Our system is composed of a laser positioning unit (LPU) and a marking robot (MR). The operation of the marking system is shown in Figure 1. In this figure, r is the distance from the LPU to the screen placed on the MR base and θ is the direction angle of the point laser. In our system, the marking flow is divided into the MR guidance phase and the cross-mark drawing phase.

In the MR guidance phase, the MR travels from the current position, A (r_a,θ), to the next target position B (r_{tgt},θ_{tgt}). At first, the LPU precisely directs the point laser parallel to the floor in the direction of the target position. Secondly the LPU turns the line laser toward the angle θ_{tgt}. The MR base includes cameras and screens. The cameras capture the screen image where the laser spot and line are projected. The MR tracks the moving laser line and travels on the circumference of a circle whose radius is r_a while keeping the screen perpendicular to the line laser. When the angle of the line laser reaches θ_{tgt}, the LPU stops turning the line laser and the MR stops. Subsequently the MR moves backward or forward on the straight line connecting the LPU and the position B so as to approach the target position B while keeping the screen perpendicular to the line laser. The MR stops when the difference between the distance r measured by the LPU and the target distance r_{tgt} become less than the threshold. However the arrival position of the MR does not exactly correspond to the target position. The actual center position of the MR is measured by the LPU and the camera.

In the cross-mark drawing phase, the MR draws a cross mark exactly on the target position. The MR has a marking device which can move a marking pen in the x, y, and vertical directions. The movement value of the marking pen is calculated by comparing the target position B and the actual center position of the MR. By controlling the marking device based on the calculated movement value, a cross mark whose center corresponds to the target position B is drawn on the floor.

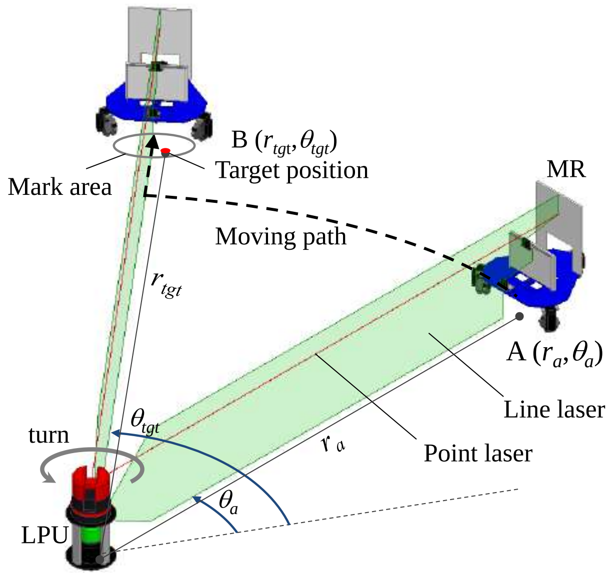


Figure 1. Outline of the marking flow using marking robot system

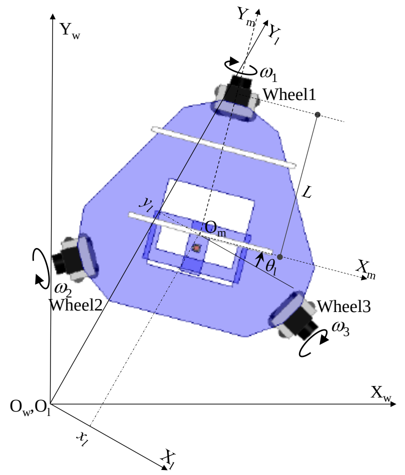


Figure 2. Kinematic model of ODV

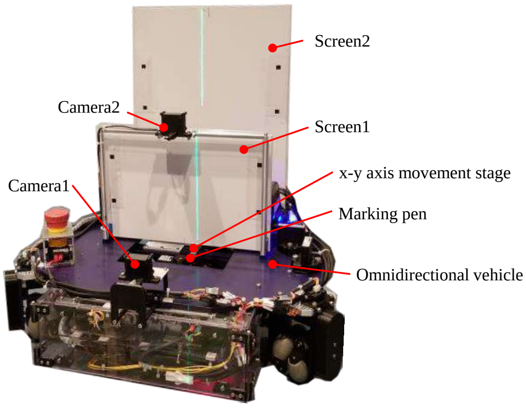


Figure 3. Photograph of marking robot

3 Composition of marking robot system

Our system consists of the MR and the LPU, each controlled by a computer. The two computers can communicate through the wireless network.

3.1 Marking robot (MR)

We use an omnidirectional vehicle (ODV) as the movement vehicle. It has three omnidirectional wheels mounted symmetrically, with 120 degrees between them. Each wheel is driven by a DC motor and is the same distance from the robot's center. Unlike the non-holonomic robots, this type of vehicle has a full mobility in the plane which means that at each instant it can move in any direction without any reorientation [9]. We can control the rotational speed of each wheel independently by sending commands to the motor driver. The kinematic model is shown in Figure 2. For the convenience of description, this paper defines three coordinate systems: Σ_w, the world coordinate system, Σ_R, the robot coordinate system, and Σ_L, the laser coordinate system, in which the coordinate Y_L axis corresponds to the direction of the line laser and the origin O_w and O_l are the same. Here ω_i (i=1,2,3) are the rotational velocities of the wheels (i represents the number of the wheel), R_w is the radius of the wheel, and L is the distance from the robot's center to the wheel. x_l, y_l, and θ_l are the positions and attitude angle in the Σ_L. The inverse-kinematic model in the Σ_L is represented in Equation (1) [10].

$$\begin{bmatrix}\omega_1\\ \omega_2\\ \omega_3\end{bmatrix} = \frac{1}{R_w}\begin{bmatrix}-\cos\theta_l & -\sin\theta_l & L\\ -\cos(\theta_l+2\pi/3) & -\sin(\theta_l+2\pi/3) & L\\ -\cos(\theta_l+4\pi/3) & -\sin(\theta_l+4\pi/3) & L\end{bmatrix}\begin{bmatrix}\dot{x}_l\\ \dot{y}_l\\ \dot{\theta}_l\end{bmatrix} \tag{1}$$

A photograph of the MR is shown in Figure 3. Two screens and cameras are placed on the ODV base. Screens 1 and 2 are parallel to each other and perpendicular to the floor. The distance between the screens is y_s. Cameras 1 and 2 face Screen 1 and 2 respectively and capture each screen image on which the laser spot and line are projected. The marking device is installed at the center of the robot. It consists of the x-y axis movement stage and the pen unit which can move the marking pen in the vertical direction. The pen unit can be moved on slider rails. By controlling the marking device, the cross mark is drawn on the floor.

3.2 Laser positioning unit (LPU)

This unit is composed of the guide laser unit (GLU) and the three dimensional measuring instrument (3D-MI: in our system, this is a Leica Geosystems 3D Disto. The accuracy of angle measurements is 5 seconds and the accuracy of the distance between two points about 10 m apart is approximately 1 mm). Like a total station, the horizontal and vertical axes of the 3D-MI can be motorized. This can direct the point laser accurately in the direction indicated in advance and measure the distance to the object on which the laser spot is projected. The GLU consists of a laser marker and a rotation stage. The laser marker can generate a vertical line laser. Construction workers often use this for drawing a reference line on the floor, wall and ceiling and so on. This is placed on the rotation stage. The vertical axis of the 3D-MI agrees with that of the rotation stage. It is also motorized and the rotational speed is controlled through the RS485 interface. A photograph of the LPU is shown in Figure4.

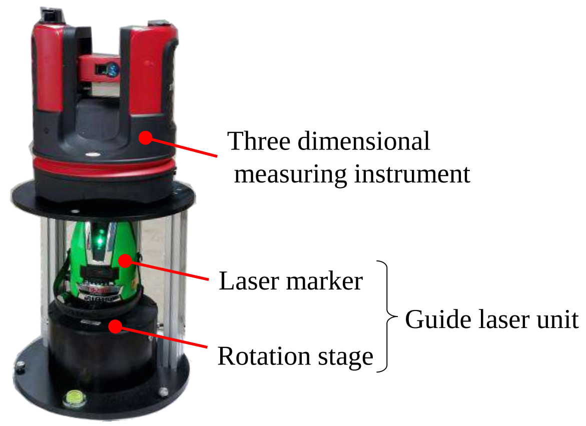
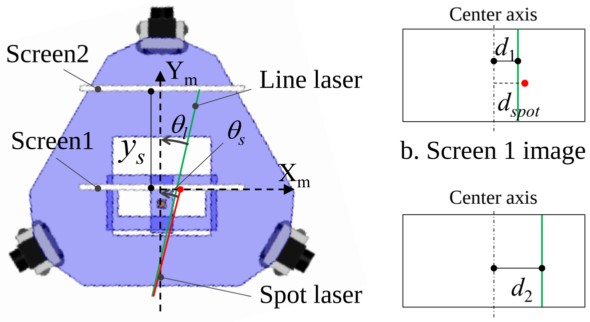


Figure 4. Photograph of laser positioning unit



a. MR and laser layout c. Screen 2 image

Figure 5. Screen layout and laser projected on the screen

4 Control of MR and LPU

4.1 Mechanism for measuring MR position

As shown in Figure 5, the attitude angle θ_l in the Σ_l is calculated from Equation (2), where, d_1 and d_2 are the x-coordinates of the laser line projected on each screen in the Σ_R. In the drawing cross mark phase, a laser spot is projected on Screen 1. Δx_r and Δy_r, which are respectively the movement values of the pen unit in the x and y-axis directions in the Σ_R are calculated from

Equation (3) and (4) using the geometric relationship, where, d_{spot} is the x-coordinate of the laser spot in the Σ_R, r_{screen} is the distance from the LPU to Screen 1, and θ_s is the attitude angle of the MR with respect to the direction of the spot laser. The laser spot does not necessarily overlap the laser line exactly because of the rotation stage control error. Since θ_l is nearly equal to θ_s, we use θ_l instead of θ_s in Equations (3) and (4). By controlling the marking device, the cross mark is drawn on the target position exactly.

$$\tan\theta_l = \frac{d_2 - d_1}{y_s} \tag{2}$$

$$\Delta x_r = d_{spot} + (r_{screen} - r_{tgt})sin\theta_s \tag{3}$$

$$\Delta y_r = (r_{screen} - r_{tgt})cos\theta_s \tag{4}$$

4.2 Detection of laser line and laser spot

It is difficult to measure the laser position accurately from a captured image without image processing because the captured image has two types of distortions which we have to remove. First, the lens distortion is removed by using Zhang's method [11]. Figures 6a and 6b show the screen images before and after the distortion removal. Subsequently, the perspective distortion is removed by the homography transformation, based on the following formulae:

$$\begin{cases} u_i = \dfrac{a + bs_i + ct_i}{1 + gs_i + ht_i} \\ v_i = \dfrac{d + es_i + ft_i}{1 + gs_i + ht_i} \end{cases} \tag{5}$$

Where

u_i,v_i: camera coordinates after the transformation

s_i,t_i: camera coordinates before the transformation

Eight unknown parameters a, b, c, d, e, f, g, h are obtained by solving the Equation (5) substituting a combination of more than four known points (u_i, v_i) and (s_i, t_i). In our system, a calibration mark is drawn on the screen. Four black squares are arranged at the four corners of a rectangle whose width and height are W and H respectively. Figures 6b and 6c show the screen images before and after the homography transformation. The position of the laser line and the laser spot are measured from this image. First, the red, green, and blue channels are extracted. In each channel image, the average pixel intensity of each column is calculated as shown in Figures 7a, 7b, and 7c. Since the laser marker emits a green laser in our system, the difference pixel intensity is calculated by subtracting half of the red and blue channel components from the green channel component as shown in Figure 7d. $u_{max,j}$ (j is the screen number) is the horizontal camera coordinate with the largest pixel intensity. d_j which is the x-coordinate of the laser line in the Σ_R is calculated using Equation (6).

$$d_j = (\frac{u_{max,j}}{N_H} - 1/2)W \tag{6}$$

Where, N_H is the number of the horizontal pixel.

The laser spot with the 3D-MI is red. A binarized image is obtained from a red channel image utilizing a binarization threshold. The binarized image is smoothed by expansion and contraction processing. As shown in Figure 8c, the laser line and block noise are removed and only the laser spot remains after this process. From this image, the area centroid is calculated. After that, as shown in Figure 8d, the masked image is obtained by setting the pixel intensity except for the 50 x 50 pixels square region centered on the area centroid to zero in the red channel image. The horizontal camera coordinate of the laser spot, $u_{max,spot}$, is calculated as the brightness center of gravity in this masked image. d_{spot} , which is the x-coordinate of the laser spot in the Σ_R, is also obtained from Equation (6). This image processing is conducted by the computer installed on the MR. The calculation cycle depends on the computer performance. In our system, it is approximately 0.17 seconds.

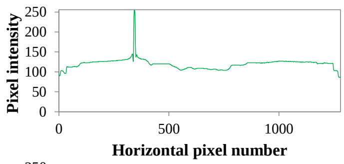
a. Captured image

b. Image after distortion removal

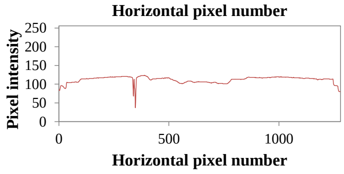
c. Image after homography transformation

Figure 6. Images before and after distortion removal

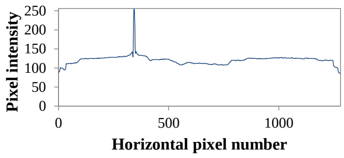
a. Green channel



b. Red channel



c. Blue channel



d. Difference component

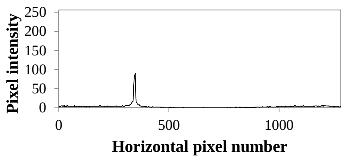


Figure 7. Average pixel intensity

a. Original image

b. Red channel image

c. Binarized image

d. Masked image

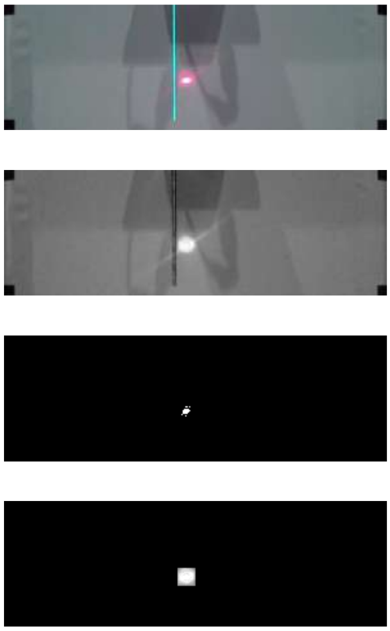


Figure 8. Spot laser image before and after image processing

4.3 Motion control

4.3.1 Control system

In our system, the MR tracks the line laser. The block diagram for tracking the line laser is shown in Figure 9. The meaning of each symbol is listed in Table 1. This PI (Proportional-Integral) control system feedback-controls the rotational speed based on the tracking error (e_x,e_θ) in Table 1. By converging the tracking error to zero, the MR tracks the laser line while keeping the screen perpendicular to the line laser. The actual center position and attitude angle is measured by the method detailed in the former section.

4.3.2 Traveling on the circular path

As explained in Section 2, as the line laser turns, the MR travels on circular path while keeping the screen perpendicular to the line laser. In the experimental setup shown in Figure 10, the tracking performance on the path was evaluated by changing the rotational speed of the rotation stage to 0.3, 0.6 and 0.9 degrees per second. The reference center position, attitude and translational velocity for the y axis direction in the Σ_l and the proportional and integral gains were set as listed in Table 2. Because $\dot{y}_{l,d}$ was set to zero, the MR tracked the moving line laser without approaching or moving away from the LPU. The proportional and integral gains were adjusted based on the values obtained in the simulation and preliminary experiment result. Figure 11 shows the relationship between x_l or θ_l and time. In the all rotational speed, the screen was nearly vertical to the

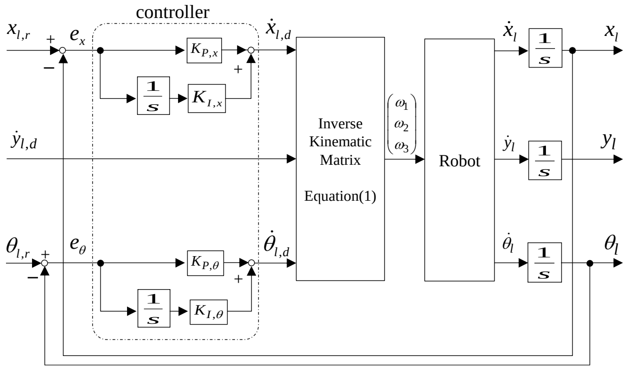


Figure 9. Control system

Table 1 Setting parameter

Parameters	Details
$(x_l,\ y_l,\ \theta_l)$	The actual coordinate and attitude of the MR in the Σ_l
$(x_{l,r},\ \theta_{l,r})$	The reference x-coordinate and attitude of the MR in the Σ_l
$(e_x,\ e_\theta)$	The deviation between the reference and actual value
$(\dot{x}_{l,d},\ \dot{y}_{l,d},\ \dot{\theta}_{l,d})$	The direction value of the translational and rotational speed of the MR in the Σ_l
$(\omega_1,\ \omega_2,\ \omega_3)$	The direction value of the rotational speed of each wheel
$(\dot{x}_l,\ \dot{y}_l,\ \dot{\theta}_l)$	The actual translational and rotational speed of the MR in the Σ_l
s	Differential operator

Table 2 Setting parameter

Parameter	value
$x_{l,r}$	0
$\theta_{l,r}$	0
$\dot{y}_{l,d}$	0
$K_{p,x}$, $K_{p,\theta}$, $K_{I,x}$, $K_{I,\theta}$	20, 0.244, 4, 0

line laser. When the screen is vertical to the line laser, x_l indicates the deviation between the line laser position and the screen center. In our system, W is 270mm. Although the laser line remained on the screen with any rotational speed, the translational speed of the laser line projected onto the screen increases as the distance between the MR and the LPU increases. Therefore, our system is designed to change the rotational speed of the rotation stage based on the distance from the LPU to the MR to prevent the laser line from being off the screen. That is, the rotational speed is inversely proportional to the distance.

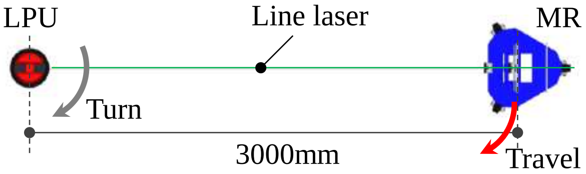
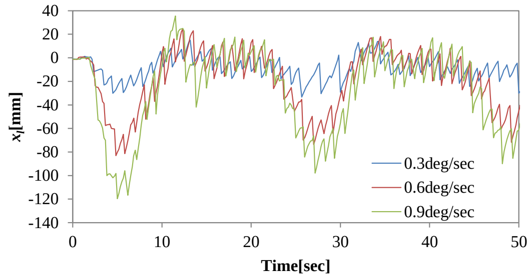
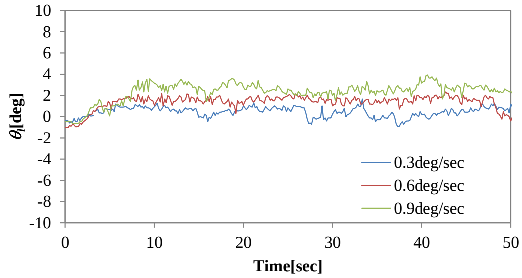


Figure 10. Experimental layout



a. Relationship between x_l and time



b. Relationship between θ_l and time

Figure 11. Tracking performance traveling on the circular path

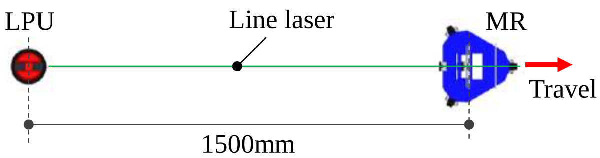


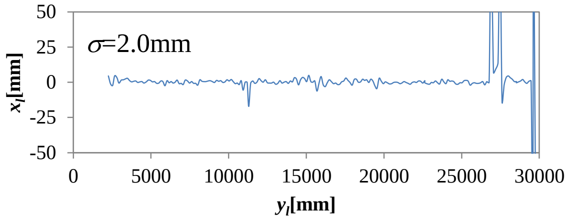
Figure 12. Experimental layout

4.3.3 Traveling on the straight line

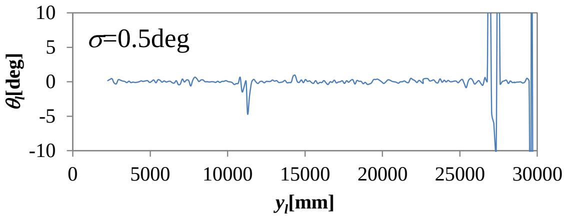
When the line laser stops turning, the MR travels on the straight line connecting the LPU and the next target position while keeping the screen perpendicular to the line laser. In the experimental setup as shown in Figure 12, the tracking performance during travel on the straight line was evaluated. The setting parameters are listed in Table 3. Except for $\dot{y}_{l,d}$, they are the same as those for travel on a circular path. The MR travels at a speed of 50mm per second in the direction of the line. Figure 13 shows the relationship between x_l or θ_l and y_l. We confirmed that the MR stably traveled on the straight line until y_l was about 27 meters using this motion control method. The absolute values of x_l and θ_l were less than 25mm and 5 degrees respectively. Each standard deviation is 2.0mm and 0.5 degrees respectively. These values are very small.

Table 3 Setting parameter

Parameter	value
$x_{l,r}$	0
$\theta_{l,r}$	0
$\dot{y}_{l,d}$	50
$K_{p,x}$, $K_{p,\theta}$, $K_{I,x}$, $K_{I,\theta}$	20, 0.244, 4, 0,



a. Relationship between x_l and y_l



b. Relationship between θ_l and y_l

Figure 13. Tracking performance traveling on the straight line

5 Experiment

In order to evaluate the performance of the developed marking system, a basic test was executed. The experimental layout is shown in Figure 14. In the 4m x 10m test area, we set 50 target positions, which were grid intersections at intervals of 1m. The MR marked from Position A0 to Position J0 position in order. The total time spent marking was about 100 minutes. After marking all positions, the coordinates of the centers of every cross mark were measured using the 3D-MI.

Figure 15 shows the frequency distribution of x_l or θ_l, in the MR guidance phase. They are created from the measured x_l and θ_l every 0.17 seconds. They concentrate near zero. Each average value was 0.9mm and 0.03 degrees, and the standard deviation was 26.8mm and 1.2 degrees respectively. These results show that the MR stably tracked the line laser while controlling the attitude so that the laser line was in the screen center and vertical to the screen surface.

All of the deviations between the target positions and marked positions are summarized in Figure 16. Figure 16a shows the deviations at all marked positions. Figure 16b shows the deviations distribution. In this figure the radius of the red circle is 3mm. Figure 16c shows the frequency distribution of the deviation. The average deviation was 1.5mm, and the maximum value was 3.9mm. 94% of the measured values are within less than

3mm deviation. There is no strong correlation between the distance from the LPU to the MR and the deviation. Relatively large deviations are thought to be due to the local unevenness of the floor surface and detection error of the laser spot center from the screen image. By setting the target positions in advance, accurate and automatic marking was achieved in this system.

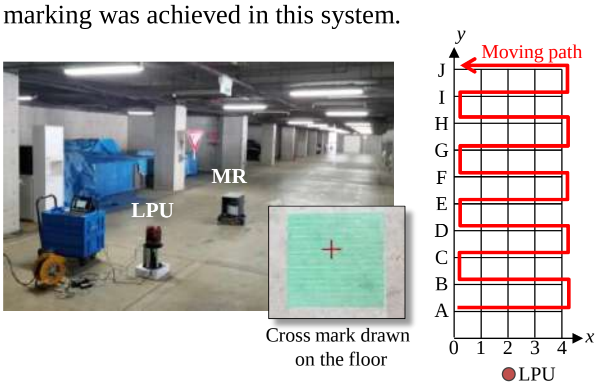
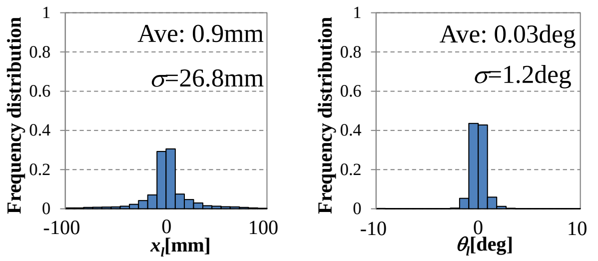
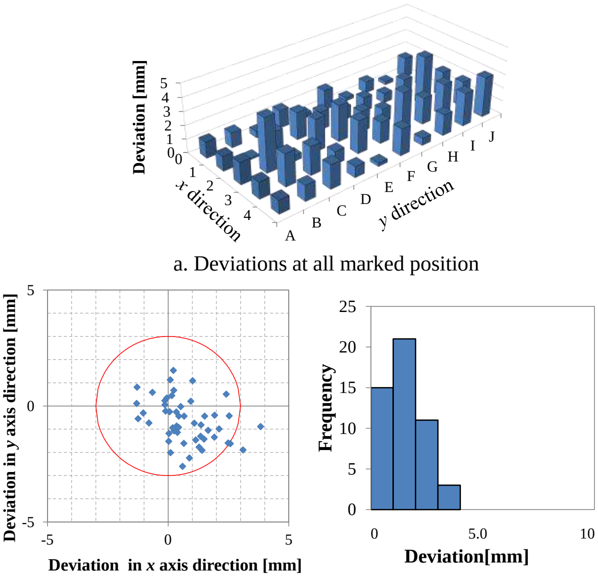


Figure 14. Experimental layout



a. Frequency distribution of x_l b. Frequency distribution of θ_l

Figure 15. The performance for line laser tracking



a. Deviations at all marked position

b. Deviations distribution

c. Frequency distribution of the deviation

Figure 16. Experimental Result

6 Conclusion and future research

We described the mechanism of our automated mobile marking system for free access floors in detail. In the experiment at the test site, the MR stably tracked the laser line generated by the LPU and then reached predetermined target positions. Furthermore, we confirmed the deviation between the mark drawn by the MR and the target coordinate was 1.5mm in average and 94% of the deviations are less than 3mm. This marking operation was fully automated. Therefore improved productivity in the construction work is expected.

However, some limitation can be identified. First, the time spent on marking is long. This work usually requires two workers using carpenter's ink pads or chalk line and measure. Experienced workers can mark with more than 10 times faster. Second, direct sunlight disturbs the detection of the line laser and the MR cannot track it. That is, the area where we can control the MR becomes smaller due to the influence of sunlight. Finally, some large deviations between the target positions and marked positions have been observed in the experiment. Some factors are considered. One is the local unevenness of the floor surface. The other is detection error of the laser spot center from the screen image. We have to solve these problems to improve performance of the MR in the future research.

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Automatic Tracking Camera System for Construction Machines by Combined Image Processing

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Abstract -

The damaged area caused by disasters must be restored as soon as possible. So, remotely controlled construction machines are used to execute this dangerous work, safely.

In the remote construction, machine operators always watch images of the working field from pan-tilt monitoring cameras controlled by camera operators. Then, the automatic camera control system without camera operators is expected for machine operators.

Based on the above requirement, we are developing an automatic tracking camera control system for construction machine operators by using image processing. The most difficult point for this system is to realize a stable outdoor object detection by image processing. So, we proposed a new image processing method which is a combination of "Improved template matching" and "Moving object detection". From experimental results, we confirmed that the proposed method is improved about the robustness of outside construction machines tracking.

Keywords -

Unmanned construction; Camera tracking; Image processing

1 Introduction

A lot of disasters occur in Japan. So, the damaged area must be restored as soon as possible. However, the workers cannot approach the area because of dangerous. Therefore, the remotely controlled construction machines are used to restore there. In the remote construction, machine operators always watch images of the working field from pan-tilt monitoring cameras to control the construction machines. Therefore, the machine operators need to be helped by camera operators. Then, using an automatic camera control system without camera operators is expected for machine operators.

Based on the above requirement, we are developing an automatic tracking camera control system for construction machine operators. In order to track the construction machinery, it is necessary to detect the position of the heavy machine.

There are several methods to detect a construction machine and its position.

One is a method using UWB (Ultra Wide Band). In this method, an active electronic tag is mounted on the construction machine, and the receiving antenna is installed in the construction area. Based on the communication time between the tag and the antenna, the position of the construction machine is measured [1].

There is another method using BLE (Bluetooth Low Energy) technology [2]. In this method, a Bluetooth oscillator is installed in the construction area. The position of the device which has an antenna is measured based on the received radio wave intensity. The location of the installed antenna and the oscillator must be known accurately for this method. However, accurate installation of sensors at the desired positions in disaster areas is difficult.

The research of object tracking using a TOF (Time-of-Flight) camera is also conducted [3]. The TOF camera can get depth information of the acquired image, and track the desired object in the image based on this information. However, this method needs the TOF camera, and the effectiveness of this method is confirmed in the limited environment like on the belt conveyor. So, it is considered that the detection of the construction machine by this method is difficult in the actual disaster area.

In the actual disaster area, GPS is normally used to detect the position of the construction machine. However, unfortunately, some construction machines do not have GPS sensors. Usually, cameras are always used in unmanned construction. Then, we set our target to develop an automatic tracking monitor camera system for construction machines only using image processing.

Many methods have already been proposed for object tracking by image processing technology. However, camera tracking of construction machine based on image processing is difficult because of the following reasons.

- Generally, image processing is weak in outdoor environment. But, construction machines are used in outdoors, mainly. Depending on the weather and brightness change of the day, the color of the heavy machine recorded by the video camera changes.
- The construction machine changes its orientation during its works. So, its image recorded by the camera changes when the machine turns. Furthermore, since the heavy machine has a complicated shape and its appearance image changes drastically depending on its orientation.

As described above, camera tracking for construction machine in various environments by image processing is difficult. Therefore, we considered a solution, and proposed a new image processing method which is a combination of template matching and motion detection. Generally, template matching is weak to the change of the target shape. So, we added the detection of moving object process for our method to overcome the weaknesses of template matching. Our proposed method is explained in detail from the next chapter.

2 The Problem of Image Processing for Object Tracking and Its Resolution

2.1 The Problem of Image Processing for Object Tracking

Color based object tracking is one of the simplest method for image processing based tracking. The method is robust in changing of object's shape and turning of object. In addition, construction machines have conspicuous color, so this method seems effective for construction machines tracking. But, The problem of image processing for object tracking object detection by image processing and color based object tracking is difficult for outdoor objects because the object color data is affected by the sunlight. Furthermore, the recorded color data of construction machine and sand by video camera is sometimes very similar. Then, color based object tracking is not suitable for construction machine tracking.

Some tracking methods which are not color based tracking are provided by OpenCV libraries. These methods are MIL, TLD, MedianFlow, KCF, and Boosting [4]. We tried using these methods for construction machine tracking practically, and confirmed that these methods are not appropriate for it. Because, the speed of these image processing methods is slow, and the tracking by using these methods sometimes failed when the construction machine turns for changing its moving direction and input camera image drastically changes.

It is found that the accuracy of kernel based object detection is high in the construction site [5]. However, based on our trial, the processing time of KCF method which is one of the kernel-based methods was long, then we considered other simple methods.

As another object tracking method, there is a moving object detection using background subtraction method [6]. This method is robust for the above problems in the fixed camera image, but it cannot track the object when the camera is moving, because all camera image moves with camera's moving.

2.2 The Basic Idea to Resolve the Problem of Object Tracking by Image Possessing

Object tracking by image processing is achieved by the continuous detection of object in a camera image. This study proposes combination of two detection methods for robust object tracking. One of them is a template matching which is a simple and fast object tracking method. The other is a detection of moving object using background subtraction method. Generally, object tracking using template matching method prepares a template image for its target, beforehand, and tries to track it by searching the most similar area with the template image. Therefore, the template matching is weak in the appearance change of tracking object. In the construction machine tracking, the target machine moves and its appearance taken by the camera changes, so we considered that the combination method of template matching object tracking and moving object detection can track the construction machine, robustly.

First, we confirmed the ability of template matching based camera tracking method. This method can track construction machine in some cases, but it sometimes fails when the appearance of the construction machine changes drastically. This is a common issue of the image processing based object tracking methods. However, this method is effective for object tracking under camera moving situations.

Next, we confirmed the ability of construction machine detection based on the moving object detection by using background subtraction method. When the construction machine is moving in the captured image, this method certainly detects it. But, needless to say, this method cannot detect the construction machine when it is stopped, or camera moves.

The advantages and disadvantages of these two methods are confirmed, then we decided to combine these two detection methods for construction machine tracking. This combination method tracks the construction machine by using the result of moving object detection when the construction machine is moving, and the result of template matching based detection when the camera is moving. By combining these two methods, the system can track construction machine even if its appearance changes drastically.

Some people may think that the tracking camera moves continuously during its object tracking and moving object detection method cannot be used for construction machine tracking. However, it is no problem because the tracking camera does not move continuously in our target situation. There are two ways of construction machine tracking by the camera. One of them is a method for capturing the construction machine always at the center of camera screen by moving the camera continuously. The other is a method for capturing the construction machine not out of the camera screen by moving the camera with some intervals. In this case, the camera is stopped until the construction machine moves near the edge of the camera screen, and moved before the construction machine is out from the screen. In the actual construction site, the latter method is used for the remote control operation of the construction machine. If the former method is used, the machine operator cannot recognize the speed of the construction machine because of the camera's moving. Therefore, we adopted the latter method in our study, and we could use the moving object detection process based on the background subtraction method for the construction machine tracking.

3 The Trucking Method Combining Template Matching and Background Subtraction.

3.1 The Tracking Method Base on The Template Matching

Template matching is an object detection method in the camera image. It finds an object image part which matches the template image. In the construction machine detection, a template image of construction machine is prepared, and the construction machine image part is found from the image acquired by the camera. Even if the completely matched part with the template image is not found in the camera image, the most similar part is detected as the construction machine. Repeating this process in real time, we can track the target construction machine, continuously. However, object tracking by template matching is weak when the image of tracking object drastically changes. We made an experiment of construction machine tracking using template matching, and found that the tracking of the construction machine failed in several second after it start moving. Therefore, we improved the tracking method using template matching.

We updated template images in real time, so the tracking robustness has improved more than before. Generally, the template image is prepared in advance and the same template image is used during its process, but in this method, the template image is updated as the progress of the tracking process. The detailed process is explained as follows:

First, rectangular template image is selected in the camera image by dragging the mouse. The most similar part with the selected template image is detected from the next frame image acquired by the camera. A new template image is created from the detected image and this process is repeated for continuous tracking. By using this improved method, we could track the construction machine continuously. However, when the distance between the construction machine and the camera changes and the construction machine image size changes, or when the appearance of the construction machine drastically changes due to its turn, the similar matching part with template image disappears and the template matching method fails to track it. We also improved the processing speed of template matching based object tracking method. Matching process is executed only around the template image not for whole screen image because the construction machine moves gradually in the screen.

3.2 Object Detection by Background Subtraction

Template matching based object tracking cannot track the object when the construction machine moves hard. Therefore, we focused on the movement of the object and adopted the background subtraction method which is a typical motion detection method.

Background subtraction is a method which compare two images and extract the different parts. It can extract the changed part by comparing the current frame with the past frame of the camera image. So, it is possible to detect the moving objects and used for motion detection. However, in case when the camera moves or zooms and the whole screen changes, it is difficult to detect the moving objects. We tried to detect construction machines using background subtraction. The moving parts were extracted by comparing the images, but we could not detect the construction machine as one moving object. Figure 1 shows the result of moving construction machine detection using the background subtraction. The white points indicate the extracted parts which the frame image changes.

From background subtraction method, only the moving object edges are extracted in many cases as shown in Figure 1, so we improved this method. The background subtraction data obtained in the past several frames were overlapped and made an image like afterimage (Figure 2). After that, the expansion process is added to the overlapped image (Figure 3). As a result, moving parts can be extracted, clearly. However, moving parts are not yet recognized as one object at this point. Then, labeling is added to this image for recognizing the connected parts as one object. The rectangle in Figure 4 shows the recognized moving object by labeling process.

From the above results, we confirmed that it is possible to detect moving objects by using background subtraction method. Of course, when the camera moves and the whole screen image moves, or plural objects exists in the camera image, it is difficult or not able to detect the target construction machine, accurately by this method.

3.3 Proposed Combination Method of Template Matching and Background Subtraction

The improved template matching based object tracking method can track the construction machine, continuously. However, when the size or appearance of the construction machine image acquired by the camera changes, the

Figure 1. The results of object detection by background subtraction

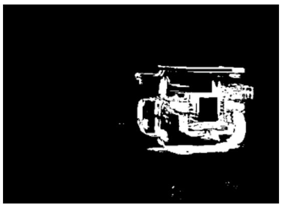

Figure 2. The result of past several frames overlapped image

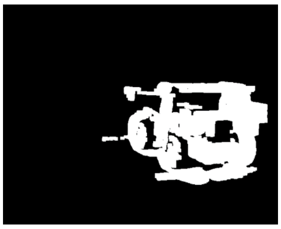

Figure 3. The result of expanded image

Figure 4. The result of moving object detection by background subtraction

matching part with template image includes some errors, and finally the template matching method fails to track it due to their accumulation. On the other hand, background subtraction method can detect and recognize the overall shape of the construction machine accurately when it is moving. But, the background subtraction method cannot detect the object when the camera is moving, or the target object is not moving.

Therefore, we considered to combine the template matching and background subtraction for the construction machine tracking. When the moving construction machine is detected by the moving object detection method, its result is compared with the result of improved template matching based method. If these two results are similar, the matching template is updated based on the result of moving object detection method.

The improved template matching method finds the most similar part with the template in the camera image, and draw a rectangle at the detected area. And, the moving object detection method finds the moving part, and draw a rectangle surrounding the moving object. When the results of rectangles from the moving object detection method and improved template matching method are similar, the template image is updated by replacing to the image of the result of moving object detection method surrounded by the rectangle. In other words, when the results of two methods are similar, the result of moving object detection is used preferentially as the updated template image. The degree of similarity of two results is determined using IoU (Intersection over Union) [7].

This method has the following three great advantages.

The first advantage of this method is that the object recognition ability is improved to the appearance change caused by the object turning. The main reason why the improved template matching lost tracking the construction machine is that the visible surface becomes invisible for its turning, that is, a big change of its appearance has occurred. Therefore, it this case, the construction machine can be tracked by the moving object detection method.

The second advantage is that the size of the template image becomes variable for the object recognition. In the template matching method, the template image size cannot be changed because of its algorithmic limitation. On the other hand, the image size of the construction machine detected by the moving object detection method changes. It changes gradually, because the construction machine approaches to or leaves from the camera gradually. So, the template image size acquired by the combination method also changes gradually. Here, the template image is generated from the result of moving object detection method based on the background subtraction similar to the result of template matching method.

The third advantage of this method is that this combination method prevents detection failure which is likely to occur in background subtraction method. In general, it is difficult to use background subtraction method when the camera moves. Also, if another moving object exists while the tracking object is stopping, the detection failure is caused in the background subtraction method. In the combination method, when the camera moves, the entire screen image acquired by the camera moves, and it is detected as one moving object. In this case, the result of moving object detection method is not similar to the result of improved template matching method, then the system recognizes that the detection failure occurs, and its result is ignored. The improved template matching method is less affected by the changes of the surroundings. So, even if the camera or another object is moving, it keeps tracking the target construction machine.

This combination method is better to be able to compensate for the each disadvantage of the combined two methods, and use their advantage points.

4 Evaluation Experiments

We conducted some experiments to confirm the effectiveness of the proposed method. In the experiments, we used a radio- controlled heavy construction machine model, and recorded its moving images by the fixed video camera. The experiments were conducted to evaluate whether our proposed combination method can track the heavy construction machine model in the video image or not. Tracking failure will occur in the moving object detection process of the combination method when the camera moves. In this case, the system will recognize it and the result of moving object detection will be ignored. Therefore, we also executed the experiment to confirm whether the proposed combination method can track the heavy machine model even the camera moves.

4.1 Robustness Confirmation of The Proposed Method

We prepared a video image of heavy construction machine model which includes large distance change between the object and the camera, and large orientation change by the turning of object, and made comparative tracking experiments using only improved template matching method and combination method. The experimental results are as shown from Figure 5 to Figure 12. The left figures of each row are the results of tracking only by the improved template matching, and the right figures are the results of tracking by the combination method. In these figures, the detection results are shown by the bold lined red rectangles, which are used as the updated template images in the next detection process. (The thin lined red rectangles show the image processing area around the template images for their speeding up.)

4.1.1 Results of Tracking Experiments Only Using Improved Template Matching Method

The initial template is set by the manual mouse operation on the beginning image of the movie. The heavy construction machine model is tracked by the improved template matching method at the beginning phase. It is shown in Figure 5.

However, when the heavy construction machine model approaches to the camera, the detection result does not cover the whole detected object because the improved template matching method cannot change the size of template shown in Figure 7. In other words, we confirmed that this method is not good for the distance change between the object and the camera. In addition, when the heavy construction machine model turns, the position of red template rectangle gradually deviates from the object, and finally it becomes impossible to detect the object. It is shown in FIgure 9 and 11.

4.1.2 Results of Tracking Experiments Using Combination Method

From the results of combination method, we can confirm that the tracking of heavy construction machine model is completely succeeded. After the object starts moving, the initial template image is updated and fitted to the external shape of the object shown in FIgure 6. Figure 8 shows the detection result by the combination method when the object approaches to the camera. This result shows that the moving object detection method can change the rectangular size. In other words, we confirmed that this method is good for the distance change of the object and the camera.

Figure 10 and 12 show that the continuous detection of the heavy construction machine model is succeeded even the object changes the moving direction by its turning. This result shows that the moving object detection method can update the template properly, and continuous tracking is achieved. In other words, we confirmed that the combination method is robust for the appearance change by the object turning. Comparing with the improved template matching based tracking and the tracking by the combination method, we confirmed that the ability of the proposed tracking method is greatly improved.

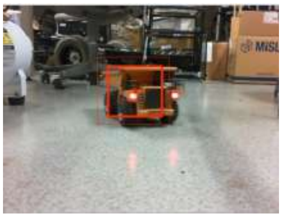

Figure 5. The result of improved template matching method at the beginning phase

Figure 6. The result of combination method at the beginning phase

Figure 7. The result of combination method when the object is approaching to the camera

Figure 8. "Combining method" at closing

4.2 Confirmation of The Influence of Camera's Moving

Tracking the heavy construction machine model only by moving object detection method is difficult when the camera moves or the object is stopping. Therefore, we made an experiment to evaluate the tracking ability of the proposed method by using the video image of these situations. Figure 13 shows the result of the experiment

Figure 9. The result of improved template matching method at the small turning

Figure 10. The result of combination method at the small turning

Figure 11. The result of improved template matching method at the big turning

Figure 12. The result of combination method at the big turning

when the camera and the object is stopping. In the right figure, white dots show the detected parts of the changing. As shown in Figure 13, some moving objects are detected (shown by small blue squares), but the heavy construction machine model is properly detected (shown by red square). This result shows that the combination method ignored the detected moving objects because they are not similar to the result of improved template matching method. Figure 14 shows the result of the experiment when the camera is moving. We can confirm that almost all area of the screen is white from the right figure, and the light blue rectangle surrounds the entire screen from the left figure. In other words, when the camera is moving, the whole screen is detected as one moving object. However, the heavy construction machine model is surrounded by the red rectangle and properly detected. This result also shows that the combination method ignored the detected moving objects including whole screen because they are not similar to the result of improved template matching method. And, we confirmed that the proposed method can track the object robustly in these situations.

4.3 Features of Proposed Combination Method

In this section, the features of the improved template matching based tracking and tracking by the combination method are summarized. Table 1 shows the comparison of

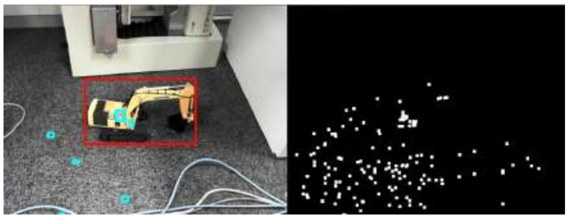

Figure 13. The result of moving object detection method when the camera is stopping

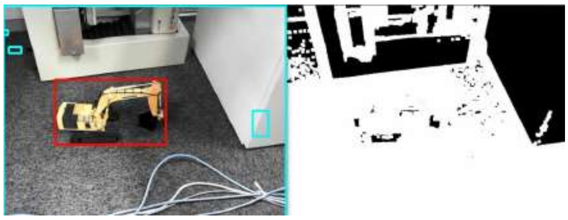

Figure 14. The result of moving object detection method when the camera is moving

the tracking ability in various assumed situations. Table 1 shows tracking accuracy in various situations.

About the tracking only by the improved template matching method, high tracking ability is achieved when the camera or the object moves on the plane parallel to the imaging surface of the camera (for example, move leftwards or rightwards, or move up or down in the camera image). This is because the appearance of the object on the camera image does not change significantly. On the other hand, high tracking ability is not achieved when the object is turning, or moving toward or from the camera, because the visible surface changes drastically. However, the proposed combination method is robust about the turning motion and the translational motion which changes the distance between the object and the camera.

Table 1. Features of Improved Template Matching Method and Proposed Combination Method

Situations	A	B
pan-tilt of camera	◎	◎
Zoom in-out of camera	△	△
Moving heavy machine right and left	○	◎
Moving heavy machine back and forth	△	◎
Turning heavy machine	△	○

A : Improved template matching method

B : Proposed combination method

◎: good ○: not bad △: not good × : bad

5 Conclusion

We proposed the robust camera tracking method for construction machines by image processing which is combining the improved template matching method and the moving object detection method. The proposed method compensates each weak point of both methods by adopting the reliable result according to the situation. By using this method, we succeeded to track the moving objects in outdoor environment where color-based tracking is difficult.

The monitoring of heavy construction machine is very important in unmanned construction site. This camera tracking system will be used instead of the camera operator. So, this system will contribute the improvement of unmanned construction technologies.

In near future, we will confirm the effectiveness of this method at the actual construction work site.

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A model for increasing the security of internet of things in smart transportation systems

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Abstract –

The usability of the Internet of Things (IOT) is accelerated by making intelligent and equipping different machines and devices with smart sensors. IOT is used in smart cities, transportation, construction cases. IOT has the capability to provide real-time information for drivers and citizens to design their routes to avoid traffic and reduce fuel consumption. However, there is a significant number of IOT barriers to IOT utilization such as the distrust of users and managers in sharing information, suspicion to privacy and the ease of using the relevant applications. Despite the importance of these factors, a model for predicting the use of this technology for specific disciplines has not yet been developed, especially for developing countries. Therefore, this research attempts to propose a model for prediction of application, taking into account the increased security of IOT in intelligent transportation. To this end, influential constructs on user trust were collected and tested by questionnaire from 62 experts. The data were analyzed using Smart PLS using confirmatory factor analysis. The results show that 11 hypotheses in the research have been confirmed. The results of this study are very important for technology specialists and urban managers to establish the IOT in the field of urban transport.

Keywords –

Security, Internet of Things, Smart Transportation, Model

1 Introduction

Application of new technologies such as Internet of things (IOT) helps to increase the performance of smart cities The high number of intra-city trips is one of the reasons that cause traffic jam and air pollution, which can be reduced or monitored using IOT applications. However, managers in developing countries have encountered barriers to adopt IOT such as uncertainty and lack of trust. Whereas the amount of users' activity in the urban areas of developed countries is dependent on the IOT measured from the number of connected devices to the Internet at the end of 2015, was about 4.9 billion [1]. This growing trend reflects the increasing impact of IOT in life. Therefore, in close future without IOTs we are not able to control digital things in our life [2]. Therefore, the issues of security and confidentiality need to be considered to increase the IOT adoption rate. The purpose of this paper is to provide a model to increase the security of IOT in smart transportation in developing countries.

The paper seeks to answer how we can increase the security of IOT in urban transportation in developing countries. To answer this, based on the factors taken from theoretical foundations and reviewing the literature of research, twelve hypotheses are developed. Then, using the Smart PLS software, through expert analysis and expert interviews, hypotheses are examined and ultimately we tried to provide an effective model for increasing the security of IOT in smart transportation. This can increase the security of the smart city network.

In general, the structure of this paper is as follows: the first part, entitled literature review, according to the interdisciplinary nature of the research, requires some concepts examined and a common view of them. Therefore, there is a common chapter in the topics of the security domain, the IOTs, and smart transportation. In this section, the models and theories used in the analysis are identified and, in continue, the status of the constructs related to the security of the IOTs in these models is identified. In the second part, the method of confirmatory factor analysis is introduced as a research method to test the hypotheses of the proposed model for increasing the security of IOT in smart transport in smart city. In the third part, the results of factor analysis are presented and the conceptual model of increasing the security of IOTs in the urban transport sector is tested, corrected and finalized in order to realize the smart urban management. Finally, the results of the analysis are summarized in the final section.

2 Literature Review

One of the most controversial topic in the area of security is the emergence of a new paradigm for IOTs, which include a range of electronic devices that can connect to the Internet. The problem anticipated in IOTs is that things cannot be safely stacked and there is not enough memory to install and run security software on them. Therefore, the network should be protected to detect violations and prevent the entry of attacks [1]. Web-based technologies are moving at a fast pace and realizing the ideas of the smart city. Despite the speed of technologies that guarantee the security of users and their information, it is far behind the technology itself, and there are fewer studies in the research literature. The IOT has shown its most importance and application in the field of urban transportation [3-8].

The review of the literature in this field requires a lot of vigilance. However, what has been tried in this research is to investigate the IOT, network security and smart transportation. So, in the following, we try to identify shortcomings in each of these three areas in order to identify the effective factors in increasing the security of IOTs in smart transportation. Over the past decade, the IOT has entered silently and gradually in our lives, and we need to thank the availability of wireless communication systems, which are increasingly used as a technology motive for highly smart monitoring and application control [9]. The IOTs can be a collection of Web services, devices (RFIDs), infrared sensors, global positioning systems, barcode scanners, networking, and etc. by using the conventional protocol, the exchange of information and communication in order to achieve identification, tracking, monitoring and smart management of objects are used [10]. In other words, the IOT can be seen as a new form of network based on the Internet, which is much larger. A network is made up of advanced computers [11]. In the area of security of IOTs, it can also be said that traditional security interactions and privacy enforcement, due to their limited computing power, cannot be directly applied to the IOTs; in addition, the large number of connected devices causes scalability issues. Simultaneously, in order to gain full acceptance by users, it is necessary to define valid security models, privacy, and trust in the context of the IOT applications projects [12]. The purpose of security is to ensure that data anonymity, confidentiality, and integrity are guaranteed, as well as authentication and authorization mechanisms to prevent unauthorized users (i.e. humans and devices) to access this system. While privacy requirements are in place, data protection and the confidentiality of personal information of users must be guaranteed, as devices may handle sensitive information (for example, user habits). Finally, trust is an important issue because the IOT environment is characterized by a variety of devices that must process and manage the data in accordance with the needs and rights of the users.

Previous studies investigated sub topics of enabling technologies and middleware technologies in the IOT from the perspective of an application, analysis, and security and privacy issues with standardization, addressing, and the network is provided [13]. Security and privacy challenges were examined only from a legal perspective, with particular regard to the guidelines of the European Commission [14]; [15] in his paper discussed the Internet underwater objects, and only did a few notes present on the security issue; In another study [16], the advantages and disadvantages of centralized and dispersed architectures in terms of security and privacy on the IOTs, along with analysis of major attack patterns and threats, were examined. Yan et al. [17] focused solely on the issue of trust management in the IOTs.

Here are some brief references to some of the most important security issues on the IOTs. In relation to the issue of access control, various articles have addressed the subject from a variety of perspectives. For example, Ma et al. [18] is focused on the data literacy layer, which is responsible for the direct collection of information. An approach that addresses the outsourcing-data authentication problem can be found in [19, 20]. Sicari et al. [9] also suggests a semi-distributed approach. More precisely, in this research, a security framework and an access control model were proposed to secure the so-called DSMSs that extend the Borealis data flow engine to security requirements [21]. Finally, in [22], a UML conceptual model was defined for all objects and Internet architectures.

Review of resources about privacy on the IOT is also indicative of useful research. In the research [23], data labeling is proposed for managing the privacy of the IOTs; in [24], an access-controlled protocol by user is proposed; In [25], the continuous anesthetization of data flows was presented through the adaptive cluster; In [26], traditional privacy mechanisms are divided into two categories: optional access and limited access.

Another method, which uses a sign-on signing scheme to guarantee privacy on the Internet, is presented in the research [27]. [28] in their paper began to work on data mining privacy techniques, which aims to minimize the probability of disclosure of critical data and decomposing sensitive content.

In reviewing resources on the topic of trust of the IOTs are also briefly referred to several articles. [29] wrote about the evaluation of the trustworthiness of IOTs inputs. A similar methodology for evaluating reliability is provided by [30] on the so-called Internet of Social Things. This paradigm is due to the integration of the social networking concepts within the things of the Internet. The articles mentioned so far are merely to illustrate the large volume of studies on the dimensions of the IOTs. But this area of knowledge is less applicable to urban life applications and urban management.

The third area used in leading research to achieve the purpose of the research is smart transportation. The concept of smart city has been adapted from a variety of definitions that include the intelligent city, the information city, the knowledge city, the digital city, and the same concept as the smart city [31]. Cities play a prominent role in social and economic aspects all over the world [32]. The smart transportation system is a general term for the application of a combination of communication technologies, control and information processing for the transportation system. Using it will save lives, saving time, money, energy and environmental benefits.

An overview of the available resources shows that there are two theories of diffusion of innovation and technology acceptance model, which are rlated to technology acceptance dimensions. Having a special position in terms of both personal and psychological aspects, the technology acceptance model is one of the most widely-used models. This model addresses the causes of technology rejection from the psychological point of view for users. Other popularity that can be effective in achieving this goal is diffusion of innovation theory. This theory has redefined a set of constructs that can be used to study the adoption of individual technology.

The review of resources clearly refers to the extensive efforts of researchers in the field of the applicability of the IOTs. However, the lack of acceptance of this termination due to the lack of security in its application is one of the most important reasons that has not been tested in the field of smart transportation from the psychological point of view in developing countries. In the next section, with a closer focus on effective constructs in increasing the security of IOTs in the field of smart transportation, the paper is trying to provide an effective model in this regard.

3 Conceptual framework

In this part, the initial conceptual model to increase the security of IOTs in smart transportation is presented. Figure 3 illustrates the process of modeling the technology acceptance model by users in Iranian metropolitan areas in four main stages. In this research, in order to provide a proposed model for increasing the security of IOTs in smart transportation, the researcher is attempting to cover as broadly as possible a theoretical concept. For this purpose, both theories are used. Since the roots of the two models are common in some constructs, the two models can be considered together to provide the theoretical basis for their proposed model. In this paper, the implications of the proposed theory that affects the security of the IOTs in the field of smart transportation are introduced as construct, including the perceived usefulness, compatibility, or trial ability. In Figures 1 and 2, technology acceptance model and diffusion of innovation theory are introduced.

The investigating of the constructs of the models shows that the two constructs, the relative advantage and complexity, of the diffusion of innovation theory have the same concepts with the two constructs, perceived usefulness and perceived ease of use, respectively, of the technology acceptance model. As mentioned, the theoretical basis of the proposed research model was introduced in order to increase the security of IOTs in smart transportation as Fig. 4. Based on the theoretical foundations, eleven constructs are presented to provide the views and theories on which they are based. Table 1 lists the 12 final constructs used in the proposed model.

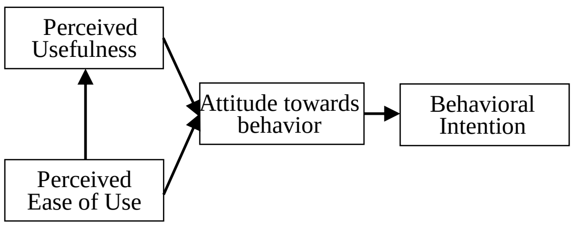

Figure 1. Technology acceptance model
Reference: [33]

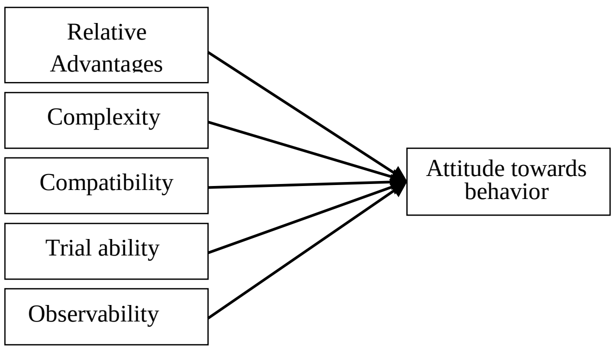

Figure 2. Diffusion of innovation theory
Reference: [34]

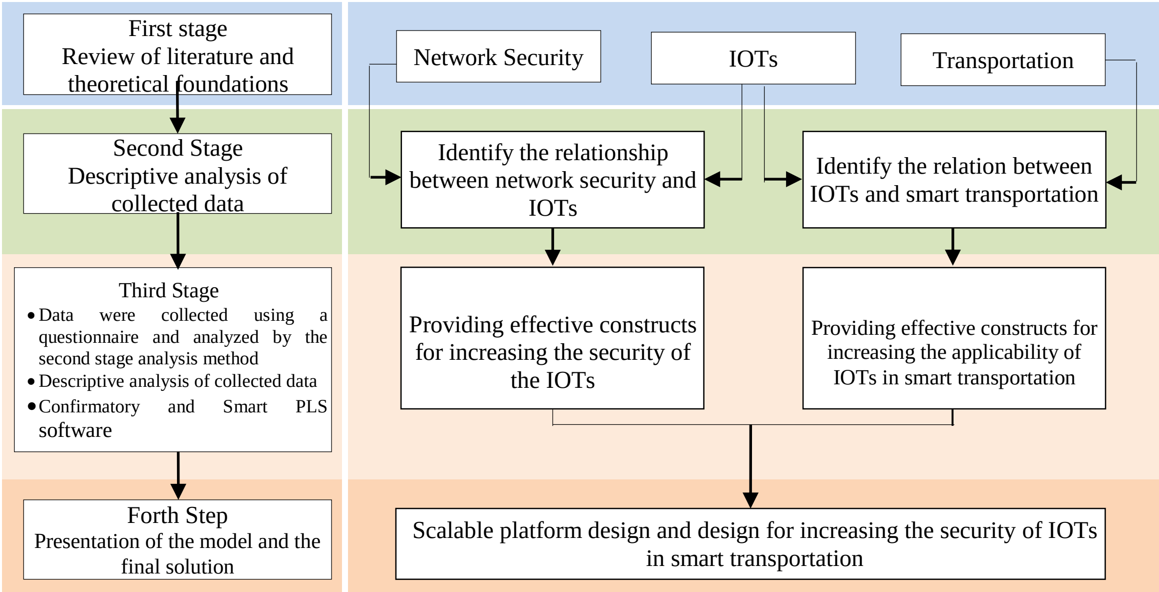

Figure 3. Conceptual model making process enhancement of security IOT in smart transportation

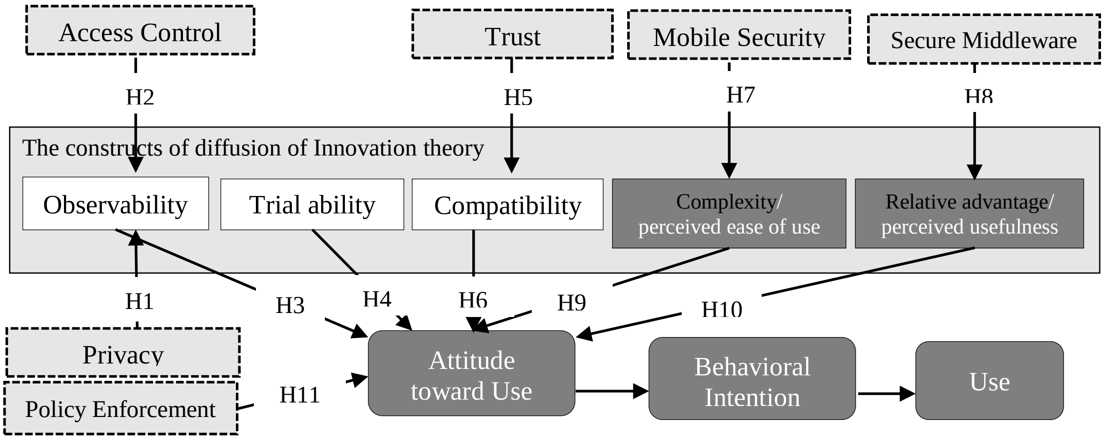

Figure 4. Theoretical basis of the proposed model for increasing the security of IOTs in smart transportation

4 Research Method

In this research, eleven hypotheses have been developed based on the relations among fifteen constructs taken from the theoretical foundations to achieve its goal of increasing the security of the IOTs. The main purpose of this paper is to formulate hypothesis and develop the conceptual model rather than analyzing the data which require further investigation.

As shown in Fig. 1, a quantitative confirmatory factor analysis was used to test the model of increasing the security of IOTs in smart transportation. Factor analysis is performed using Smart PLS software. A questionnaire was used to collect the data to test the hypotheses. This means that for each hypothesis related to model constructs, questions have been raised and forwarded in the form of a questionnaire among experts. To determine the sample size, based on the method of structural equations, ten times more than the number of markers forming a construct is selected as the sample size. Namely, in the model, identifying the instruments that have the largest number of constituent markers, and this amount is 10 times that of the desired sample size [35]. Since in this research according to Fig. 4, in the attitude construct, there are 7 indicators, the sample size was determined to be 70. This sample size is used to collect data through questionnaires forwarded. These individuals have been selected by experts in the field of transportation, computer and information technology in organizations under the supervision of the municipality of Tehran. 62 questionnaires were returned to perform the analysis. Therefore, the return rate of the questionnaire is 88%. The validity of the proposed constructs for the model is validated using a confirmatory factor analysis method. The Smart PLS was used to test the model. This software is used to analyze multi-construct data. Smart PLS is based on the estimation of the least number of variables in order to optimize the explanation of variance in the constructs dependent on the structural equation models. The purpose of this is to maximize the variance of dependent variables defined by independent variables [35].

Table 1. Reviewing Constructs Extracted from Theoretical Foundations, the three criteria of Cronbach's Alpha, AVE and CR for all constructs and Factor Loading of Research Questions

Models	Construct	Acronym	Cronbach's Alpha	CR	AVE	Measure	Loading
Technology Acceptance Model	Perceived Ease Of Use	PEOU	0.84	0.85	0.73	PEOU1	0.942
						PEOU2	0.963
						PEOU3	0.894
						PEOU4	0.741
	Perceived Usefulness	PU	0.75	0.85	0.66	PU1	0.892
						PU2	0.875
						PU3	0.908
	Attitude toward Use	AU	0.91	0.92	0.59	AU1	0.811
						AU2	0.829
						AU3	0.821
						AU4	0.987
						AU5	0.855
	Behavioral Intention	BI	-	-	-	-	-
Diffusion of Innovation Theory	Relative Advantages	RA	-	-	-	-	-
	Observation	OB	0.95	0.72	0.51	OB1	0.766
						OB2	0.946
						OB3	0.812
	Compatibility	CT	0.78	0.87	0.7	CT1	0.819
						CT2	0.926
						CT3	0.750
	Trial-Ability	TA	0.83	0.89	0.66	TA1	0.855
						TA2	0.705
						TA3	0.919
						TA4	0.760
	Complexity	CX	-	-	-	-	-
Security of IOTs	Secure Middleware	SM	0.76	0.82	0.7	SM1	0.776
						SM2	0.884
	Trust	TR	0.77	0.85	0.59	TR1	0.826
						TR2	0.716
						TR3	0.734
						TR4	0.883
	Mobile Security	MS	0.71	0.81	0.51	MS1	0.845
						MS2	0.977
						MS3	0.787
	Privacy	PY	0.83	0.73	0.54	PY1	0.884
						PY2	0.942
						PY3	0.722
						PY4	0.787
	Access Control	AC	0.83	0.91	0.84	AC1	0.747
						AC2	0.872
	Policy Enforcement	PE	0.86	0.91	0.72	PE1	0.840
						PE2	0.945
						PE3	0.856
						PE4	0.736

Note: average variance extracted (AVE), composite reliability (CR).

4.1 Hypotheses Formulation

In this section, research hypotheses that are presented on the basis of the relationships between the research constructs and the literature review are briefly presented. These relationships are shown in Figure 4.

- H1: Privacy has a negative relationship with observability in using IOTs in smart transportation.
- H2: Access Control has a negative relationship with observability in using IOTs in smart transportation.
- H3: Observability has a positive relationship with Attitude toward Use in using IOTs in smart transportation.
- H4: Trial ability has a positive relationship with Attitude toward Use in using IOTs in smart transportation.
- H5: Trust has a positive relationship with Compatibility in using IOTs in smart transportation.
- H6: Compatibility has a positive relationship with Attitude toward Use in using IOTs in smart transportation.
- H7: Mobile Security has a negative relationship with Perceived Ease of Use in using IOTs in smart transportation.
- H8: Secure Middleware has a negative relationship with Perceived Ease of Use in using IOTs in smart transportation.
- H9: Perceived Ease of Use has a negative relationship with Attitude toward Use in using IOTs in smart transportation.
- H10: Perceived Usefulness has a positive relationship with Attitude toward Use in using IOTs in smart transportation.
- H11: Policy Enforcement has a positive relationship with Attitude toward Use in using IOTs in smart transportation.

In continue, based on the analysis done on the hypotheses carried out using the data collected by the questionnaires, the hypotheses are either confirmed or rejected.

5 Data Analysis and Results

In order to evaluate the proposed model, the structural equation modeling is utilized using the Smart PLS 3.0 [36]. The paper also presents the results of two tests of the measurement model in terms of validity and reliability, the structure of the model in terms of the relationship among variables, and fitness of the model. If the model passes all three stages successfully, it shows the correctness of the selected constructs and their dependent terms. For testing the measurement models, we examined the ‘convergent validity’ and ‘discriminant validity’.

5.1 The Measurement Model

In this section, each of the proposed factors is referred to the construct and questions related to each construct. T-value is a test used to validate measurement models in statistics science. The t value for meaningful factor loads in the corresponding fields of each variable in the study indicates that the value greater than 2.66 is significant for the values of t obtained at the error levels of 0.01 [36]. Other indicators are categorized into two groups of convergent validity and discriminant validity for measuring the model of measurement. In the following, these two categories of tests are discussed.

5.1.1 Convergent Validity

Convergent validity is used to determine construct validity by defining factor loading, Cronbach's alpha, Average Variance Extracted (AVE), and Composite Reliability (CR) [40]. Table 1 shows the loading coefficients of the corresponding measures of each construct varying from 0.7 to 0.9. The load value of each item on the corresponding construct is well above the recommended value of 0.7 [39] indicating the proper and desirable load factor of each item on its related construct. Measures with the value of less than 0.7 can be omitted. Cronbach's alpha was applied to assess the validity of the measures. The CR coefficient distinguishes the correlation coefficient of measures in one dimension for fitting adequate measurement models [39]. The results validate the criteria as Cronbach's alpha is well above 0.7, and the AVE is also above 0.8, which surpasses the recommended threshold of 0.5 [39]. The CR is above 0.7 [38] for all constructs [39] excluding CT and PREL, which are very close to 0.7. The results validate that all criteria were satisfactory, since they are above the recommended values.

5.1.2 Discriminant validity

Divergence validity of the model was assessed through the comparison of the correlation coefficient of constructs with its indexes versus the correlation of that constructs with other constructs was presented. The results are shown in Table 2. According to [38], AVE the constructs located in main diameter of matrix are more than the correlation between them, which are arranged in the lower and left boxes of the main diameter. Therefore, it can be concluded that in the above model, the constructs interact more with their own indicators than with other constructs. This shows that the divergence validity of the model is appropriate.

5.2 Structural Model

To test the construct validity of factors in the model, a confirmatory factor analysis was conducted. To investigate the CFA using structural equation modeling, a model was first created based on the type of constructs such as observability and related measures of each construct such as OB1 to OB3. This analysis and model development were done in Smart PLS 3.0. The hypotheses were examined by assessing the parameters of the PLS structural model. The R^2 value for constructs vary from 0.16 to 0.92. The result of R^2 values shows the predictive power of the model including four dependent constructs is acceptable and indicates that the theoretical model explained a substantial amount of the variance in performance. The value of R^2 for observation, compatibility, perceived ease of use, and attitude toward use are 0.31, 0.3, 0.28, and 0.39, respectively. The standardized path coefficients also show the strength of the relationship between the independent constructs (e.g. PSY) and the four dependent constructs (e.g. OB). The multi-collinearity between the variables in our model was evaluated, and no cause was found for concern related to the variance inflation factor (VIF) criteria, as according to the Table 3 all of the values of VIF are below the proposed value of 5.00 [40]. In addition, the model's predictive relevance was assessed by using the blindfolding procedure [40]. The values of Q^2 which are greater than zero, indicate the sufficient predictive relevance of the model. If the model passes the determined tests in the confirmatory factor analysis method using smart PLS successfully, the proposed conceptual model and; in other words, the factors and the related questions (items) to each factor are verified. As the results are shown in Table 3, Access Control, Observability, Mobile Security, and Secure Middleware have not been able to explain more than 50% of the corresponding construct variance. The t-value was compared with the error level to assess the relationship between dependent constructs and independent constructs. Where the values are greater than of the minimum of 1.64 recommended by [40], all relationships were confirmed. At the error level of 0.01%, 0.05%, and 0.1. %, path coefficients with the minimum of 2.58, 1.96, and 1.64 in t-value are confirmed [40]. Table 3 shows that the value ranging from 0.03 to 30.79 and the hypotheses excluding H2, H7, and H9 are supported.

Table 2. Discriminant Validity

construct	PY	PU	PE	AC	OB	TA	TR	CT	MS	SM	PEOU
PY	**0.81**										
PU	0.49	**0.84**									
PE	0.63	0.83	**10.5**								
AC	0.43	0.17	0.36	**0.66**							
OB	0.63	0.43	0.54	0.13	**0.59**						
TA	0.29	0.52	0.68	0.31	0.47	**0.78**					
TR	0.39	0.71	0.76	0.23	0.56	0.75	**0.89**				
CT	0.51	0.72	0.72	0.23	0.5	0.53	0.78	**0.8**			
MS	0.72	0.48	0.48	0.19	0.23	0.09	0.39	0.45	**0.73**		
SM	0.62	0.45	0.4	0.02	0.28	0.02	0.29	0.44	0.08	**0.66**	
PEOU	0.64	0.84	0.91	0.46	0.52	0.59	0.84	0.83	0.56	0.48	**0.86**

Table 3. Results of the tested hypotheses including path coefficient, significance index and explained variance

Hs	Path Relationship	Std. Beta	Standardized Path Coefficient	Path Significance Index (t-value)	Decision	Explained Variance (R^2)	VIF	Q^2
H1	PY → OB	5.71	0.50	11.42	Supported ($p<0.001$)	0.51	2.04	0.31
H2	AC → OB	0.29	0.76	0.38	Not supported	0.16		
H3	OB → AU	9.61	0.40	24.02	Supported ($p<0.001$)	0.41		
H4	TA → AU	2.34	0.49	4.77	Supported ($p<0.001$)	0.5		
H5	TR → CT	22.79	0.74	30.79	Supported ($p<0.001$)	0.74	3.84	0.3
H6	CT → AU	2.52	0.70	3.6	Supported ($p<0.001$)	0.71		
H7	MS → PEOU	0.68	0.53	1.28	Not supported	0.34	1.51	0.28
H8	SM → PEOU	1.31	0.64	2.04	Supported ($p<0.05$)	0.24		
H9	PEOU → AU	0.03	0.92	0.03	Not supported	0.92		
H10	PU → AU	2.36	0.75	3.14	Supported ($p<0.001$)	0.76	4.16	0.39
H11	PE → AU	4.31	0.89	4.84	Supported ($p<0.001$)	0.9		

5.3 Fit Model

The third step that needs to be considered in the proposed model is the overall model fit index. Model fit index is an acceptable criterion for confirming the developed theoretical model using the collected data [41]. The method for calculating the overall model Goodness of Fit (GoF) index [42] is as follows:

$$GOF = \sqrt{\overline{Communalities} \times \overline{R^2}}$$

The Communalities value is obtained of the average shared values of all constructs or, in other words, it is obtained of the average variance extracted presented in Table 1. The R^2 value is also obtained from the mean R square or explained variance of all model' constructs in Table 3. R^2 of determination is a number that indicates the percent of variances in the dependent variable. If R^2 be 1, it indicates that the regression line perfectly fits the data. The amount of GoF was checked at three levels: GoFsmall = 0.1, GoFmedium = 0.25, and GoFlarge = 0.36. The amount of GoF more than 0.36 represents a perfect fit conceptual model of research [42]. Therefore, the value of 0.67 for GoF of present research model is suitable fit and the proposed conceptual model is confirmed.

In general, due to the proper quality of the measurement models, the structural model, and also the appropriate model fitness, it can be concluded that according to the confirmatory factor analysis for this study, the items of the questionnaire can be used to explain the identified factors or suggested constructs.

6 Discussion

The purpose of this study is to propose a conceptual model, which can be used for increasing the security of IOTs in smart transportation in developing countries. For this purpose, firstly, the literature on the three areas of the IOTs, the security, and smart Transportation have been investigated. Then, based on theoretical foundations, the research hypotheses were presented. These hypotheses have been investigated by confirmatory factor analysis and Smart PLS software. Further confirmation or rejection of hypotheses has been discussed, but a large amount of data is required to exactly test the hypotheses and generalize them. The contribution of this paper is to propose a conceptual acceptance model.

Two factors should be considered to confirm or reject the research hypotheses. The first factor is the path coefficient. The positive path coefficient represents a direct relationship between constructs and the negative path coefficient represents an indirect relationship. This value in large measure represents the power of the relation that decreases with the establishment of indirect relations from the magnitude of a path coefficient. The second factor is t value. The t-value was compared with the error level to assess the relationship between dependent constructs and independent constructs. Where the values are greater than of the minimum of 1.64 recommended by (Hair Jr et al., 2016), all relationships are confirmed. At the error level of 0.01%, 0.05%, and 0.1. %, path coefficients with the minimum of 2.58, 1.96, and 1.64 in t-value are confirmed (Hair Jr et al., 2016). The results of the table 3 show that the t-statistic for hypotheses with an error level of 0.001 is greater than 2.58, except for H8, which is more than 0.05 with an error level of 1.96. Based on this index, three hypotheses H2, H7, and H9 are rejected based on t value. In the first section, the hypotheses that have been confirmed are discussed, and the following three rejected hypotheses are introduced.

Another importance point related to hypotheses is the power of them. In this way, the greater amount of the coefficient, the more powerful hypothesis whether this is negative or positive. Therefore, the hypotheses are further reviewed on the basis of their power. As shown in table 3, H5 has a lot of power and is very close to reality. The sharp difference between this hypothesis and other hypotheses can be attributed to the importance of questions related to this construct in the questionnaire for questioners. Accordingly, trust in the IOTS in the transportation system is important in connection with technology adaptation to increase the security of the IOTs in the transportation system. It was stated in the hypothesis that the confidence would be obtained when the system could be compatible with the existing values and psychological needs of the recipients and their experiences. Therefore, systems in the IOTs must be compatible with the values and psychological needs of its adopters. The path coefficient of H1 is in second place. In this hypothesis, privacy, when using IOTs in the transportation system, has a negative relationship with one's perception of being viewed by others. The almost strong significance of this hypothesis is that IOT users in urban transport are important in protecting their privacy when using this technology. This hypothesis has a third degree of importance for users. In H11, it has been argued that the policies enforcement by planners and supersonic devices, when using IOTs in the transport industry, have a positive relationship with the perception of the proportion of increasing the security of the IOTs in the transportation system. Thus, users tend to display government agencies and administrators their supervisory role to increase the security of the IOTs. So they will feel more secure. This hypothesis can also confirm the results of the previous hypothesis (H1). In H3, it is stated that observation by supermodels, when using IOTs in the transport industry, has a positive relationship with the individual's tendency to increase the security of the IOTs. Therefore, this category will be the second most important issue for IOT users in the transportation system. H8 also states that the interconnection between the large number of communication devices at different levels in the middleware at the time of using IOTs in the transportation has a negative relationship with the perception of the person's ease of use of the system. H10 discusses about having a positive relation between the usefulness of using IOTs in the transportation and a person's perception of the security of IOTs and his attitude toward its application. According to H6, compatibility of IOTs in the transportation system has a positive relationship with the perception of the individual about increasing the security of the IOTs. H4 also states that the ability of an individual to test the IOTs in the transport industry has a positive relationship with the perception of the individual about increasing the security of the IOTs.

As the results of table 3 show these three hypotheses are rejected. H7 is about the complexity of relationships in mobile devices when using IOTs in the transportation. According to this hypothesis, mobile security will have a negative impact on the perception of ease of use in using this type of technology. H2 anticipated that there is an inverse relationship between the access control of users to resources and data by government and supranational institutions, and the perception of one's being seen by others. This matter that this hypothesis is rejected indicates that there is not a positive relation between these variables. In other words, controlling the access of users during the use of IOTs in the transportation system is negatively related to the perception of the person than to be seen by others. In H9, it is stated that the perceived ease of using the IOTs in the transport industry has a negative relationship with the perception of the person about the security of IOTs and his attitude towards its application.

7 Conclusion

The purpose of this study is to achieve a model for increasing the security of IOTs in smart transportation. For this purpose, based on the review of the literature, the model was first proposed and the results of the 62 questionnaires collected by the experts were analyzed using a confirmatory factor analysis method based on the structural equation model. The validity of this model is confirmed by using a t-student test with an error rate of 0.001%. The results of Tables 1, 2, and 3 confirm the appropriateness of the reliability and convergence validity of the research model. In addition, according to the results of the appropriate quality of the measurement model, the structural model, as well as the fit model that was calculated in formula 1, the theoretical model confirmed by using the collected data confirms. Because of the confirmatory factor analysis for this research, the variables of the design questionnaires in the research can explain the identified factors or suggested constructs.

The results of the confirmatory factor analysis carried out on the hypotheses in the proposed model, examine the confirmation or rejection of the hypotheses based on the path coefficients in them comparing the t-value at the standard error level. According to Table 3, hypotheses 2, 7, and 9 are rejected. But the strength of the hypotheses can be determined based on their path coefficient. So the hypothesis 5, which has the highest path coefficient, has the strongest effect. It was stated in the hypothesis that the trust would be obtained when the system was compatible with the existing values and psychological needs of the recipients and their experiences. Therefore, existing systems in the IOTs should be compatible with the values and psychological needs of its users. Hypotheses 3 and 1 also are too strong. Finally, hypotheses 2, 7, and 9, which are rejected hypotheses, have a low path coefficient and are weak. The conceptual model presented in this paper is important for transportation, information technology, computer and urban managers and decision-making organizations for the provision and deployment of the IOTs in the field of urban transportation. However, the statistical results may very in larger samples and different contexts. The proposed model helps to provide a powerful tool for increasing the security of IOTs to increase the level of user's interest in this technology.

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Issues and Needs for Standard Classifications for Facility Management in Smart Manufacturing

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Abstract –

As construction projects become larger and more complicated, the importance of information sharing among various project participants throughout the entire life-cycle of a facility is ever-increasing. Establishment of standard classification system is the most fundamental task for systematic and efficient management of construction information. In recent years, technology advancement of smart manufacturing, which is for intelligent factories supported by ICT combined with existing manufacturing technology, is becoming a key issue.

However, due to the lack of information exchange (IE) standards for the management of smart manufacturing's construction and operation, it is very limited for various construction participants to generate and share information by using the standards. In addition, each standard classification should be used in a combined manner in order to improve information processing efficiency.

Standard classification requires a variety of facets such as facility, space, element, and work section. The purpose of this study is to propose a physical breakdown structure (PBS) that best reflects distinct characteristics of smart manufacturing. Firstly, the influencing factors for defining PBS were identified. A methodology for creating the facility classification suitable for smart manufacturing was then developed. Finally, cost breakdown structure (CBS) and work breakdown structure (WBS) were developed by combining the PBS and other standard classifications. This case-study of CBS and WBS formulation were used as a validation for the proposed methodology. The concept of "flexible WBS" by Jung and Woo [6] were utilized in this case study as well, in order to accommodate the managerial requirements of an owner organization from the display industry.

Keywords –

Standard classifications; Smart manufacturing; Facility management; Information exchange

1 Introduction

Recently, as part of the fourth industrial revolution, technology development and standardization of smart factories that can optimize relevant management by sharing and utilizing all production information and knowledge in real time based on ICT has become a key issue in the manufacturing industry. Planning, design, production, distribution, and sales could be conducted at lower cost and reduce time through the development of technology and standardization [9]. In addition, it is possible to build a next-generation factory that actively responds to new environments such as productivity improvement, energy saving, implementation of people-oriented working environment, and personalized manufacturing [9].

A lot of standards have been developed for standardized information exchange (IE) among the various components of the manufacturing process. However, due to the lack of information exchange standards for construction and operation management of smart factories, it is very limited for various construction participants to generate and share information by using the standards. Therefore, a great deal of effort is required to rework the data for the operation and maintenance (O&M) phase.

In an effort to develop standard classifications for airport projects, Jung et al. [2] pointed out that "the issues of information exchange could be discussed from various perspectives including level of detail (LOD), diversity of various facets, and business requirements".

The purpose of this study is to develop a physical breakdown structure (PBS) that best reflects distinct characteristics of smart manufacturing. Firstly, the influencing factors for defining PBS were identified. A methodology for creating the facility classification suitable for smart manufacturing was then developed. Finally, cost breakdown structure (CBS) and work breakdown structure (WBS) were developed by combining the PBS and other standard classifications.

This case-study of CBS and WBS formulation were used as a validation for the proposed methodology.

2 Needs for Standard Classifications in Smart Factory

There are two types of standards for smart manufacturing. One is directly related to manufacturing and the other one is indirectly related to manufacturing process [8]. Lee et al. [9] summarizes current ISO standard activities as listed in Table 1 based on KATS [7].

Table 1 International Organization for Standardization for smart manufacturing [7] [9]

IEC/SEG 7	- Smart manufacturing
IEC TC 65	- Industrial process measurement, control and automation
ISO TC 184/SC 4	- Industrial data
ISO TC 184/SC 5	- Interoperability, integration, and architecture for enterprise systems and automation applications
ISO/IEC JTC 1/WG 9	- Big data
ISO/IEC JTC 1/WG 10	- Internet of things
oneM2M	- Standards for M2M and the Internet of Things
IEEE P2413	- Standard for an Architectural Framework for the Internet of Things

These standards have been developed by ISO mainly in the fields of IoT, big data, cloud computing, security CPS, M2M, etc. For example, most of ISO TC 184/SC 4 is the series of representation and information exchange for product data (ISO 10303). IEC TC 65 mainly covers standards for industrial cable, wired and wireless network, and system integration [9].

However, due to the lack of information exchange (IE) standards for construction and operation of smart factories, it is very limited for various construction participants to generate and share information by using the standards. Therefore, the establishment of a standard classification for construction information exchange will contribute not only to realization of data-centric factory construction management but also to the improvement of managerial effectiveness.

From the owner's perspective, standard classifications enables to collect standardized information from many construction participants, like designers, engineers, contractors, operators, etc. This also allows new construction participants to share information automatically.

3 Standard Classification and Numbering System (SCNS)

Like the smart manufacturing, the construction industry has been using international standards for a long time. For example, MasterFormat [10], Uniclass [12], OmniClass [11], etc. In particular, information exchange through the standard classifications is a very important factor in terms of managerial effectiveness and information consistency, as there are many participants, including owners, designers, engineers, contractors and operators in factory construction projects.

In the early stage, this study attempted to use existing international standards for factory construction projects. However, existing international standards cannot adequately reflect the characteristics of the factory. Among the various classification facets, the facet that best reflects characteristics of factory is 'facility'. However, it is difficult to classify 'facility' according to existing construction standards, because the level of 'facility' classification is too high to present a special-purpose building to a factory. It is also difficult to define an equipment or a system as a part of a 'facility' classification in the existing construction standard classifications.

In order to solve this problem, a 'facility' classification of owner's perspective is developed, known as physical breakdown structure (PBS) in practice, which reflects characteristics of smart manufacturing for systematic and efficient management and utilization of construction information on factory.

As shown in Table 2, PBS is developed by the concept of standard for classification and numbering system (SCNS) [3]. SCNS consists of standard classifications (CLN) and project numbering system (PNS).

Establishment of CLN and PNS is the most fundamental task. It forms a framework for all related project management tasks, such as scope management, design management, process control, cost control, quality control [4].

There are many different facets in CLN that satisfies general requirements. ISO [1] recommended facility facet, space facet, element facet, work section facet, material facet, construction aids facet, management

Table 2 SCNS - Standard Classification and Numbering System [3]

L I	Level II	Level III	Remarks
Standard Classification and Numbering System (SCNS)	Standard Classifications (CLN) *	(CLF) Facility Facet	e.g. Building, Airport
		(CLS) Space Facet	e.g. Office, Bed room
		(CLE) Element Facet	e.g. Column, Beam
		(CLW) Work Section Facet	e.g. Steel structure
		(CLM) Construction Material/Assembly Facet	e.g. Re-bar, Concrete
		(CLA) Construction Aid Facet	e.g. Wood form, Crane
		(CLG) Management Facet	e.g. Cost, Contracting
		(CLP) Attribute and Property Facet	e.g. Heat transmission
	Project Numbering Systems (PNS)	(GBS) Geometry Breakdown Structure **	Multi-facet for 3D design
		(WBS) Work Breakdown Structure	Multi-facet for scheduling
		(CBS) Cost Breakdown Structure	Multi-facet for cost
		(EBS) Equipment Breakdown Structure	Multi-facet for procurement
		(OBS) Organization Breakdown Structure	Multi-facet for stakeholders
		(RBS) Risk Breakdown Structure	Multi-facet for risk
		(MBS) Measurement Breakdown Structure	Multi-facet for estimating
		(SBS) Specifications Breakdown Structure	Multi-facet for specs
		(DBS) Drawing Breakdown Structure	Multi-facet for drawings
		(PBS) Physical Breakdown Structure	Single facet
		(FBS) Functional Breakdown Structure	Single facet

* Eight facets defined by ISO [1], ** Patented by Myongji University [5]

facet, and attribute facet as the top level categories. In addition, combining these facets could be used as a PNS for specific purposes (e.g. cost, scheduling, etc.) [3]. Therefore, the continuous development of standard classifications for other facets in smart factory would be able to expand the influence for extensive application in practice.

As discussed previously, PNS has a structure that combines several different CLNs. As shown in Table 2, most of PNSs are 'multi-facet'. For example, CBS can be defined by combining CLF with CLW of CLN. However, PBS and FBS are 'single facet' and PBS can be defined as a 'facility' classification, which is CLF. Therefore, CBS also can be defined as a combination of PBS and FBS in this study.

4 Physical Breakdown Structure (PBS)

The proposed PBS of a factory construction project in the display industry has three-level structure as shown in Figure 1. The first level has eight categories. There are 'project general (000), panel equipment (100), module equipment (200), fab common facility (300), utility (400), electric power facility (500), architecture/civil (600), and trunkline (700)'.

The second level of 'project general (100)' has 'planning (010), site acquisition (020), licensing/permission (030), project/production management (050), and indirect cost/others (090)', which includes general items to perform the project. 'Panel equipment (100)' includes several panel-related production equipment, and 'module equipment (200)' includes module-related production equipment. 'Fab common facility (300)' includes several common items for fabrication buildings, and 'utility (400)' includes utility-related equipment. Items belonging to the second level of 'panel equipment (100) and module equipment (200)' are not open to the public at the display company's request.

'Fab common facility (300)' has 'CR (310) and FA (320)' as the second level, which are facilities that common includes 'panel equipment (100) and module equipment (200)'. 'Utility (400)' includes 'gas (410), chemical (420), water (430), vacuum (440), emission (450), waste (460), and air (470)', which are utility equipment. 'Electric power facility (500)' includes 'electrical facility (510), distribution facility (520), and generating facility (530)'. 'Architecture/civil (600)' has 'infrastructure (610), stock (620), storage (630), auxiliary building (640), and temporary facility (680)', which includes general buildings. Finally, the second level of 'trunkline' includes 'system wiring (710),

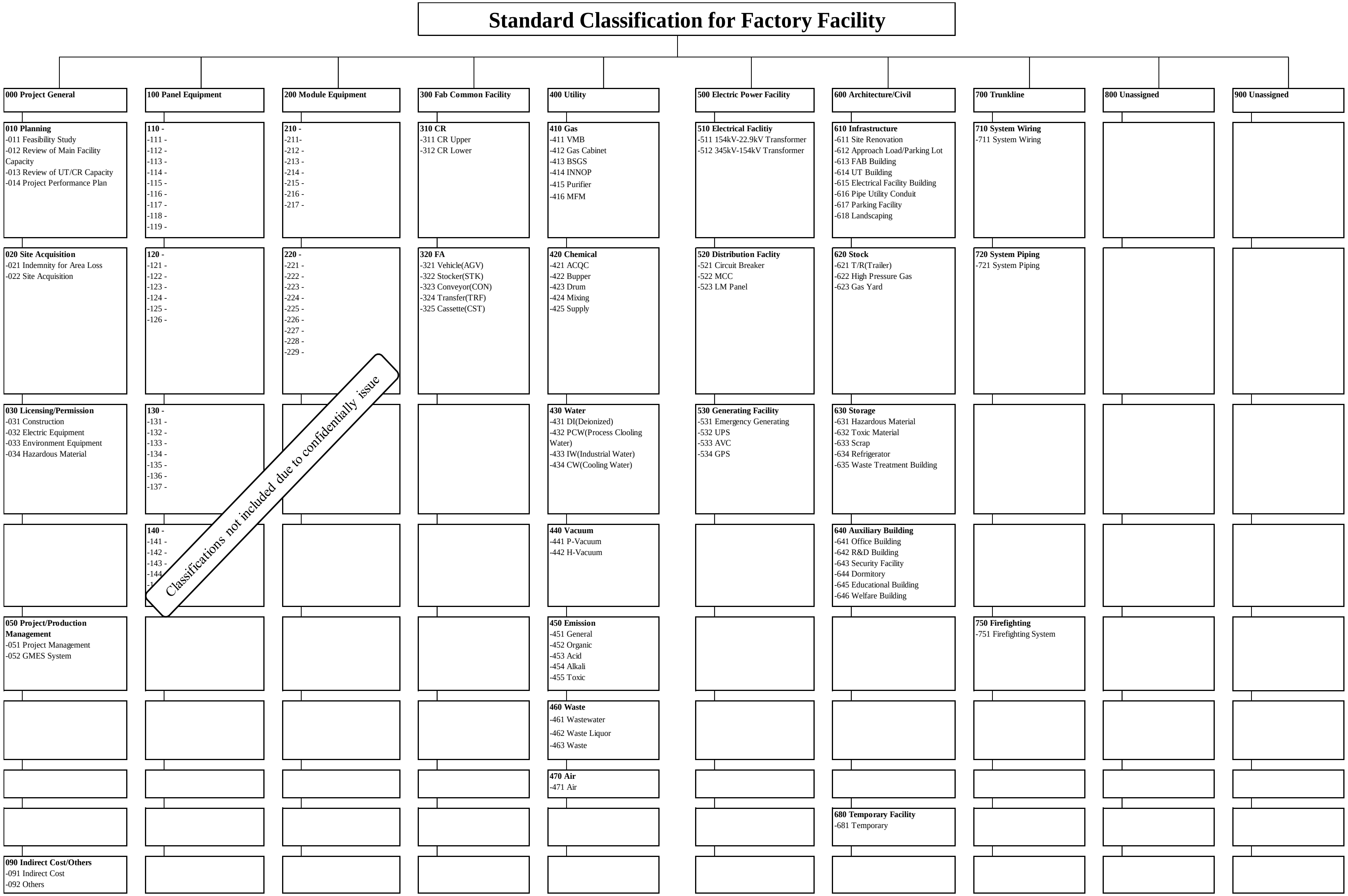


Figure 1. PBS Structure for Factory Facility

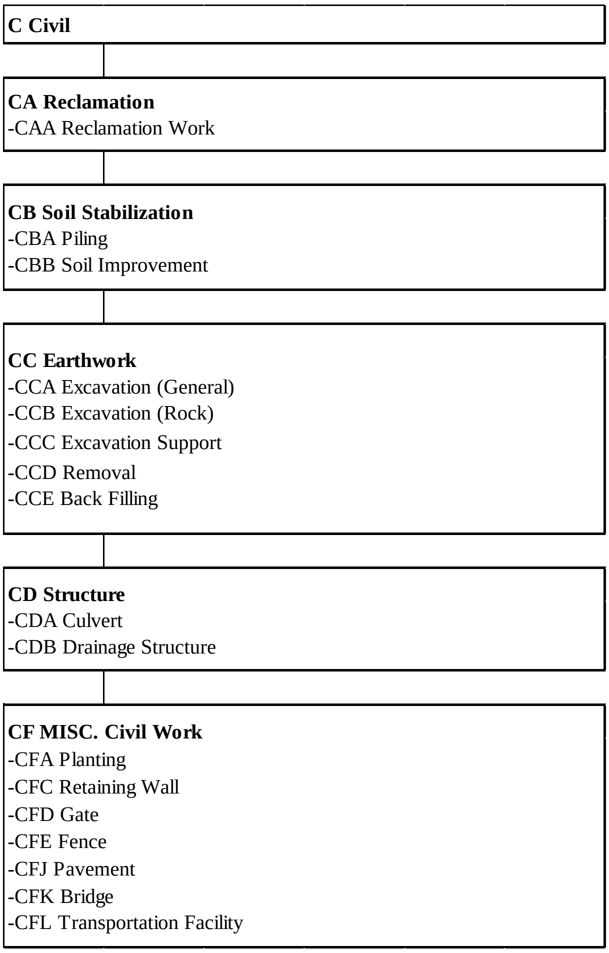


Figure 2. Part of PBS

system piping (720), and firefighting (750)'.

For example, Figure 2 shows the category of 'architecture/civil (600)'. 'Infrastructure (610)' includes 'site renovation (611), approach load/parking lot (612), fabrication building (613), utility building (614), electrical facility building (615), pipe utility conduit (616), parking facility (617), and landscaping (618)', which are infrastructures. 'Stock (620)' has 'trailer (621), high pressure gas (622), and gas yard (623)'. 'Storage (630)' includes 'hazardous material (631), toxic material (632), scrap (633), refrigerator (634), and waste treatment building (635)'. 'Auxiliary building (640)' includes 'office building (641), R&D building (642), security facility (643), dormitory (644), educational building (645), and welfare building (646)'. Finally, 'temporary facility (680)' includes 'temporary (681)'.

As a result, this category has five sub-categories in level 2 and twenty three items in level 3. In this way, PBS is defined that including a total of 8 categories in level 1, 31 sub-categories in level 2, and 125 items in level 3.

The proposed 'facility' classification in this study shows unique characteristics that cannot be found in existing construction codes. More specifically, 'project general (000)' are the general factors to perform a project. (700)' are defined with the factors for machines and 'Panel equipment (100), module equipment (200), utility (400), electric power facility (500), and trunkline systems rather than facilities. Because unlike general buildings, these factors are essential for supporting managerial tasks such as cost, scheduling, and operating in the factory construction project.

5 Case-Study

Due to the characteristics of factory construction, each standard classification of different technical fields should be used in a combined manner in order to improve information processing efficiency of construction participants according to share necessary information on entire related technical fields, such as civil, architecture, machinery, electricity, instrumentation, and communication.

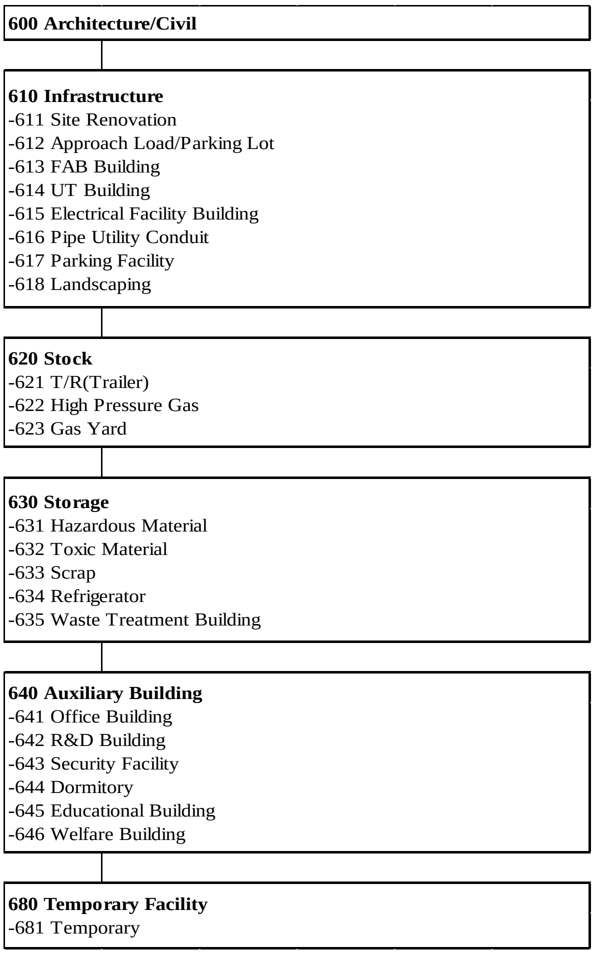


Figure 3. Part of FBS

Table 3 Criteria for combining PBS and FBS

PBS Division		FBS01		PBS01	PBS02	PBS03	PBS Division		FBS01		PBS01	PBS02	PBS03
000	Project General	L	Planning		●		400	Utility	D	Design	●		
		K	Consulting		●				M	Mechanical Equipment		●	
									E	Electrical Equipment		●	
100	Panel Equipment	D	Design	●					S	Commissioning		●	
		M	Mechanical Equipment			●							
		E	Electrical Equipment			●	500	Electric Power Facility	D	Design	●		
		S	Commissioning			●			E	Electrical Equipment	●		
200	Module Equiepment	D	Design	●			600	Architecture/Civil	D	Design	●		
		M	Mechanical Equipment			●			G	Temporary		●	
		E	Electrical Equipment			●			C	Civil			●
		S	Commissioning			●			A	Architecture			●
									M	Mechanical Equipment			●
300	FAB Common Facility	D	Design		●				E	Electrical Equipment			●
		A	Architecture			●			N	Automatic Control			●
		M	Mechanical Equipment			●			T	ICT			●
		E	Electrical Equipment			●							
		N	Automatic Control			●	700	Trunkline	D	Design	●		
		S	Commissioning			●			M	Mechanical Equipment	●		
									E	Electrical Equipment	●		

A case study of cost breakdown structure (CBS) structure is introduced by combining PBS and functional breakdown structure (FBS) at a display factory in this chapter.

Like PBS, FBS also has three-level structure. The first level has 12 categories. There are 'architecture (A), civil (C), design (D), electrical equipment (E), temporary (G), consulting (K), planning (L), mechanical equipment (M), automatic control (N), contract (P), commissioning (S), and ICT (T)'.

For example, Figure 3 shows the category of 'Civil Engineering (C)'. This category has 5 sub-categories. These include 'reclamation (CA), soil stabilization (CB), earthwork (CC), structure (CD), and MISC. civil work (CF). 'Reclamation (CA)' includes 'reclamation work (CAA)'. 'Soil stabilization (CB)' includes 'piling (CBA) and soil improvement (CBB)'. 'Earthwork' includes 'excavation (general) (CCA), excavation (rock) (CCB), excavation support (CCC), removal (CCD), and back filling (CCE)'. 'Structure' includes 'culvert (CDA) and drainage structure (CDB)'. Finally, 'MISC. civil work (CF)' includes 'planting (CFA), retaining wall (CFC), gate (CFD), fence (CFF), pavement (CFJ), bridge (CFK), and transportation facility (CFL)'.

As a result, this category has 5 sub-categories in level 2 and 17 items in level 3. In this way, FBS is defined that including a total of 12 categories in level 1, 45 sub-categories in level 2, and 130 items in level 3. If looking at the components of FBS, it also could define as a 'work section' classification.

In this case study, it has one specialty in CBS. When combining PBS and FBS, the FBS is combined at level 3, but PBS is combined at different level according to managerial objectives of owner. The criteria for combing PBS and FBS is shown in Table 3. In this table, level 1 is used as code '01', level 2 is code '02', and level 3 is code '03'.

Items of 'project general (000)' are combined PBS02 with the work items about 'planning (L) and consulting (K)'. Items of 'panel equipment (100) and module equipment (200)' are combined PBS01 with the work items about 'design (D)', and PBS03 with the work items about 'mechanical equipment (M), electrical equipment (E), and commissioning (S)'. Items of 'fab Common facility (300)' are combined PBS02 with the work items about 'design (D)', and PBS03 with the work items about 'architecture (A), mechanical equipment (M), electrical equipment (E), automatic control (N), and commissioning (S)'. Items of 'utility (400)' are combined PBS01 with the work items about 'design (D)', and PBS02 with the work items about 'mechanical equipment (M), electrical equipment (E), and commissioning (S)'.

Items of 'electric power facility (500) and trunkline (700)' are combined PBS01 with the work items about 'design (D) and electric equipment (E)'. In addition, items of 'trunkline (700)' are combined PBS01 with the work items about 'mechanical equipment (M)'. Finally,

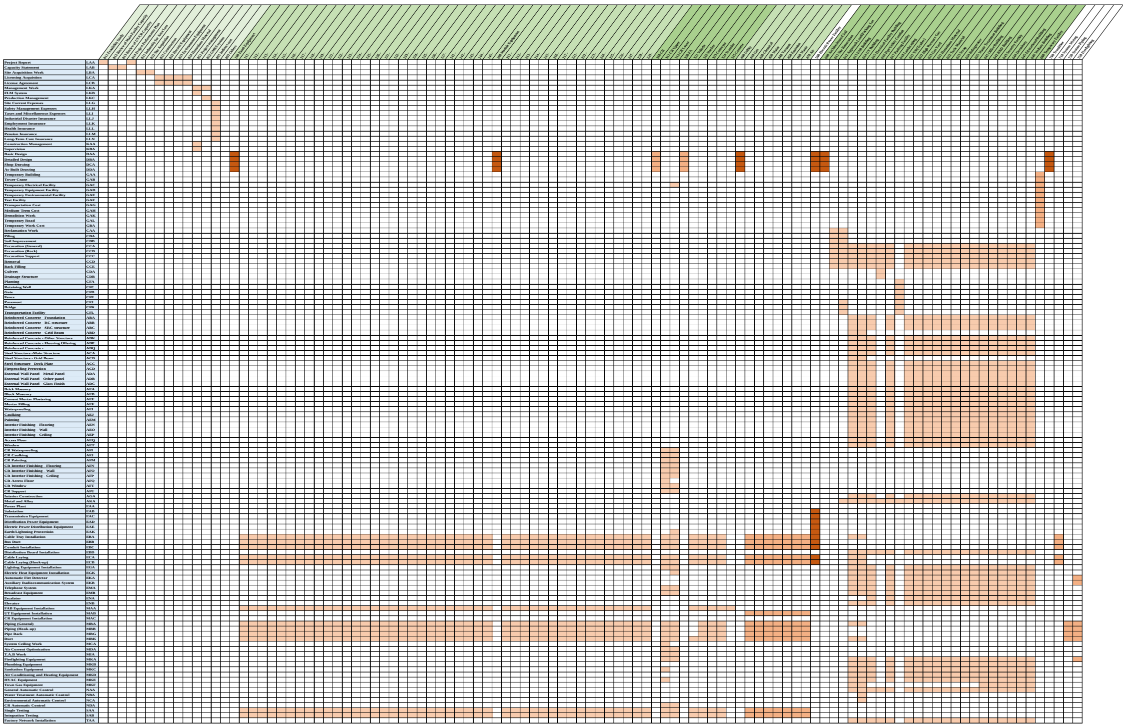


Figure 4. Matrix combining PBS and FBS

items of ‘architecture/civil (600)’ are combined PBS01 with the work items about ‘design (D)’, PBS02 with the work items about ‘temporary (G)’, and PBS03 with the work items about ‘civil (C), architecture (A), mechanical equipment (M), electrical equipment (E), automatic control (N) and ICT (T)’.

As shown in Figure 3, different CBS packages (cell) may have different levels in terms of combining a PBS with a FBS. The rationale behind having different levels is to accommodate the different importance of managerial requirement for a specific from the owner’s perspective. In other words, the concept of “flexible work breakdown structure (WBS)” is used in this research [6]. Due to the characteristics of the display factory in this case, ‘panel equipment (100) and module equipment (200)’ are very important parts. On the other hand, ‘electric power facility (500) and trunkline (700)’ are supporting function throughout the entire project.

In this way, a total of 1,709 Items for CBS are identified by combining PBS and FBS. It is represented by a matrix as shown in Figure 4. In this figure, a darkest cell is the combination of PBS01 and FBS03, dark cell is the combination of PBS02 and FBS03, and the lightest cell is the combination of PBS03 and FBS03.

The main objective of this case study is to develop criteria for managerial effectiveness of project cost on the owner’s perspective in the preliminary stage. In other words, it is to develop a standard CBS, which proposed in this study.

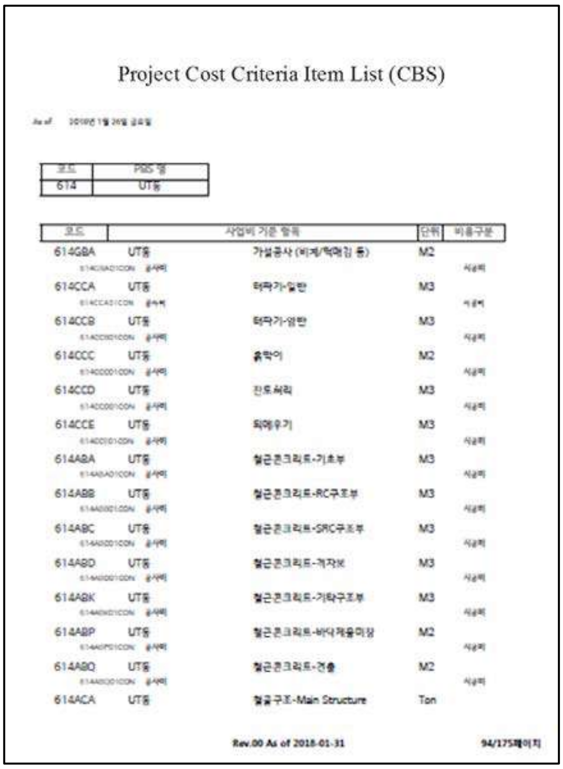
The case-study firstly defined FBS, which covers an entire life-cycle of smart factory construction based on the existing data of the display company. And each FBS was assigned standard code. CBS is developed by combining PBS and FBS with standard codes. This study used a relational data-base (RDB) system to create a list of CBS items through established relationship between each standard classification (Fig. 5). Therefore, historical data will be connected with the CBS items and it is possible to manage automatically and systematically. Standards codes can also be used to automatically information exchange (IE) among many different organizations [2].

6 Conclusions

Due to the lack of standard classifications for construction and operation management of smart factories, it is very limited for various construction participants to generate and share information by using the standards. This requires a great deal of effort to rework the data for the operational phase.

The purpose of this study is to develop a standard classification that could improve the effectiveness of information exchange among construction participants, and for systematic and efficient management and utilization of construction information for factory construction projects.

As firstly, PBS which is a standard classification for ‘facility’ facet that best reflects the characteristics of smart manufacturing has been proposed in this study.



Project Cost Criteria Item List (CBS)

코드	PBS 명
614	UT동

코드		사업비 기준 항목	단위	비용구분
614GBA	UT동	가설공사 [illegible]	M2	
614CCA	UT동	터파기-일반	M3	
614CCB	UT동	터파기-암반	M3	
614CCC	UT동	흙막이	M2	
614CCD	UT동	잔토처리	M3	
614CCE	UT동	되메우기	M3	
614ABA	UT동	철근콘크리트-기초부	M3	
614ABB	UT동	철근콘크리트-RC구조부	M3	
614ABC	UT동	철근콘크리트-SRC구조부	M3	
614ABD	UT동	철근콘크리트-[illegible]	M3	
614ABK	UT동	철근콘크리트-기타구조부	M3	
614ABP	UT동	철근콘크리트-[illegible]	M2	
614ABQ	UT동	철근콘크리트-견출	M2	
614ACA	UT동	철골구조-Main Structure	Ton	

Rev.00 As of 2018-01-31

Figure 5. Example of CBS Criteria Items List

The proposed PBS is verified through a case-study in the display industry. It could be seen that the CBS constructed through the combination of PBS and FBS best reflects the characteristics of the factory.

Although the smart manufacturing industry has been utilizing many well-established standards for a long time, standards for factory facilities have not been actively reviewed. In this context, the issues proposed in this study will contribute to the development of smart manufacturing industry.

Acknowledgements

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Integration of a Wearable Interface in a Design-to-Robotic-Production and -Operation Development

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Abstract –

This paper presents the integration of an *Internet of Things* wearable device as a personal interfacing node in an intelligent built-environment framework, which is informed by *Design-to-Robotic-Production and -Operation* principles developed at *Delft University of Technology*. The device enables the user to act as an active node in the built-environment's underlying *Wireless Sensor and Actuator Network*, thereby permitting a more immediate and intuitive relationship between the user and his/her environment, where this latter is integrated with physical / computational adaptive systems and services. Two main resulting advantages are identified and illustrated. On the one hand, the device's sensors provide personal (i.e., body temperature / humidity, physical activity) as well as immediate environmental (i.e., personal-space air-quality) data to the built-environment's embedded / ambulant systems. Moreover, rotaries on the device enable the user to override automatically established illumination and ventilation settings in order to accommodate user-preferences. On the other hand, the built-environment's systems provide notifications and feedback with respect to their status to the device, thereby raising user-awareness of the state of his/her surroundings and corresponding interior environmental conditions. In this manner, the user becomes a context-aware node in a *Cyber-Physical System*. The present work promotes a considered relationship between the architecture of the built-environment and the *Information and Communication Technologies* embedded and/or deployed therein in order to develop highly effective alternatives to existing *Ambient Intelligence* solutions.

Keywords –

Design-to-Robotic-Production & -Operation, Internet of Things, Ambient Intelligence, Wireless Sensor andNetworks, Adaptive Architecture.

1 Background and Introduction

The present work is situated at the intersection of the *Ambient Intelligence* (AmI) [1] and the *Adaptive Architecture* (AA) [2, 3] discourses. While AmI promotes a vision of future dwelling spaces integrated with sophisticated systems built on *Information and Communication Technologies* (ICTs), AA approaches the same endeavor via both high- and low-tech [4] architectural devices as well as physical transformations in order to instantiate active, reactive, and interactive built-environments. A common denominating objective of both AmI and AA is the promotion and prolongation of occupant well-being via built-environments capable of adapting to user-preferences as well as of encouraging healthy habits via non-invasive feedback loops (e.g., [5, 6]). At present, there are research groups and/or projects developing expressions of similar intelligent built-environments (e.g., [7–9]) via a variety of approaches. In this development, *Design-to-Robotic-Production & -Operation* (D2RP&O) [10] principles developed at *Delft University of Technology* (TUD) are used. D2RP&O extends beyond the AmI and AA discourses to conceive of built-environments imbued with high-resolution intelligence whose architectural and ICTs considerations mutually inform one another from the early stages of the design process. More specifically, D2RP promotes material and formal intelligence via geometry-optimization and heterogeneous material composition as well as *componentiality* and *hybridity* principles [11], while D2RO promotes the integration and deployment of sophisticated robotic as well as computational agents and mechanisms within the D2RP-informed architecture. In this manner, the sophistication of the physical built-environment as well as that of its ICTs mutually correspond to and complement one another, which results in more intuitive and effective solutions.

The present implementation builds on a D2RP&O-enabled system architecture previously developed by the authors [12]. The *Internet of Things* (IoT) wearable device (wearable, henceforth) described develops the

Wearables subsystem of said system architecture in order to render the user a *de facto* context-aware node in its *Wireless Sensor and Actuator Network* (WSAN), which underlies the *Cyber-Physical System* (CPS) that is the built-environment with its physical / computational mechanisms and services. Consequently, the built-environment is able to access user-specific physical / environmental data to consider in conjunction with data gathered by architecture-embedded sensors, which together enable the system's decision-making mechanism to yield highly informed actuations sensitive to the user. Similarly, the user is made aware of the status of his/her built-environment and of its interior environmental conditions, enabling direct or wireless intervention. This expression of intelligence in the built-environment supervenes on human and non-human collaboration.

2 Concept and Approach

The present implementation is divided into two main components developed in parallel, one corresponding to D2RP (see Section 3.1) and another to D2RO (see Section 3.2). Although the development focuses on a wearable belonging to D2RO systems, its proper operation requires the establishment of a WSAN that includes architecture-embedded nodes with which to exchange data and/or to instigate actuations. Such embedded nodes are integrated into architectural components specifically designed via D2RP to accommodate them in a seamless and considered manner. In this configuration, the very architecture of the built-environment is able to complement the technical sophistication of the wearable deployed within it. Without the architecture-embedded ICTs, the operability of the wearable would be limited to the services enabled by its own sensors, which would only provide information about the immediate surroundings of the user, leaving him/her unaware of the interior environmental conditions of the remaining surroundings. Moreover, without complementing architecture-embedded ICTs, the wearable would be unable to engage remotely with mechanism inherent in adaptive architectures.

In the present setup, real-scale architectural fragments composed of robotically fabricated components are developed via material subtraction in D2RP in order meet a variety of environmental, structural, and functional requirements as well as to host said embedded nodes (see Figure 1). That is to say, from the early stages of the design process, the envisioned technological services are taken into consideration along typical architectural considerations. In this manner, the resulting components are deliberately fabricated to sustain adaptive mechanisms in the form of computational services as well as in physical actuations in the built-environment.

With an established complementary infrastructure, four instances of the presented wearable—worn by four different users occupying the same built-environment—are developed and integrated into the WSAN via *Bluetooth Low Energy* (BLE). These wearables exchange sensor data and/or actuation commands with two coordinating nodes as well as with six router nodes, which in turn exchange data and/or actuation commands with one another via ZigBee, BLE, and/or WiFi (depending on distance, frequency, and/or latency requirements). This limited setup is intended to demonstrate seamless interoperability with respect to heterogenous microcontrollers / development platforms as well as to communication protocols within the WSAN.

Each wearable is equipped with eight attached sensors, regulators, and LED-bar displays, viz.: (1) an *MQ-4 Air-Quality* sensor to gauge air-quality within the user's personal space; (2) a *DHT-22 Temperature and Humidity* sensor to ascertain the user's thermal comfort; (3) an illumination override rotary as well as (4) a ventilation override rotary to enable the user to deviate from prescribed standards according to preference; (5) a notification confirmation button to acknowledge sent notifications by other WSAN nodes; (6) a notification buzzer to enable other WSAN nodes to provide audible prompts; (7) a LED-bar indicator of human presence or environmental events (e.g., gas-leaks, etc.) in any of six presently defined regions within the built-environment to notify the user; and (8) a LED-bar indicator of the immediate air-quality to warn the user of personal-space air-contamination levels. Additionally, the *Microcontroller Unit* (MCU) on which the wearable is based is integrated with a *BOSCH BMA250E triaxial accelerometer*, which may be used for gathering spatial displacement data for latter *Human Activity Recognition* (HAR) (see Figure 2 and Section 3.2). The functional advantage of these attached and integrated mechanisms is discussed in Section 3and demonstrated in Section 4.

Finally, the values and states of each mechanism of every wearable-instance are relayed to any of the architecture-embedded nodes for real-time streaming to Plotly© [13] for remote visualization and/or subsequent analysis of gathered datasets (within cloud-service storage limits) (see Figure 3).

3 Methodology and Implementation

3.1 Design-to-Robotic-Production: Intelligent Architectural Components

The developed D2RP components are considered from three different perspectives, each pertaining to a different set of functional requirements and scale—i.e., *Macro*, *Meso*, and *Micro*—in order to yield geometries with deliberate densities and porosities (see Figure 1).

Figure 1. Robotically fabricated components via material subtraction in D2RP. Left-to-Right: Single-layer physical prototype, (1) front-view and (2) side-view; Virtual 3D model, (3) single-layer side-view and (4) double-layer (inner and outer) side-view. Concept by Chong Du, Jihong Duan, and Floris van Buren [14].

The components are fabricated from Styrofoam blocks via material subtraction with a 6-axis KUKA robot [15]. From the *Macro* perspective, human movement is mapped unto an initial geometry with data from human body-posture analysis. The resulting form is optimized via structural analysis, consideration of environmental conditions and loads (e.g., wind direction and loads, etc.), and solar radiation with respect to a specified geographical location. Throughout this process, *componential* principles inform the design, which ensures that differentiated components are deliberately fabricated to conform seamlessly with one another to yield a unified whole. Furthermore, *hybridity* principles enable material heterogeneity within specific components as required by functional considerations. For example, structural analysis identifies areas across the geometry that are subjected to tension, compression, shear, bending, and torsion forces. The components within which these areas are located require deliberate material heterogeneity in order to properly account for said forces while preserving componential principles

From the *Meso* perspective, each component is designed to consist of two irregular yet mutually complementary layers—one external and one internal (see Figure 1, item 4)—while conforming a middle cavity as a continuous air-channel. Moreover, other cavities across both layers are designed to integrate mechanized cooling, heating, ventilation, and illumination systems, where their operation is controlled by architecture-embedded nodes in the built-environment's WSAN.

From the *Micro* perspective, variation of densities and porosities at the material level are considered with respect to functional requirements related to natural illumination and ventilation as well as to the potential for particular views.

3.2 Design-to-Robotic-Operation: Bluetooth Low Energy Wearable node

The developed D2RO wearable is built with a battery-powered PunchThrough© LightBlue Bean+™ (LBB+) MCU, a corresponding *Groove Expander*, and the eight previously listed mechanisms (see Figure 2, *WSAN/BAN: BLE Wearable Node*). The four instances of this wearable exchange data (via BLE) with two Raspberry Pi© 3 Model B™ (RPi3) *Single-Board Computer* (SBC) coordinating nodes as well as with six router nodes—i.e., three Asus© TinkerBoard™ SBCs and three Intel© Joule™ system on modules (see Figure 2, *WSAN: Arch. Embedded Nodes*)—which exchange data via ZigBee, BLE, and WiFi. These six nodes correspond to the six defined regions in the built-environment of this setup. As mentioned earlier, this heterogeneity in systems and communication protocols serves to highlight the effective interoperability between diverse ICTs within the WSAN. Nevertheless, these specific ICTs are deliberately included in the WSAN for their individual capabilities.

For example, all of the presently mentioned coordinating and router nodes may be dynamically clustered together *ad hoc* for Machine Learning activities as described and implemented by the authors elsewhere [12].

In the inherited and presupposed system architecture, a variety of environmental sensors monitor the *Interior Environmental Quality* (IEQ) [16] of the inhabited space. Whenever sensed-data deviates from prescribed illumination, ventilation, cooling, and heating standards, mechanical systems are activated in order to restore and sustain values within optimal thresholds. The wearable adds another dimension of sensing and aids the built-environment's decision-making mechanisms in accurately gauging the environmental conditions of the inhabited space, while simultaneously raising awareness in the user via its notification / feedback mechanisms.

In order to describe how this wearable does this, the implementation and functionality of each one of its attached and embedded mechanisms is described as follows:

1. *MQ-4 Air-Quality sensor*: This sensor has a methane-gas detection range of 300-10,000 *parts-per million* (ppm) [17]. Its purpose on the wearable is to detect the immediate air-quality surrounding the user. Should the built-environment's embedded-sensors fail to perceive contamination, the wearable's air-quality sensor instigates localized ventilation mechanisms nearest to the user to activate. In order to reduce unnecessary energy-consumption, the sensor is programed to take a reading every ten minutes. However, if sudden deterioration of air-quality is detected, the frequency increases to five minutes.

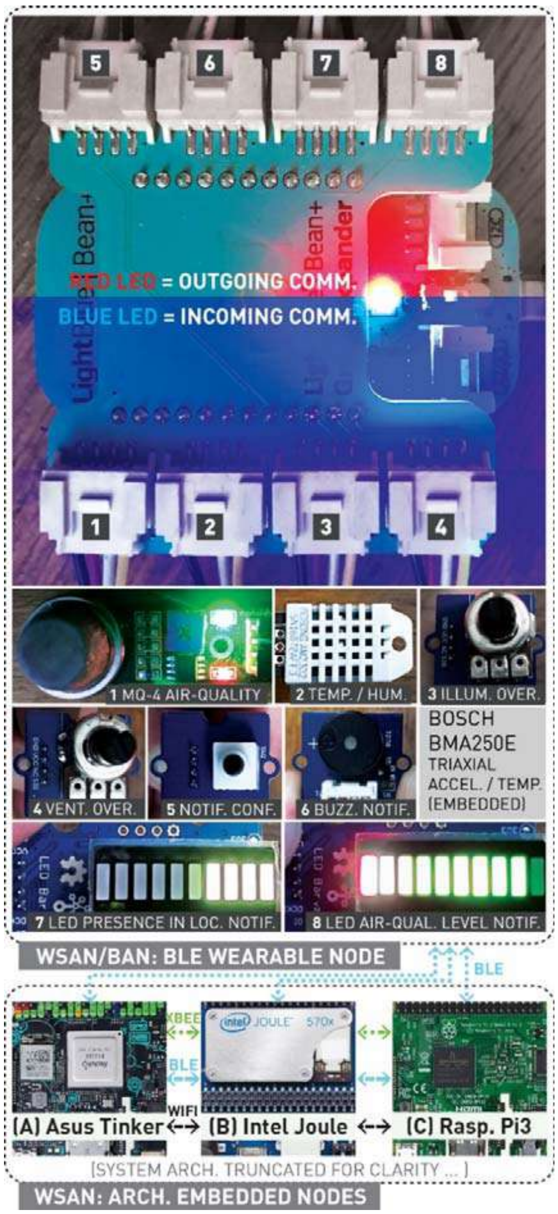

Figure 2. BLE Wearable Node as WSAN / BAN, Features.

2. *DHT-22 Temperature and Humidity sensor*: This sensor detects the temperature and humidity within the user's personal space. Like the previous sensor, if it detects deviations from optimal thresholds (in conjunction with or independently of architecture-embedded counterparts), localized cooling or heating mechanisms activate to sustain user comfort. Since the probabilities of a sudden drop in temperature and humidity within an enclosed environment are low, the sensor is configured to take readings every half hour.
3. *Rotary Illumination override*: This rotary mechanism enables the user to override illumination settings automatically determined by the built-environment's decision-making mechanism, should personal preferences deviate from optimal standards. Unlike the previous two sensors, this mechanism does not have a predetermined activation interval, as its activation requires the user's manual rotation.
4. *Rotary Ventilation override*: This rotary mechanism performs as the previous one only with respect to ventilation. The IEQ-sustaining mechanisms in the built-environment are configured to maintain conditions within *Comité Europeen de Normalisation* (CEN) Standard EN15251-2007 [18] thresholds, but precedence is assigned to human prerogative. Contingency measures limiting this override prevent sustained over-heating or over-cooling detrimental to human well-being.
5. *Notification Acknowledgement button*: There may be instances when the built-environment attempts to notify the user of urgent environmental events and/or conditions in particular regions (see item 7). This button serves to acknowledge such notifications.
6. *Notification Buzzer*: Two kinds of notification are implemented for this paper, one using visual cues (see items 7 and 8) and the other using sound. This buzzer is used only for urgent notifications, where a range of tones correspond to varying degrees of urgency. This mechanism works in conjunction with items 7 and 5.
7. *LED-bar "Presence / Event in Location" notification*: This LED-bar represents a visual cue that notifies the user of either human presence in a given regions of the built-environment or environmental events and/or conditions in those regions. For example, with respect to its *notification of human presence* function, the user may be notified of the presence of other users in any of the six hypothetical regions defined in this setup. It may be observed in Figure 2 that this LED-bar indicates that four regions are occupied by other users. With respect to its *notification of environmental events and/or conditions* function, it may be that a given region has detected a gas-leak, and in this case the LED corresponding to that region would turn red and the buzzer (i.e., item 6) would require acknowledgement via the notification button (i.e., item 5). The architecture-embedded ventilation mechanisms themselves would automatically intervene in such a scenario, but the user is notified to raise awareness of his/her surroundings.

8. *LED-bar "Air-Quality in personal space" notification*: This LED-bar works in conjunction with item 1 and serves to inform the user of the air-quality of his immediate surroundings. In order to prevent unnecessary energy-consumption, this visual cue only activates when the user raises his/her arm in a specific gesture—a mechanism adapted from Fitbit© Activity Trackers such as the *Charge HR*™, which also belongs to the *Wearable* subsystem of the inherited WSAN.

Finally, the embedded *BOSCH triaxial accelerometer* is used for HAR as a secondary data-source, if a primary accelerometer-enabled smart-device is absent from the ecosystem. This is due to the energy-consumption of continuous streaming of accelerometer data. In the inherited system architecture, HAR via smartphones [19] is preferred.

4 Results and Discussion

As mentioned in earlier sections, in the present setup four instances of the wearable are developed and used in a built-environment containing six defined regions, each one monitored via real-time streaming of the data generated / gathered by its attached and embedded mechanisms to Plotly in different frequencies—for example, accelerometer data frequency, for purposes of HAR, must be higher than that of the Temperature and Humidity sensor. Since the wearables only work with BLE, their generated / gathered data is streamed to any of the architecture-embedded nodes, where each may write directly to data streams pertaining to the attached and embedded mechanisms of any of the wearables. All the data emitted by the wearables include a device identifier which is used to ascertain that each of their corresponding data is fed to the correct Plotly stream. In this section, the Plotly charts corresponding only to one wearable— shown in Figure 3—are discussed (from top to bottom).

The first chart in Figure 3 shows that in that particular instance of the test-run, the air-quality surrounding the user is consistent, which is expected from a built-environment integrated with self-regulating ventilation devices. The values of the *y-axis* range from 1 to 0, where 1 attains optimal standards.

In the test-run interval corresponding to the *temperature* component of the second chart (i.e., chart 2a), the user first manually overrides automatic settings to increase ventilation, resulting in a deviation from the optimal temperature of 22.5° C.—an average of the accepted human-comfort range of 21° C. – 24° C. [20]. That is, it may be observed that between the 7,180th and 7,190th reading the actual sensed temperature dropped to ~55% of 22.5° C.

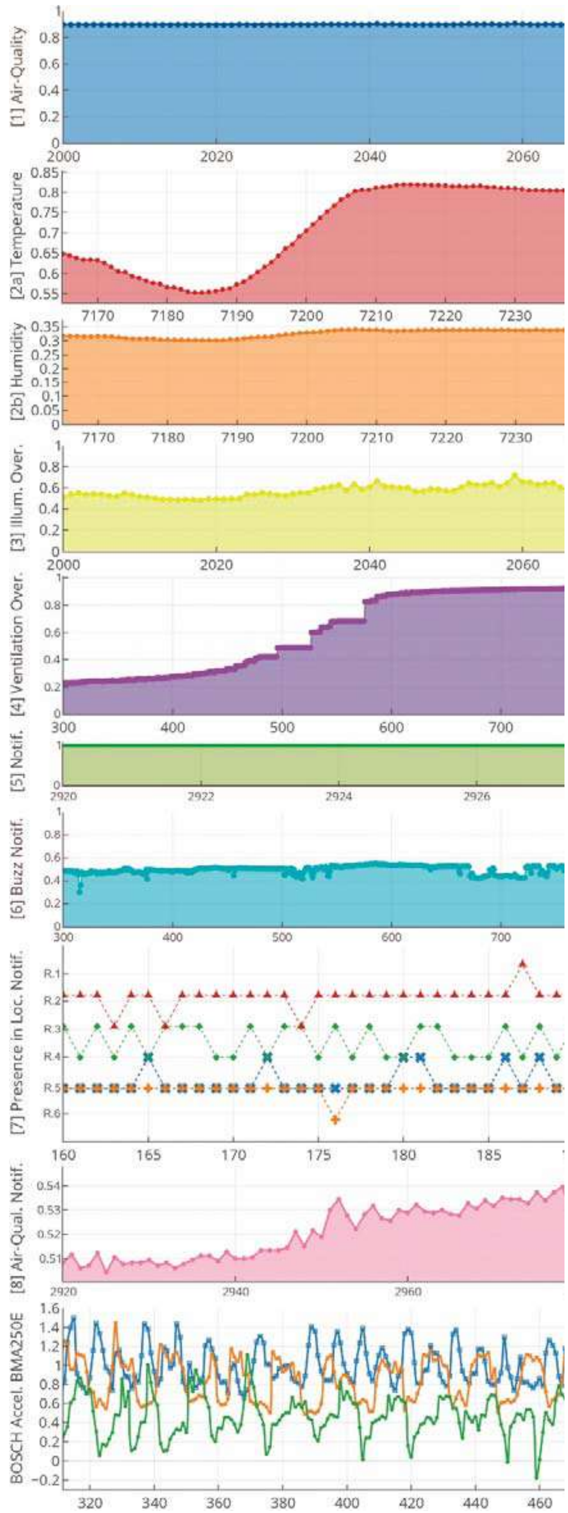

Figure 3. Gathered data plotted in real-time in Plotly©.

After this interval, and with no further human override, the temperature climbed steadily to more comfortable temperatures. The *humidity* component of this chart (i.e., chart 2b) indicates a slight decrease in humidity when ventilation systems were manually engaged, which is an expected result of higher air-flow.

The third chart indicates how much of the automatically determined values of illumination intensity is actually permitted to shine. That is to say, the illumination overriding mechanism works as a function of the built-environment determined output. For example, it may be observed in this chart that throughout this test-run interval, the actual illumination was kept between only ~50% to almost ~80% of the prescribed intensity-levels.

In the fourth chart, automatically determined temperature levels were decreased to ~21% of the actual values and gradually increased to ~90%.

The fifth and simplest chart records no instance of notification acknowledgements. The visualization of *pressed* vs. *unpressed* is inverted, where instances of the former are shown as 0 and of the latter as 1. Accordingly, no instance of notification acknowledgement is registered throughout the test-run, which corresponds to no undesirable environmental events being detected in any of the regions of the built-environment.

Urgent notifications result from a function over environmental readings. For example, it is not the case that any air-contamination triggers an urgent prompt, as healthy environments invariably contain degrees of air-contaminants, only within negligible levels. Accordingly, an urgent phenomenon is gauged based on the concentration and duration of undesired contaminants—in the present case, of methane gas, which has a *Threshold Limit Value* (TLV) of 1,000 ppm during an 8-hour period [21]. It is observed from the fifth chart that no notification acknowledgement instances are registered in the test-run's interval, which suggests an absence of urgent environmental events. This, however, does not suggest that the environmental conditions of any of the six regions are optimal. At most, it suggests that no air-contamination levels exceed accepted limits. This may be observed in the sixth chart—corresponding to the *buzzer* notification—where methane levels are detected at ~50% of a the prescribed TLV. Note that there are no instances below ~30%, since the sensor's lower-bound limit is 300 ppm.

The seventh chart maps the presence of the four users (each with a wearable, represented in red, green, blue, and orange) with respect to the six predetermined regions in the built-environment. The present set of charts correspond to the user in red. Unlike the other charts, this one in particular is common to all wearable users, which enables everyone in within the same built-environment to know one another's location.

The eighth chart, which corresponds to the LED-bar Air-Quality notification or indicator, indicates up to which LED is turned on in accordance with the air-quality ascertained (see the first chart). The *y-axis* ranges from 0 – 1, where 0 corresponds to no LEDs being turn on, 0.5 to five being on, and 1 to all being on. In this chart, it is observed that ~5 LEDs in the LED-bar were on during the corresponding test-run interval. As with the sixth chart and corresponding mechanism, the LED-bar corresponding to air-quality is driven by a function over air-quality readings, which explains the high-precision of logged values in this chart. Although at first glance it may appear simpler to define eleven possible states (i.e., 0-10) to correspond to the air-quality range of zero to ten, where high precision air-quality values with several decimals are simply rounded to the nearest single digit decimal. But this is redundant, as the eighth chart demonstrates that the present mechanism is capable of turning five LED bars on whenever the value ranges anywhere within 0.5, regardless of trailing decimal places.

Finally, the last chart—corresponding to the MCU-embedded triaxial accelerometer—demonstrates that three-dimensional displacement data is accurately logged and plotted by the present setup. As mentioned at the end of Section 3, it is preferred that accelerometer data-gathering be relegated to another smart-device (e.g., smartphone) due to the energy-consumption involved in high-frequency data transmission. However, if no such alternative is present, the wearable's accelerometer fulfills this task.

5 Conclusions

The present paper detailed the development of a wearable device to complement and to be complemented by ICTs embedded in intelligent and robotically fabricated architectural components via material subtraction in D2RP. In conjunction, said wearable and architecture-embedded systems provide higher precision and fidelity in the continuous promotion of user well-being in the built-environment, which the authors argue is a necessary feature for effective alternatives to existing AmI solutions. In the limited setup and corresponding test-run, the wearable performed as expected of a prototype, although aspects for latter optimization were indeed identified. A more efficient approach to energy consumption is to be developed in order to render the device a viable system in built-environments subsuming *high-resolution intelligence*.

Moreover, the majority of attached mechanisms will be embedded in the device in subsequent developments, which would require a custom-designed MCU. This will reduce the size of the wearable as well as moderately increase its battery-life.

Furthermore, the LED-bar indicating the position of users across regions in the built-environment will be reconsidered, as the present hardware limits the number of regions monitored to ten (i.e., ten LED bars in the module). Present work is being undertaken to replace the LED-bars with a low-energy *electrophoretic display*—i.e., Plastic Logic©'s 1.1" Lectum® display [22].

Finally, ZigBee communication capabilities are also presently being added unto the device in order to extend its longer-range data exchange capabilities.

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Photogrammetric Techniques for Monitoring Vegetation and Topographical Changes

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Abstract

Environmentalists express concerns about the health of the planet and the vital role of wetlands on Earth. Sufficient knowledge of wetland changes is becoming more crucial as loss of wetland area increases. However, an ability to efficiently map and monitor the wetland topographies requires technology advancement. Producing high resolution and high quality digital elevation models (DEMs) requires substantial investments in personnel time, hardware, and software while increasing accessibility of three-dimensional imaging methods, such as digital photogrammetry. Further refinements have highly improved the method while preserving its convenience. This study investigates the use of unmanned aerial system (UAS) coupled with structure-from-motion (SfM) technology as a new methodology for monitoring vegetation and topographical changes in the southeast Texas Wetlands. This study aimed at maximizing the efficiency and accuracy of the data collection process for mapping the wetlands and other related applications. This paper serves as a summary and evaluation of various photogrammetric and data extraction techniques.

Keywords –

Unmanned Aerial System (UAS), Unmanned Aerial Vehicle (UAV); Structure-from-Motion (SfM); Wetland Mapping; Digital Photogrammetry

1 Introduction

It has been estimated that wetlands occupy approximately 4-6% of the world's land, Southeast Texas included [1]. Wetland is a generic term used for the wet habitats impaling land that is either temporary or permanently wet. No matter to what extent human race contributes to wetland processes, wetlands are greatly beneficial for global ecology, and therefore, are valuable [1]. The study area is located on the Gulf coastal plain of the United States in Southeast Texas. Southeast Texas is located along the coast of the Gulf of Mexico and includes most of the Texas portion of the Intracoastal Waterway; it is crossed by numerous rivers and streams. The land is low, extremely flat, and often marshy - the perfect set of conditions to sustain wetlands. Along with freshwater wetlands, the area also includes salt marshes and coastal mangrove swamps that create a unique ecological system in the area. However, industrial development, human factor, and global warming tendencies contribute to freshwater losses of wetlands. Not only social well-being but also political development and economics are associated with the availability and distribution abilities of freshwater resources [2]. Furthermore, groundwater and surface water resources are essential for livelihoods [3]. This study introduces a new methodology in mapping and monitoring wetlands in Southeast Texas. Unmanned aerial system (UAS) combined with structure-from-motion (SfM) technology is able to create a new remote sensing market and open the doors to the future, where a UAS system is a necessity, not a luxury.

Today, a degraded wetland is not able to perform its functions fully, therefore, it's crucial to assess the status and quality of the wetlands frequently [4]. In order to monitor and map the wetland area, it is necessary to meet society's expectations considering the cost of analyzing method and potential benefits of sustainable wetlands. Unmanned aerial systems (UAS) coupled with structure-from-motion (SfM) photogrammetric process have a potential to revolutionize wetland mapping processes. The proposed method is gaining significant recognition from scientists, engineers, foresters, farmers, private practitioners, resource managers, and policy makers [5, 6]. Degradation of air quality, destruction of fresh water wetlands, the minimal federal standard of the environment regulation: all these factors have led to an environmental crisis in the Southeast Texas area. Some environmental problems are anthropogenic rather than natural. The loss of fresh water wetlands is caused by the urban sprawl: expansion of the industrial sector, forestry, and agriculture; tidal wetlands and beachfront are used for residential and commercial purposes [7]. Urban heat island effect significantly contributed to the current state of natural ecosystems, such as wetlands, and put habitat fragmentation at the top of the list of environmental concerns [8]. Therefore, the matter of environmental and social implications should be discussed in a specific context before it can be generalized [9].

1.1 Wetland Function and Classification

The interdependence between wetlands and aquatic ecosystems cannot be stressed enough; wetlands in southeast Texas maintain water quality and exceptional biodiversity [10, 11]. Wetlands are important components of the landscape: the holding capacity helps maintain flood control or act as a barrier to recharge, and reduce low flows [12]. Wetlands also act as recharge areas for groundwater. Groundwater supplies 25% of industrial water needs and serves as an important source of drinking water for more than half of the nation [13].

Substantial scientific evidence supports the claim that the wetland terrain type influences the hydrological cycle, colloquially known as the water cycle, the process in which water evaporates, condenses, and precipitates [12]. However, Dugan (1990) states that there are more than 50 definitions of “wetlands” in current use [14]. Defining whether it is a terrestrial ecosystem or a deep water aquatic habitat is exceptionally challenging due to their highly dynamic character and some limitations in evaluating wetlands conditions and their borders. Therefore, not all functions are present in the different types of wetlands, and many are unique due to particular floras and faunas. Wetlands include a complex range of ecosystems – for instance, nurseries for various species including shellfish and seasonally migrating birds.

Regardless of its effect on the area, the wetlands strongly influence the hydrological cycle. Successful water management proposes further research on which wetlands perform different hydrological functions [12].

1.2 Value of Wetlands

In the light of climate change, the impact of global warming on wetlands is not yet generalized or sufficiently investigated [15]. Without integrative environmental research and dialogue, solutions to environmental challenges will be unsuccessful and new problems will be kept on arising [16]. Economic methods, specifically cost efficiency and cost-benefit analysis, are a part of environmental policy evaluation and regulatory planning since 1983 in the United States [17]. The tools used for implementing a new environmental policy should adjust or limit economic activity [18, 19]. The purpose of an effective appraisal work of wetland’s potential benefits to society and environment is to efficiently reduce the cost of existing wetland monitoring methods, introduce new methods and reevaluate the importance. For instance, the World Wildlife Fund reported that coastal wetlands reduced the severity of impacts from hurricanes in the United States and provided storm protection services with an estimated value of $23.2 billion per year [20]. By providing protection against the impact of hurricanes, the wetlands significantly reduce the cost of damage repairs.

For a specific region, the value of wetlands can be measured both qualitatively and quantitatively. The value of wetlands should not only be measured by how much they contribute to the quality of life but also by how much money is associated with their functions. Despite some beliefs, assessing the value of wetlands is a complex procedure, involving a complex network of factors [2]. First, wetlands perform several processes in parallel. Optimizing for one process generally, happens at the expense of another creating the need to assign a unique value to each process. Second, based off of the economic principle of scarcity, the size of the wetland area contributes to its value. For example, the practice of wetland abundance it is often viewed as a social necessity to convert the wetlands for other needs.

The value of wetlands is evaluated by how many goods it yields, its hydro geomorphic position, and its position relative to human settlements. The ability to accurately gauge the value of wetlands allows regional, national, and international government officials to make the right decisions regarding conservation and utilization.

The importance of the wetlands and their contribution to the environment and the society is clear. However, the method through which they should be mapped and monitored is open for discussion. The difficulty of monitoring wetland is finding a spatial measurement technique that encompasses numerous desirable properties, such as reliability, accuracy, low cost, and ease of installation [21]. Many methods have been implemented throughout the years that purport some of these advantages, but this study will focus on the use of photogrammetry that can be relatively inexpensive to map and monitor the wetlands [22, 23, 24]. In the decision-making process, especially regarding technology advancement, it is necessary to take into account possible impacts evaluated by other disciplines [25]. For example, Building Information Modeling (BIM) can be used not only to analyze site conditions but also wetlands and protected habitats [26].

2 Introducing photogrammetry

The use of UAS has increased over the past years to monitor environmental changes. However, wetlands are difficult to map from the ground due to their fast-changing boundaries and the diversity of species. Adaption of innovation in any industry is a complicated and extensive process – academic researchers and educators have to pay special attention to new ways to communicate new ideas to construction industry practitioners, for example [27].

The idea of photogrammetry has been in development since 1480, and as digital technologies advance, its concepts have been used to further develop its derivative technologies such as Structure-from-Motion (SfM). "Topographic structure from motion: a new development in photogrammetric measurement" discusses the production of topographic datasets via the structure from motion photogrammetric approach. [28] produced high-resolution digital elevation models of the Pedernales River in Texas from photographs acquired by a handheld helikite using an online SfM program. The paper compares the SfM approach to the traditional photogrammetric approach. While the SfM approach uses a series of still images, the key difference between classical digital photogrammetry and SfM is the execution of image matching algorithms which calls for less strict requirements during the image acquisition phase. Substantiated by thorough comparisons and evaluations, the principal conclusion of the paper is that, compared to classical digital photogrammetry, the image matching algorithms of the SfM approach provide a higher level of automation and greater ease of use. Furthermore, the authors offer additional suggestions for future SfM implementation. The SfM approach is considered for the application discussed in this paper.

Regardless of the method of photo acquisition, many components contribute to the overall quality (i.e. accuracy and precision) of the data, and therefore, the method must be evaluated by several considerations. First and foremost, the method must be optimized for what is being observed. For example, if the goal is to estimate and monitor the vegetation that inhabits a wetland, then the incorporation of photointerpretation will be necessary to improve the quality of the data [29]. In the flow and erosion rates measurements algorithmic techniques and matrix conditioning can be applied in the data processing phase to reduce errors in the final model [30]. Other factors that strongly influence the integrity of the model include the quality of the metric camera(s), photographs scale, scanner efficiency, resolution at the ground, view angles and limitations such as surface morphology, vegetation, shadows, and atmospheric conditions [31]. Finally, the most significant and fundamental consideration is effectiveness; if the method is inadequate for the needs, then it can be dismissed. Pertinent to the scope of this paper, research has determined that digital photogrammetry can yield suitably accurate results and has a significant impact in terms of monitoring and planning for changes [32, 33, 34]. The method evaluation is complete when every factor of optimization has been considered.

This provides sufficient evidence that reinforces the necessity to map, monitor the wetlands and create a structured process for developing a method to do so. The studies explore emerging and revolutionizing technologies that are low-cost, high-quality and innovative. The use of UAS in agriculture sector alone is an emerging industry that is set to expand the next few years and become a U.S. $13.6 billion industry in the United States [35]. The research findings delivered by this review serve as a foundation for the method proposed in this paper.

2.1 Current practice of wetland mapping

The practice of monitoring the wetland changes over time is crucial to port cities, coastal communities, and wildlife habitats all over the world. Monitoring the changes in the environment can allow experts to study these changes and determine the causes of many environmental shifts. They can also use the knowledge about the changes to help slow the deterioration of the wetlands which is home to many species of animals and insects. Working with the local cities, officials across the world have several options to conduct this surveying in order to secure their environment's safety and to track the changes for the scientific study of the wetlands.

In Beaumont, Texas, the city officials are concerned with the deterioration of the wetlands caused by flooding, ship traffic, strong winds, and hurricane damage. These factors play an important role in shaping the Neches and Sabine Rivers and the wildlife that call these regions home. Currently, Beaumont opts for a geolocation technique in which videos are taken of specific points along the water front from an aerial position. These videos are taken as a panoramic view of the waterfront and the GPS coordinates where the video was taken is then documented. Once the videos are uploaded from the camera, they are linked to a map of the area. This interactive map takes the coordinates of the video taken and pins the video to the map for viewing. After several videos are taken at numerous points along the water front areas the map will represent a comprehensive string of videos that document the entire river's environment for that year. In order to take the videos, researchers must fly in a helicopter each year and hover in a specific location specified by the coordinates for each video to be taken.

This process in expensive due to the cost of renting the helicopter and the fuel cost for flying (Figure 1). The videos are generally shot over the course of two days each year. These videos are uploaded to the geolocation database where the interactive map for each year shows the change in the environment over time. These maps are very useful to the city and local industries as well as the environmental agencies tasked with the protection of the wildlife and recourses of the area. Although it is difficult to fly at the precise coordinates each year that was used the previous years, the team of surveyors does attempt to take data from the same vantage point each time they generate a geolocation map. The accuracy of the coordinates is estimated to be a 30-yard radius from the previous year's location. More accuracy could improve the quality of area mapping and vegetation observation. Helicopter-based GPS videography increases a risk of error, bias, and pseudo accuracy assessment. The conventional method of image acquisition using planes, helicopters or satellites can collect data for large land but can cost large amounts of money depending on the region of interest [5]. Nevertheless, it could be difficult to use these methods for a specific date due to weather conditions and flight regulations.

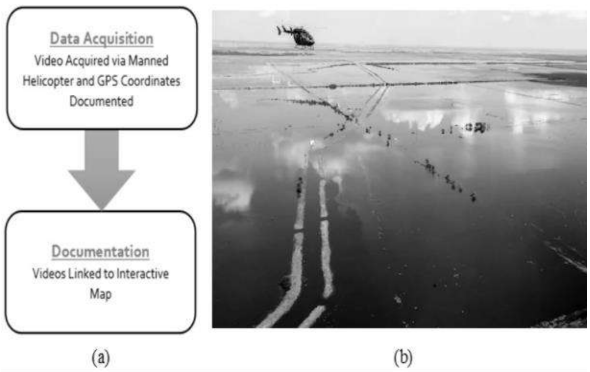

Figure 1. (a) Scheme of current practice of monitoring vegetation and topographical changes; (b) Monitoring after Tropical Hurricane Harvey - Jefferson County, Texas

2.2 Proposed method

Considering an increased awareness of wetland losses and threats to water quality, scientists recognize the importance of wetland mapping using the most advanced technology [36]. Researchers are in constant search for a more efficient, cost-effective way to monitor wetlands. Technological advances in mapping technology have opened up new avenues for innovative methods. The methodology can be greatly improved and made much more efficient through the use of UAVs (Unmanned Aerial Vehicle), aerial photogrammetry, and model overlapping analysis. Comparing to ground-based methods and any other conventional aerial technology, UAVs are cost-efficient and smaller, providing a high-resolution aerial image at low altitude [37].

The current method of the city of Beaumont does not take advantage of some of newest technology that is readily available. Instead of operating a helicopter each year to obtain videos of the area's wetlands, UAVs can be used to make the process much more cost effective and simpler. The use of a drone also makes it easier to take the video more than once a year, as it is cheaper and simplistic in comparison to helicopter usage practice. UAVs also allow for the video to be taken at a much closer distance giving a much more detailed look at the wetlands (Figure 2).

Once a video is recorded, it can be processed using a 2D or 3D aerial photogrammetry software. The two-dimensional model will be more advantageous, if erosion and the changing of the coastline location are the main areas of study, while the three-dimensional model examines the vegetation and elevation changes (Figure 3).

Figure 2. Video screenshot using UAV (Jefferson County, Texas, March 2017)

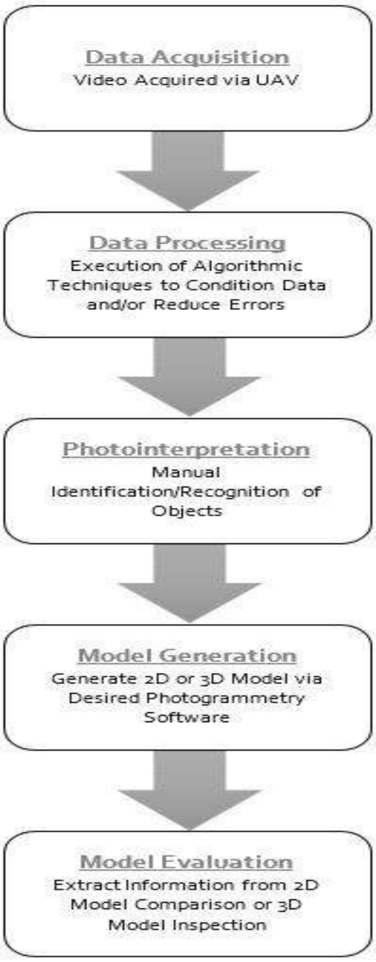

Figure 3. Current practice of monitoring vegetation and topographical changes

The two-dimensional software produces a map of the area videoed. This map can then be used to compare the same area of the wetlands to what it looked like in the past or how it looks in the future. For example, if the city of Beaumont used a UAV (a drone) to capture video of the same area every six months, the video could be turned into a map each time. These maps could be stored and used to compare the changes over a period of time using a method called layering in a program such as AutoCAD. Overlaying each map on one another would easily illustrate the changes in that particular area over time and also measure the exact change. It would simplify monitoring erosion and also help to alert trends of erosion happening at a more rapid pace.

The three-dimensional model helps monitor vegetation and sea level changes in the wetlands. The main advantage of a 3D multi-view model is the ability to examine a closely particular portion of the area at any convenience with a centimeter-level accuracy [38]. Complete control and navigation of the three-dimensional model is possible by using programs like AutoCAD. Figure 4 shows an example of created 3D model using PhotoModeler software to generate a point cloud dataset representing vegetation structure and wetland geovisualization. There are several programs that are able to convert images into useful three-dimensional data. For instance, PhotoModeler PC program is a platform that can generate the dense surface three-dimensional model, get accurate measurements and scans. PhotoModeler is able to quickly capture a large scene and to model accurate volume of stockpile using the PhotoModeler Scanner. One of the most important additions to modern UAVs (unmanned aerial vehicle) is global positioning system (GPS) – now, a UAV can determine its own location in three-dimensional space and apply this to its image data. Mapping can be a costly venture – budget is usually strictly limited or may not be sufficient enough to cover suitable mapping. With the help of all these features, a complex measurement task can be greatly simplified, done quickly, and at a low cost. Ground-based, helicopter and satellite observations do not contribute to wetland research as much as UAV practice could.

Figure 4. Sample of the created 3D model using PhotoModeler (Jefferson County, Texas, March 2017)

The process of creating two-dimensional or three-dimensional models is completely automated. Once uploaded, the software uses algorithms to detect particular features, match and mark the images, sense orientation layout, and then, produce the model using the data collected. The produced model will be a collection of point collates from the uploaded images or videos. In most cases, the model will not be entirely complete. It will be necessary to fill in the missing parts of the model, which in most cases is very minimal. This can either be done in the software where the model was created if possible, or using a program such as Adobe Photoshop.

In this study, we used a multi-rotor (DJI Phantom 3 Advanced Quadcopter Drone with 2.7K HD Video) to acquire high-resolution images and videos from a high angle. Throughout each flight, the drone sends GPS coordinates to a mobile device. The three-axis gimbal stabilizes the camera even with sudden movements or wind.

3 Discussion

Extreme summer temperatures put Texas in a position when Lone Star state faces severe, multi-year drought (Figure 5). Research shows that annual economic losses from not meeting the Texas's water needs could result in $12 billion annually and over one million jobs lost. This shows the importance and need for mapping and documenting the state of the Southeast Texas surface water for making effective decisions [39].

This section will compare the current practice and the proposed method from the previous two sections based off of the following attributes: quality of the final model, method efficiency, personnel time and effort, and cost. A comparison of the two methods will provide a sufficient foundation for method evaluation.

The current practice of mapping and documenting the state of the Southeast Texas wetlands only involves videos taken from an aerial perspective. The method proposed in this paper is an extension of the current practice; it integrates the application of photogrammetric techniques into the existing method. By doing so, this method allows for a more intensive inspection of the wetland areas through the generation of three-dimensional modeling. Furthermore, the photogrammetric techniques in the proposed method can also be coupled with photointerpretation to yield greater degrees of accuracy in estimations. While the proposed method is not designed to improve the video quality, it delivers a model that can be more thoroughly examined, and therefore, produces a final model higher in quality than the current method.

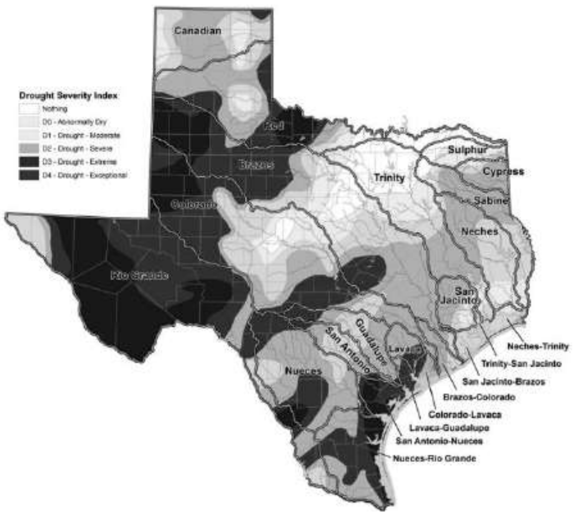

Figure 5. Drought impact on Texas surface water reported by TCEQ

The proposed method also accommodates for a more efficient process through which changes in the wetlands can be monitored. Unlike the current method, the proposed method has the ability to generate two-dimensional maps that model a specific wetland characteristic, i.e., vegetation, elevation, etc., which can then be overlaid and compared simultaneously. By overlaying two-dimensional models acquired for different dates, a more concrete comparison of the wetlands can be obtained more quickly and with less work.

Improved efficiency of the proposed method would reduce personnel time and effort, but that is without considering the learning curves associated with photogrammetry techniques, equipment, and software. Regardless, once the aforementioned learning curves have been surpassed and the method becomes a routine, the personnel time and effort will be greatly diminished.

The long-term costs required by the current method undoubtedly and significantly exceed the costs required by the proposed method. Initially, high-end photogrammetry software, equipment, and expertise must be attained with major expenses. However, the costs associated with the implementation of a UAV will be notably less than the costs associated with helicopter rentals and fuel. The reduced costs of using a UAV will also allow officials to map the wetlands more frequently, resulting in a more detailed and accurate depiction of how the wetlands change over the course of a year. Therefore, the proposed method offers long-term economic benefits which, in turn, allows officials to obtain more knowledge about the wetlands.

3.1 Limitations and optimization of the proposed method

As expected, the method proposed in this paper has several limitations. However, the number of limitations of the proposed method is less than those of the current practice. The limitations of this method affect videos that are acquired and the quality of the final product; this includes instantaneous atmospheric conditions, wetland morphology, and vegetation.

The following parameters can be considered for optimization: equipment, when videos are acquired (i.e., environmental conditions, season, etc.), how videos are acquired (i.e., camera angles, distance from objects, etc.), and photogrammetry software and algorithms. These four parameters are variable; method optimization should be contingent upon what is being mapped, measured, or estimated.

4 Conclusion

Using UAS to bridge the gap between aerial mapping and ground-based measurements can highly benefit wetland research and improve the economic situation in the area. Wetlands serve many purposes that are beneficial, and more often than not, crucial to humans. Therefore, the ability to accurately and efficiently monitor them is of high importance. Photogrammetry techniques provide a moderately inexpensive and efficient way through which accurate models and comparisons of the wetlands throughout time can be obtained. This allows officials to be more informed and make the appropriate and better decisions when planning for wetland utilization. The method proposed in this paper produces models that can be examined more thoroughly, is more efficient, does not require an unreasonable amount of personnel time, and is more cost efficient in the long-term. Although this method is designed to improve the practices used by officials in the Southeast Texas area, it is widely expandable and can be used to map and monitor most characteristics of any wetland area.

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Process- and computer vision-based detection of as-built components on construction sites

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Abstract -

Automated progress monitoring becomes more and more common in the construction industry. Recent approaches often use new methods like Unmanned aerial vehicles (UAVs) for a capturing large construction sites. However, the used methods often lack accuracy due to occluded elements and/or reconstruction inaccuracies from using photogrammetric methods. This paper presents a novel approach for further improvement of element detection rates. 4D BIM semantic information is used, to generate precise "as-planned" geometric models. These models are used to render a building from all points of view during the monitoring phase. Based on this information, a more accurate and reliable estimation of all detected elements can be achieved.

Keywords -

Progress monitoring; photogrammetry; BIM; UAV;

1 Introduction

Large construction projects require a variety of different manufacturing companies of several trades on site (e.g. masonry, concrete and metal works, HVAC). An important goal for the main contractor is to keep track of accomplished tasks by subcontractors in order to maintain the general time schedule. In construction, process supervision and monitoring is still a mostly analogue and manual task. To prove that the work has been completed as defined per contract, all performed tasks have to be monitored and documented. The demand for a complete and detailed monitoring technique rises for large construction sites where the complete construction area becomes too large to monitor by hand and the amount of subcontractors rises. Main contractors that control their subcontractors' work, need to keep an overview of the current construction state. Regulatory issues add up on the requirement to keep track of the current status on site.

The ongoing digitization and the establishment of building information modeling (BIM) technologies in the planning of construction projects can facilitate the use of digital methods in the built environment. In an ideal implementation of the BIM concept, all semantic data on materials, construction methods and even the process schedule are connected. Therefor it is possible to make statements about cost and the estimated project finalization. Possible deviations from the schedule can be detected and following tasks rearranged accordingly.

This technological advancement allows new methods in construction monitoring. As described in [3] the authors propose a system for automated progress monitoring using photogrammetric point clouds. The main idea is to use common camera equipment on construction sites to capture the current construction state by taking pictures of all building elements. When enough images from different points of view are available, a 3D point cloud can be reconstructed with the help of photogrammetric methods. This point cloud represents one particular time-stamp of the construction progress (as-built) and is then compared to the geometry of the BIM (as-planned).

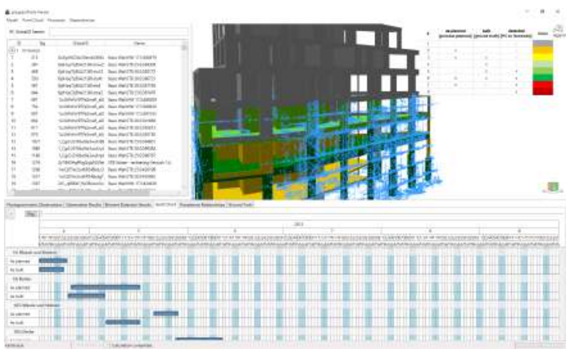

Figure 1. progressTrack: 4D BIM viewer incorporating detection states, process information and point clouds from observations

Figure 1 shows the C#-based WPF software tool, developed in the scope of this research. The tool visualizes a building information model and all corresponding semantic data. Additionally, the observation results can be selected and are supported by the possible overlay of the corresponding point clouds.

2 Related work

Several methods for BIM-based progress monitoring have been developed in recent years [15]. Basic methods make use of rather minor technical advancements like email and tablet computers into the monitoring process. These methods still require manual work, but already contribute to the shift towards a digital process. More advanced methods try to track individual building components by means of radio-frequency identification (RFID) tags or similar methods (e.g. QR codes).

Current state-of-the-art procedures apply vision-based methods for more reliable element identification. These methods either make direct use of photographs or videos taken on site as input for image recognition techniques, or apply laser scanners or photogrammetric methods to create point clouds that hold point-based 3D information and additionally color information.

In [2] and [1], a system for as-built as-planned comparisons based on laser scanning data is presented. The generated point clouds are co-registered with the model using an adapted Iterative-Closest-Point-Algorithm (ICP). Within this system, the as-planned model is converted into a point cloud by simulating the points using the known positions of the laser scanner. For verification, they use the percentage of simulated points, which can be verified by the real laser scan. [20] and [19] use and extend this system for progress tracking using schedule information for estimating the progress in terms of earned value and for detecting secondary objects. [13] detect specific component types using a supervised classification based on Lalonde features derived from the as-built point cloud. An object is regarded as detected if the type matches the type in the model. As above, this method requires that the model is sampled into a point representation. [21] introduce a measure for deciding four cases (object not in place, point cloud represents a full object or a partially completed object or a different object) based on the relationship of points within the boundaries of the object and the boundaries of the shrunk object. The authors test their approach in a very simplified artificial environment, which is significantly less challenging than the processing of data acquired on real construction sites.

In comparison with laser scanning, the use of photo or video cameras as acquisition devices has the disadvantage that geometric accuracy is not as good. However, cameras have the advantage that they can be used in a more flexible manner and their costs are much lower. This leads to the need for other processing strategies when image data is used. [16] give an overview and comparison of image-based approaches for monitoring construction progress. [11] use a single camera approach and compare images taken during a certain period of time and rasterize them. The change between two time-frames is detected using a spatial-temporal derivative filter. This approach is not directly bound to the geometry of a BIM and therefore cannot identify additional construction elements on site. [12] use a fixed camera and image processing techniques for the detection of new construction elements and the update of the construction schedule. Since many fixed cameras would be necessary to cover a whole construction site, more approaches rely on images from hand-held cameras covering the whole construction site.

For finding the correct scale of the point cloud, stereo-camera systems can be used, as done in [18, 5, 6]. [17] propose using a coloured cube of known size as a target, which can be automatically measured to determine the scale. In [7] image-based approaches are compared with laser-scanning results. The artificial test data is strongly simplified and the real data experiments are limited to a very small part of a construction site. Only relative accuracy measures are given since no scale was introduced to the photogrammetry measurements. [9] and [8] use unstructured images of a construction site to create a point cloud. The orientation of the images is computed using a Structure-from-Motion process (SFM). Subsequently, dense point clouds are calculated. For the comparison of as-planned and as-built geometry, the scene is discretized into a voxel grid. The construction progress is determined in a probabilistic approach, in which the parameters for threshold for detection are determined by supervised learning. This framework makes it possible to take occlusions into account. This approach relies on the discretization of space as a voxel grid to the size of a few centimeters. In contrast, the approach presented in this chapter is based on calculating the deviation between a point cloud and the building model directly and introduces a scoring function for the verification process.

3 Problem statement

Monitoring of construction sites with photogrammetric methods has become a working solution in many research areas. Currently a number of companies (e.g. Pix4D, DroneDeploy) already provide commercial all-in-one solutions for end users that allows to generate 3D meshes and point clouds from UAV-based site observations. All these methods give good solutions for finished construction sites or clearly visible elements of interest.

However, the authors noticed that monitoring of construction sites poses several problems. Photogrammetric methods are sensitive to low structured surfaces or windows. Because of the used method, each element needs to be visible from multiple (at least two) different points of view. Thus, elements inside of a building cannot be reconstructed as they aren't visible from an UAV flying outside of the building. Monitoring inside of a building is currently still under heavy research [14] and not available in an automated manner as orientation and observation in such mutable areas like construction sites is hard to tackle. These problems lead to holes or misaligned points in the final point cloud, that hinder correct and precise detection of building elements.

Figure 2. Occluded construction elements in generated point cloud caused by scaffolding, formworks, existing elements and missing information during the reconstruction process

As can be seen in Figure 2, another problem are elements that are occluded by temporary construction elements. Especially scaffoldings and formwork occlude the view on walls or slabs, making it harder for algorithms to clearly detect the current state of construction progress.

Since many construction elements that are correctly built and in place are occluded by other elements and hence out of view for a monitoring system outside of the building, the overall detection rates severely drop, despite the fact that most visible elements were detected correctly. Current methods do not take these problems into account and make only limited use of BIM related information such as type of construction or the general structure of a building.

As proposed in [4], the element detection based on point clouds is possible by calculating the distances between the generated point cloud and the surfaces of all building elements, derived from the BIM. After applying various optimization algorithms such as color filtering and octree based region filtering, still not all elements can be detected due to the before mentioned occlusions. Thus, the authors propose a method that includes process-based rendering of all visible elements at time of observation. In order to achieve this, all elements are rendered from all points of observation for each individual observation. After applying computer vision methods, it is possible to determine, which elements are visible at an observation. This helps to evaluate the as-built vs. as-planned comparison in regard to its efficiency and in the end results in more realistic detection rates, that take only visible elements into account.

4 Detecting visible elements

For the detection of all visible elements, the building information model needs to be rendered from all points of observation for every single observation.

4.1 Camera positions

As proposed, the point cloud is produced using photogrammetric methods. In this process, pictures are taken for example by UAVs (Unmanned aerial vehicles) from different points of view. These pictures can then be used to generate a 3D point cloud if all elements are visible from a sufficient amount of viewpoints. During the reconstruction process, the camera positions around the construction site are estimated. This is illustrated in Fig. 3. This estimation is refined during the dense reconstruction and can get more accurate by using geodetic reference points on site.

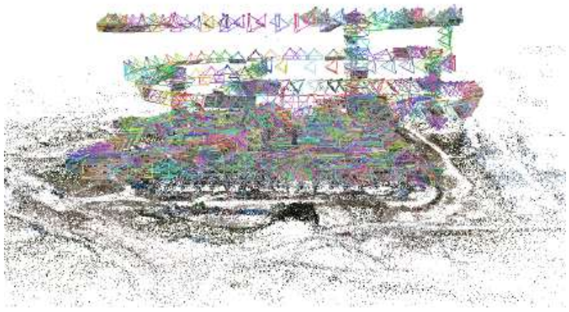

Figure 3. Estimated camera positions during point cloud generation using VisualSFM

These camera positions are required for the proposed method, as the detection accuracy will be refined by detecting all elements that are visible from these positions.

4.2 4D process data

Building information modelling can be used to combine geometry of construction elements with semantic data such as material information but also process schedules. In the scope of this research, the corresponding process schedule is connected to all elements. This allows to identify all elements that are expected to be built at each observation time stamp.

As visible in Fig. 4, the software tool used in this research is capable of integrating the building model, as well as process data and construction elements such as scaffoldings and formwork.

This data is required to define the sets of elements that are used for the visibility analysis described in this paper. Since the process schedule may change during construction, it is crucial to update the schedule permanently based on the gathered observation data.

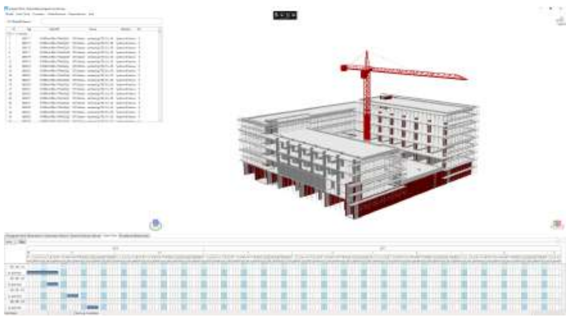

Figure 4. 4D building information model including all additional construction materials like scaffoldings and formwork

4.3 Re-projection

Based on the gathered information, it is possible to do a visibility detection using the camera positions as point of view and the process information to define the set of construction elements that are meant to be built.

To achieve this, the building model coordinate system needs to be transformed into the camera coordinate system or vice versa. Several parameters are needed for this transformation.

On the one hand, the intrinsic camera matrix for the distorted images that projects 3D points in the camera coordinate frame to 2D pixel coordinates using the focal lengths (F_x, F_y) and the principal point (x_0, y_0) is required. It can be described by the matrix K as defined in equation 1.

$$K = \begin{bmatrix} F_x & s_k & x_0 \\ 0 & F_y & y_0 \\ 0 & 0 & 1 \end{bmatrix} \quad (1)$$

Additionally, the rotation matrix for each image as defined in equation 2 is needed.

$$R = \begin{bmatrix} r_1 1 & r_1 2 & r_1 3 \\ r_2 1 & r_2 2 & r_2 3 \\ r_3 1 & r_3 2 & r_3 3 \end{bmatrix} \quad (2)$$

Using the model coordinates of all triangulated construction elements, it is possible to calculate the re-projection of each element into the camera coordinate system and therefore overlay the model projection and the corresponding picture taken from the point of observation with equation 3.

$$t = K * R * point; \quad (3)$$

The resulting 2D coordinates that are rendered into the picture are calculated by using the vector t and getting the x and y coordinates by calculating $x = t[0]/t[2]$ and $y = t[1]/t[2]$. This is done for each point belonging to the triangulated geometry representation of all construction elements.

As visible in Fig. 5 for an explanatory column, the re-projection works as expected and helps to identify the respective construction element in the recorded picture. The mentioned calculations need to include an optional transformation and rotation if the model is geo-referenced and thus the two coordinate systems differ largely.

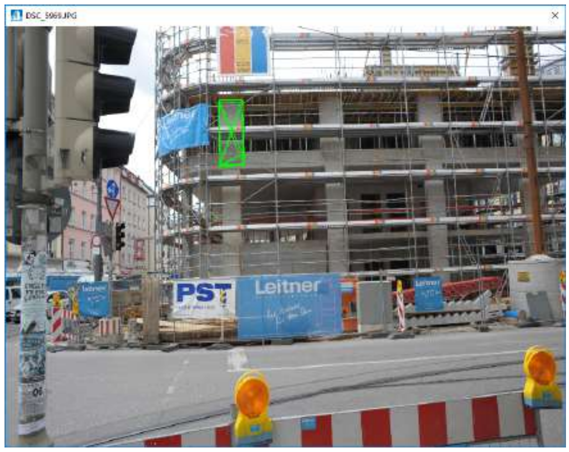

Figure 5. Reprojected triangulated column into a corresponding picture

4.4 Render model based on camera position

The algorithm introduced in section 4.3 enables the element-wise rendering of all construction elements in the respective coordinate system. In order to get a rendered image of all visible construction elements, the following steps are carried out:

1. Iterate over all pictures in observation
2. Iterate over all construction elements
3. Iterate over all points, representing the construction element
4. Get new, reprojected coordinates for all points, including distances to camera. Assign an identifier (e.g. unique RGB color) to each element
5. Iterate over all pixels/coordinates of picture and order points according to their distance to the camera

Whilst all geometric information is available, three problems need to be solved for an accurate rendering of all construction elements:

1. For triangulated elements, only the boundaries are known, however, the complete surface needs to be rendered correctly.
2. The rendered surface needs to be connected to the corresponding element since this information is crucial for a proper visibility analysis

3. Elements may blend over from the viewpoint in some circumstances. This needs to be addressed to get a correct rendering.

The first issue is solved by using basic inside/outside tests for points inside a bounding box around each individual triangle. This is combined with min/max tests to verify that all points are inside the given coordinate system of the current picture. The second issue is addressed by assigning an individual color in the RGB color range to every construction element. This allows to identify each element after the rendering is finished.

The third issue is solved by applying the Painter's algorithm [10] to each pixel in the given picture. In the given challenge, the distance to the point of view is stored for the current construction element and the color information is replaced in case an element has a smaller distance to the point of view and is also visible in the same pixel of the picture.

The applied algorithms result in a rendering as seen in Fig. 6.

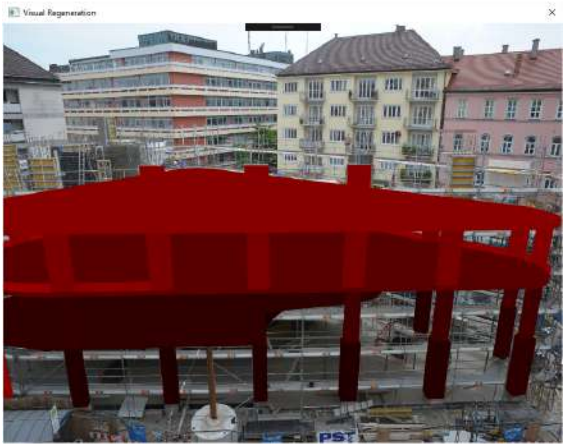

Figure 6. Using re-projection methodology for model rendering based on the Painter's Algorithm and 4D semantic information

After applying this technique to all observations and all camera positions, a distinct list of all visible construction elements can be generated by iterating over all pixels of each rendered image. The color of each pixel is assigned to an construction element and since the painters' algorithm is applied, only the element is visible, that has the lowest distance to the point of observation. Therefore, all visible, non-occluded elements can be determined with this method. This method allows for an automated construction element detection with more realistic detection rates.

5 Case study

The developed methodology has been applied to several construction sites.

As depicted in Fig. 2, most observations lack details at some point and have largely occluded areas due to the observation methods. In very disadvantageous observations the detection rate can drop down to 50% of the overall built construction elements. With the help of the presented methods, these rates can be explained since most of the undetected elements were not visible from the observation points. To quantify the efficiency of an algorithm for as-planned vs. as-built detection, it is very important to have a valid ground truth to allow a reasonable evaluation of the used methods. This approach helps to correctly quantify the used methods.

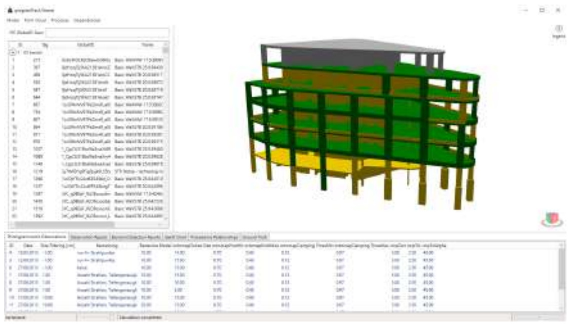

Figure 7. Detected construction elements from one observation. Green elements were successfully detected, yellow elements were not detected but are built.

This is clearly visible in Fig. 7. The green elements were detected correctly. The yellow elements, however, are actually built but were not detected. This is due to the fact that the inner walls were not visible from a sufficient number of viewpoints. Thus there was not enough points in the corresponding point cloud that allowed to validate the existence of the elements. However, these elements were identified as not visible by means of the method introduced in this paper. This helped to get a more realistic impression of the efficiency of the used detection methods.

6 Summary and Outlook

To obtain more realistic detection rates for photogrammetric monitoring methods, the paper addressed the question of visibility of individual building components. To this end the paper introduced a vision-based method which is based on rendering the building information model from all points of view of the photogrammetric capturing campaign. Since the finished building information model with installed facade elements would provide wrong information regarding element visibility during construction, only elements are rendered, that are supposed to be present at time of observation. This is achieved by using semantic and process information from the 4D building information model. The procedure's output is a list of all visible elements of a given point in time. This set of elements helps to further refine detection results based on photogrammetric methods.

Since the introduced methods do not help to identify all temporary construction elements, further research in this field is necessary. The authors are proposing to use the re-projected element positions and the relating pictures and apply machine learning methods to these parts of the picture. This could help to identify further elements such as scaffoldings or formwork, that might not be modeled in current design processes.

Acknowledgments

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Infrastructure Asset Management For Strategic Planning

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Abstract

The inventory of deteriorating infrastructure is increasing, and government resources are contracting inversely. The added expenditures of "emergency" repairs caused by asset mismanagement is too expensive and untenable. In response to the funding shortfall for transportation projects throughout Wisconsin, the Wisconsin Department of Transportation (WisDOT) needs to develop a strategic level asset management analysis tool for strategic planning. Infrastructure Asset Management (IAM) is a cohesive process that integrates data storage, software systems and analytical methods for strategic planning. The purpose of this paper is to analyze how the WisDOT currently manages their infrastructure assets and demonstrate how IAM technologies could improve efficiency and cost savings. Interviews were conducted with WisDOT staff on multiple occasions to ascertain current methods of asset management and project planning. Case study research and comparisons of successful asset management by other progressive state agencies were utilized to formulate the results. It was determined that the only instrument that can effectively realize long term performance, dependability in financial assessment, and prevent an unanticipated inflow of repair work is an Infrastructure Asset Management (IAM) system.

Keywords

Infrastructure; Asset; Management; Information; Technology;

1 Introduction

The costs associated with America's deteriorating infrastructure is well documented, along with a chronic shortage of funding available for maintenance, repairs or replacement. Additionally, much of America's infrastructure is nearing the end of its design life and will need to be replaced over the next decade. The American Society of Civil Engineers estimates that $3.3 trillion dollars is needed over the next 10 years just to maintain our aging public transportation network [1]. Meanwhile, government agencies are encountering increasing difficulties because of the aging and decline of infrastructure assets, insufficient budgets, escalating repair costs, swelling demand, and new environmental requirements to comply with.

Unfortunately, it has become obvious how dilapidated the state of Wisconsin's transportation infrastructure has become. The American Society of Civil Engineers 2017 Infrastructure Report Card estimates that, 1) of the 14,230 vehicular and pedestrian bridges in the state of Wisconsin, 1,232 (8.7%) are classified as structurally deficient, and 2) of the 115,372 miles of Public Roads, 27% are in poor condition [2]. Several years before the $1.7 billion Zoo Interchange reconstruction project began in Milwaukee, one of the existing bridges had a catastrophic failure and needed an emergency, temporary replacement. More recently, there was a WisDOT project where a bridge was overlaid with new asphalt as part of a larger project, and shortly thereafter it was determined that the bridge was failing and needed a fast track replacement. With the list of aging assets growing and government budgets shrinking in comparison, the additional costs of "emergency" repairs due to asset mismanagement is unaffordable and unsustainable. Or as Curry puts it, "Putting aside the complete chaos that any major failure of our infrastructure would cause to the economy, it's just flat out unsafe" [1].

Infrastructure Asset Management (IAM) is a fundamentally cohesive process that requires the integration of an array of information, methods and IT/software systems [3]. New asset management technology can greatly reduce the need for emergency repairs and replacements, as well as "to store and manage information and to support tactical and strategic decisions regarding the operation, maintenance, rehabilitation, and replacement of their infrastructure. Implementation of efficient and cost-effective management strategies largely depends on the ability of these systems to share and exchange asset life cycle information" [4]. IAM is "helping to control costs and program maintenance by combining its various infrastructure inventories into a single platform, resulting in an integrated pavement, bridge and utility management tool. It will overlay sewer, water line, pavement and bridge conditions to facilitate programming of maintenance and capital projects by city management, as well as assist in determining optimal allocation of the city's funds" [5]. Mahmoud Halfawy also points out that many of WisDOT's software tools were not developed to exchange data with other systems. The unforeseen result is information "silos" causing issues with "data consistency, accuracy, and accessibility" [3].

The intention of this paper is to illustrate how escalating construction and preservation costs along with amplified traffic loads have momentously increased the need for an effective Infrastructure Asset Management (IAM) software at WisDOT. This paper will also investigate the use of the IAM to supplement or replace existing management tools for strategic planning at WisDOT by exploring data flows, return on investment, I.T support requirements, staff requirements, and data analysis outcomes.

2 Measuring Infrastructure Deterioration

Currently, WisDOT is using legacy systems such as META manager. These systems have several shortcomings. They:

- Do not all connect to Geographic Information Systems (GIS).
- Do not connect to Building Information Modeling (BIM).
- Are not stored in the cloud.
- Do not communicate with each other, creating information silos.
- May only have printed copies for output.
- Are up to thirty years old.

2.1 Current Measuring Techniques

Due to the excessive costs of replacing infrastructure there has been an increased focus on maintaining existing infrastructure to extend its useful lifespan as much as possible. This strategy is also used to maximize the usefulness of the limited funds available by spending it where it is most needed and preventing larger replacement costs in the future. Bridges can suffer structural deterioration due to aging, misuse or lack of proper maintenance. It is crucial to inspect the bridge periodically and to assess its condition and evaluate any possible damage.

Visual inspection, complemented with Non-destructive Testing and Evaluation (NDT/NDE) has long been used to determine the structural health of bridges. The Wisconsin DOT relies almost exclusively on manual inspections to determine the status of their infrastructure. These inspections are recorded either on paper copies in the field and then manually entered in to a data base or tablets that can input the inspections directly from the field. These inspections follow the National Bridge Inspection Standards (NBIS) and the requirements are explained in detail in the WisDOT Structure Inspection Manual. Table 1 below contains an overview of inspection types and recommended intervals.

Table 1. WisDOT Structure Inspection Manual Requirements

Structure Type	Inspection Type*	Max. Inspection Interval
Public Roadway Bridges	Initial/Inventory Update	After Const. & Major Rehab. or 48 months
	Routine Visual	24 months
	Damage	As needed
	Interim	As needed
	Load Posted	12 months
	In-Depth	72 months
	In-Depth with NDT	72 months
	Fracture Critical	24 months
	Fracture Critical with NDT	72 months
	Paint Assessment	As needed
	Movable	12 months
	Underwater Survey	24 months
	Underwater Diving	60 months
	Underwater Probe/Visual	24 months
Traffic Operations Support Structures	In-Depth	48 months
	NDT	As needed
Roadway Lighting Structures	Routine	48/96 months
	NDT	As needed
Earth Retention Structures	Routine	48 months
Noise Barriers	Routine	60 months
Culverts and Tunnels	Routine	24/48 months
Impact Protection Systems	Routine	60 months
Other Structures over Roadways	Routine	24 months
Pedestrian Bridge	Routine Visual	24 months
Ferries and Ferry Terminals	Routine	24 months
	Underwater	60 months
Truck Weigh Scales	Inspection and Maintenance	48 months
	Calibration	12 months

The key inspection points are as follows:

- All bridges with spans over 20 feet must be regularly inspected.
- There are several types of inspections that are classified based on their level of thoroughness. The normal inspection frequency is 2 years, but this can be extended to 4 years when an in-depth inspection has not reveled any major deficiencies.
- Both WisDOT and the NBIS have stringent qualification requirements to becoming certified to perform bride inspections. The inspector has five general responsibilities:
    1. To ensure public safety and confidence.
    2. To protect the public's investment.
    3. Identify and assess structure needs.
    4. Provide accurate structure records.
    5. Fulfill legal responsibilities.

- The best approach at present is to obtain a baseline evaluation of all bridges and note any damage. 2-3 inspection cycles will yield excellent prognostic data on bridge deterioration. Those structures found with deterioration not yet requiring repair should be monitored closely, at shorter time intervals.
- The WisDOT Structure Inspection Manual discusses testing methods in detail, ranging from visual and audible inspections to ultrasonic and impact echo testing.
- The WisDOT Structure Inspection Manual provides all the forms required for carrying out an official bridge inspection.

These inspections show how the bridge is deteriorating with time, and provide inspectors and engineers with information about how long before repairs are necessary.

2.2 Current Data Management

In theory, this system is simple, effective, and easy to track. However, Wisconsin Department of Transportation is responsible for approximately 13,400 fixed roadway bridges, 50 moveable bridge, and 100 pedestrian bridges over highways [6]. This makes it extremely difficult to efficiently prioritize maintenance needs. Often preventive maintenance actions should occur when a structure appears to be in a “state of good repair” to nonprofessionals, which compounds the challenge of demonstrating and communicating the value of the right sequence of actions over a facility’s life cycle [7]. In times of significantly constrained resources, delaying preservation activities is often attractive in the short term to fund other programs even though the long-term costs and consequences of such a strategy can be significant. There is currently no “golden measure” that is likely to resolve all the difficulties in properly evaluating and communicating preservation needs. Every transportation agency is different. Each face unique challenges in measuring performance and preserving their transportation system.

The next challenge is to be able to analyze data from all the bridges in the state and rank them to determine which have the greatest need for repair or maintenance to prevent higher repair costs in the future. Over the past ten years, a significant amount of research has focused on performance measures, data requirements, analytic tools and approaches for integrating measures into a performance management process that supports performance-based decision making at both the state and regional levels. With recent advances in computer technologies, developing intelligent bridge monitoring systems is becoming a more viable option. Data sensing is become more common.

A data sensing system will typically consist of six common components:

- Sensors and data acquisition networks;
- Communication of data;
- Data processing;
- Storage of processed data;
- Diagnostic and prognostic analysis (i.e. damage detection and modeling algorithms, event identification and interpretation)
- Retrieval of information as required.

3 Literature Review

When transportation departments are considering whether to make the investment into IAM, it can appear expensive. There can be costs associated with gathering new data and modernizing existing data. Fortunately, WisDOT has done an admirable job of inspecting their assets. The costs would be in integrating and managing asset data. To positively influence data management, Brous et al. [8] proposes four fundamental facets to data governance. These facets are; Coordination mechanisms, data quality requirements, monitoring data quality, and creating shared data commons. Naturally, because IAM is a data driven discipline, its effectiveness is dependent on the data being of superior quality as well.

Governing bodies at every level acknowledge the need for asset management as reflected by regulations such as ISO-55000 and the Moving Ahead for Progress in the 21st Century Act [9]. These are devised to swing management approaches away from funding reactive repairs, and toward embracing strategies to proactively finance a more enduring infrastructure. “The most efficient way to satisfy these requirements, secure funding and ensure a process that proactively detects needed repairs and safely prolongs the life of equipment is by investing in asset management and the technologies that provide the needed visibility and predictive maintenance.” [1]

Because of IAM’s dynamic nature, integrating sustainability practices is straightforward [10]. When making sustainability decisions, each phase needs to consider the triple bottom line (TBL) of sustainability to create greater value [10]. The TBL framework considers the potential social, environmental, and financial impacts. The US Environmental Protection Agency (EPA) has provided direction [10] to facilitate agencies to establish targets and execute methods that feature TBL considerations. Adding sustainability to IAM can compensate for shifting environmental changes and fluctuation in transportation demands.

Finally, as agencies consider and evaluate the implementation of asset management, a cohesive management team who share a common vision for system objectives is critical to success. [9]

4 Asset Management Software

As an example, Deighton is an asset management software used by several transportation departments. It is designed specifically to prevent data fragmentation and incorporate pavement, bridges, subsurface utilities, signs, safety, and traffic data using cross-asset analysis capabilities [5]. Regulations such as ISO-55000 and the Moving Ahead for Progress in the 21st Century Act are devised to swing the approach away from using funding to go after reactive repairs, and rather implement a strategy to proactively finance a more enduring infrastructure [1]. "The most efficient way to satisfy these requirements, secure funding and ensure a process that proactively detects needed repairs and safety prolongs the life of equipment is by investing in asset management and the technologies that provide the needed visibility and predictive maintenance. Government agencies that can administer public infrastructure are finding that new asset-centric software helps them prioritize projects based on risk and criticality, and invest their capital improvements funds in ways that will have the greatest impact [1].

4.1 Pricing

There are several (IAM) software packages available to Departments of Transportation, such as Deighton's Total Infrastructure Management System (dTIMS), Bentley AssetWise, or Decision Lens. For simplicity, this paper will use pricing information for Deighton software. The dTIMS software appears to contain an initial cost for the license and an annual fee dedicated towards maintenance and updates for the software. A comparison between various infrastructure asset management (IAM) software conducted by an individual at Saitama University in Japan found the initial cost of the license to be in the range of $60,000 to $80,000 and the annual fee to be around $4,000 per license. Considering these costs, they estimated that the typical cost to implement the dTIMS CT software at around $225,000 [8].

4.2 Price Comparison

Several department of transportation (DOT) budgets were examined to determine the costs of a single license. The City of Des Moines (Iowa) paid an initial cost of $64,125 for a single license in 2016, with the annual fee at $12,000 [9]. The South Dakota DOT conducted a year-long research project into the life-cycle sustainability for various rehabilitation structures and paid $65,000 for a single license. An annual maintenance cost did not appear in the budget for the project due to the project taking less than one year [10]. Research conducted by the University of Wisconsin-Madison into the Wisconsin DOT budget yielded a cost of $60,000 for license, and an annual maintenance and support fee of $7,000 [11]. An investigation by Caltrans into the Colorado DOT's use of the dTIMS software estimated that the total cost to implement the software at $225,000. This supports the claim that was made earlier from Saitama University; however, this includes the cost of approximately 2000 working hours dedicated to the investigation [12]. Even assuming a high hourly wage (such as $80/hour), the labor cost comes out to $160,000, leaving $65,000 for the initial purchase of the software. Table 2 contains a summary of the various costs researched:

Table 2. Summary of dTIMS CT

Source	Single License Cost	Annual Fee
City of Des Moines	$64,125	$12,000
South Dakota DOT	$65,000	-
Wisconsin DOT	$60,000	$7,000
Saitama University	$60,000 to $80,000	$4,000

4.3 Return on Investment

Purchasing IAM software and incorporating it can pay for itself by preventing only one of the two instances of resource mismanagement at WisDOT. Earlier in the paper, a project was mentioned that included a bridge that was overlaid and then needed emergency reconstruction. This is a perfect example of why an IAM system is needed to prevent further occurrences, and it is also an optimal demonstration of the Return on Investment (ROI) potential. The initial project was three miles long, or 15,840 linear feet. The cost of the initial project was $1.5 million. The cost of the initial project divided by the length of the initial project results in a cost of $94 per linear foot of overlaid roadway. On a similar project with a road overlay that included a bridge reconstruction, the length of the bridge reconstruction "footprint" was 0.5 miles, or 2,640 linear feet. It is assumed that the initial projects bridge reconstruction "footprint" will also be close to 2,640 lineal feet, multiplied by the overlay cost of $94 per lineal foot, the lost funds spent on the overlay are $248,160. This one occurrence cost WisDOT is $23,000 more than the projected price of implementing dTIMS CT, for $225,000.

4.4 Workflow

Investigating two state DOTs can provide useful insight into the workflow for the implementation and use of the dTIMS CT software. Two are examined: Pennsylvania and Colorado.

The Pennsylvania DOT (PennDOT) uses dTIMS as a pavement asset management system for its interstates, US highways, and state roadways. There are two types of primary inputs into the analysis: inventory, current conditions, and financial records, along with decision criteria and performance. The inventory, current conditions and financial records come from diverse types of monitoring and control software, such as PennDOT's Engineering and Construction Management System (ECMS) or Multi-modal project management system interactive query (MPMS) [13]. Data from the two types of main inputs are then inputted into the dTIMS CT software. The analysis from the software then outputs strategies, recommendations and strategic reports. This is then given to other field and office staff. Field personal end up submitting maintenance records to the dTIMS analysis, while office staff provide feedback in what PennDOT calls the district feedback program. Figure 2 demonstrates an overview of the dTIMS workflow.

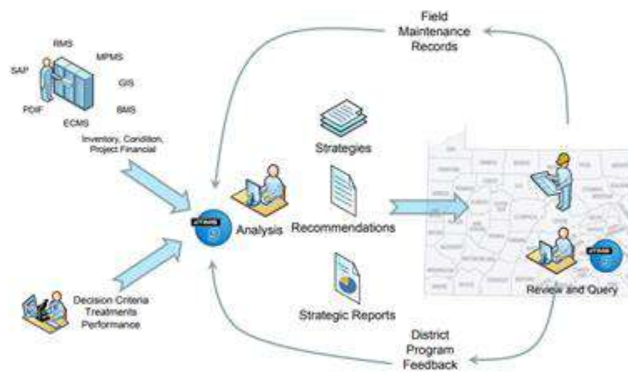

Figure 2. PennDOT Workflow for dTIMS CT (PennDOT, n.d.)

The Utah DOT (UDOT) provides a simpler outline for their implementation of dTIMS CT. They are applying it on a larger scale compared to PennDOT, using it not only for pavement, but bridges, safety, mobility and maintenance features. This appears to be part of a cross-optimization model, which will be discussed later. UDOT's two inputs are infrastructure data, and analysis parameters [14]. Presumably, like PennDOT, they have their own ways of collecting and gathering infrastructure data. These, along with the required analyze parameters, are analyzed by dTIMS. Outputs are provided in terms of long-term impacts and construction schedules [14]. The workflow process for dTIMS CT is illustrated in Figure 3.

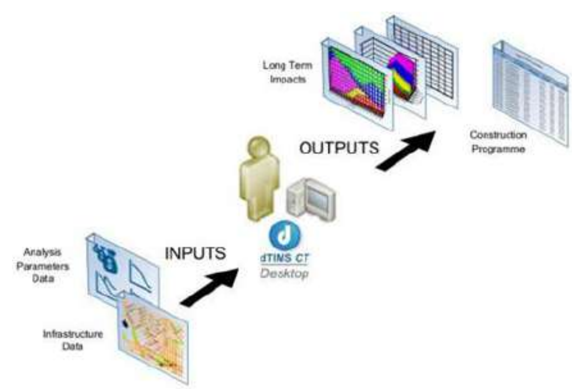

Figure 3: UDOT Workflow for dTIMS CT [14].

The Colorado DOT and others utilize a Cross Optimization Model. Cross optimization IAM systems take in multiple types of asset data, such as pavement data, structure data and safety data, runs it through the dTIMS software, which provides analyses in the distinct types of assets, suggests strategies based on the various assets analyzed, and finally culminates in a cross-asset analysis report [15]. Figure 4 shows an illustration.

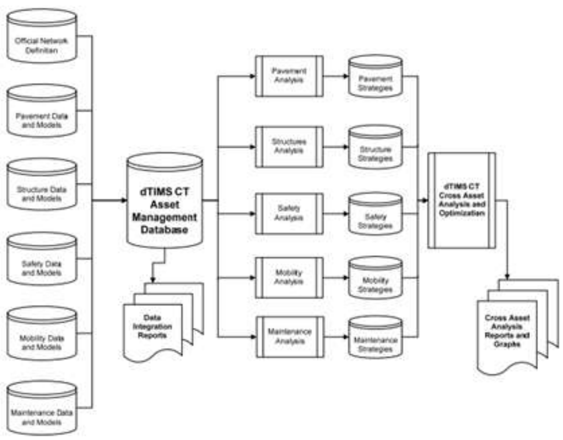

Figure 4. Typical Workflow for Cross Optimization Model Analysis [15].

The Wisconsin DOT is plagued by information silos as seen in Table 5. Because there isn't the opportunity for communication between systems, cross-optimization cannot occur. Which results in departments taking a reactionary, tactical approach instead of a proactive, strategic one towards asset management.

Table 5. Typical WisDOT Workflow demonstrating the creation of information silos.

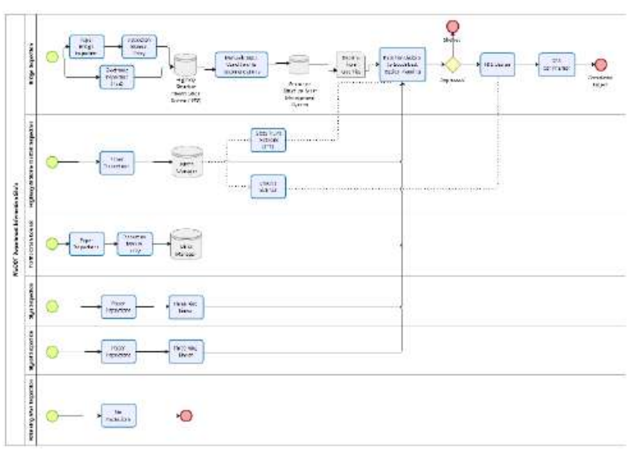

Figure 5 contains a proposed WisDOT dTIMS CT workflow. It attempts to streamline the workflow from Table 5, as well as a cross-asset optimization model hybrid as seen in Figure 4.

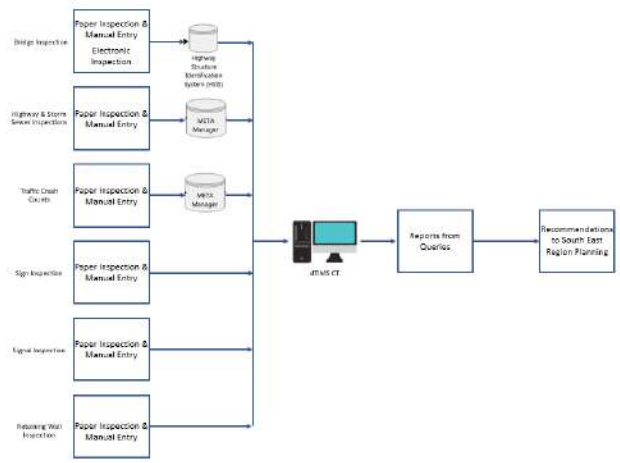

Figure 5. Proposed WisDOT dTIMS Workflow to achieve streamlined integrated outcomes

5 Conclusion

Exact long-term planning of maintenance and management is critical to safeguarding the 115,145 miles of Wisconsin's public roads [16] and ensuring their performance is in appropriate condition for today and in the future. Often, road controlling authorities are using decision-making tools that work on a snapshot of the condition of roads. To achieve for any given time, an appropriate analysis approach needs to be selected for the best possible results. For short term planning, field decisions and project prioritization may be appropriate to deal with various maintenance situations, while longer terms require more specialized and accurate planning. Deterministic models can often provide a reliable measure of the condition of the assets for medium-term planning, and anything longer requires more full-picture type techniques, such as stochastic models. There is a fine balance between attending to the urgent short-term maintenance needs of a road network, and at the same time plan well-ahead into the future to avoid an unexpected influx of maintenance work. It is not only important to know what the next treatment should be for a site, but it is also beneficial to identify the follow-on treatments based on today's decisions and planning. Currently the only tool that can successfully achieve these objectives is an Infrastructure Asset Management (IAM) system.

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Supporting feature-based parametric modeling by graph rewriting

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Abstract –

Sophisticated geometric and semantic models are the basis for many applications in the field of Building Information Modeling. While the requirements in terms of detail, flexibility and conformity on those models and thus on the corresponding modeling tools increase, especially in the case of parametric and procedural modeling, open questions remain regarding the support of the user during the modeling process and the loss of modeling knowledge after finishing a modeling task. Graph Theory can be used when addressing these questions. It can be employed to represent parametric models in a vendor-neutral way and to capture modeling operations by formalizing them in graph rewrite rules. This paper describes the further development and generalization of graph-based model creation for the support of feature-based parametric modeling. We show how such procedural 3D models that are based on two-dimensional sketches can be represented by graphs and how modeling steps can be formalized by using rule-based graph rewriting. This approach enables a user to semi automatically reuse previously formalized modeling tasks, thereby supports and accelerates the modeling process and, additionally, allows the formal definition of expert engineering knowledge for later use and reapplication.

Keywords –

Graph rewriting; Parametric modeling; Modeling support

1 Introduction

Realizing the design and engineering of construction projects successfully is a challenging process for all the parties involved.

While even small and straightforward projects may evoke complex issues, this is typically the case for large projects in which various boundary conditions and constraints as well as a vast number of participants from different areas of expertise are involved.

The technological advancements developed alongside the ongoing introduction of Building information modeling have addressed those challenges and support designers and engineers in their daily work and their interdisciplinary communication. However, the availability of sophisticated models containing geometry as well as semantics are a major requirement for many applications and workflows. Use scenarios such as automated construction progress monitoring [1], automated code compliance checking [2], automated cost analysis or BIM-based generation of construction schedules [3] would not be possible without underlying BIM-models comprising various kinds of information.

The task of creating models is therefore an indispensable prerequisite for the use cases mentioned above as well as a large variety of additional scenarios. The modeling of shield-tunnels, for example, can benefit from geometric models comprising different Levels of Detail (LoD) as introduced by Borrmann et al. [4]. To avoid inconsistencies among the different LoDs, it is necessary to apply parametric modeling techniques, which allow the automatic preservation of the model's consistency across the different LoDs in case of alterations. The research by Borrmann et al. has revealed that the manual creation of consistency preserving parametric product models is a very complex, time consuming and error-prone task. An approach by Vilgertshofer and Borrmann [5,6] introduces the possibilities of using graphs and graph transformation to support the necessary modeling process by formalizing parametric 2D sketching operations and subsequent procedural operations, which semi-automatically create 3D models for linear parts of shield-tunnel facility models. In this context, "linear" denotes the part of the model that rely solely on the course of the alignment, the most important basis for infrastructure facilities ranging over longer distances. Parts of the model which are positioned at specific points on the alignment (crosscuts, fire exit shafts, etc.) are called "non-linear".

An overview of the concept of this existing approach is shown in Figure 1, which conceptually illustrates how a model is represented by a graph and how this graph is

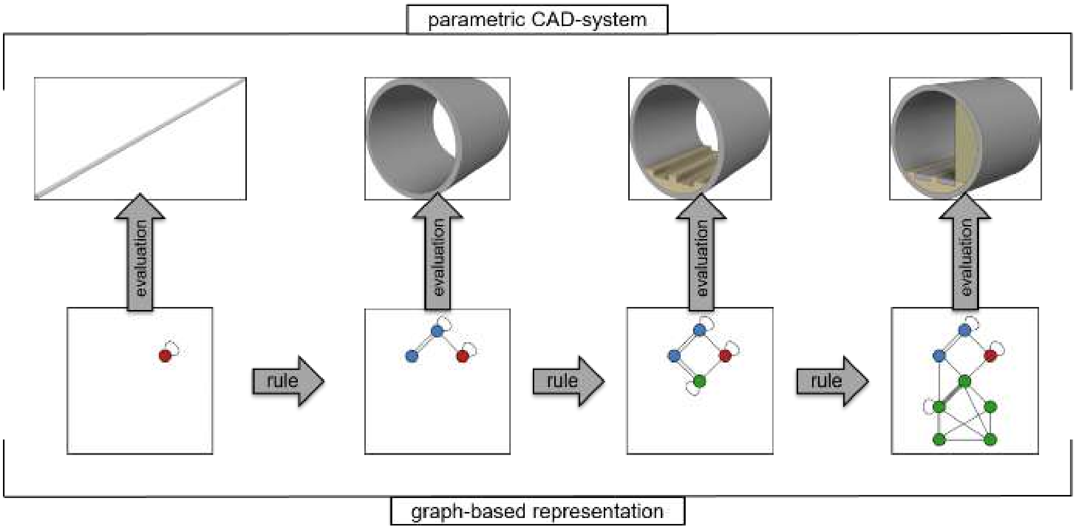

Figure 1: Conceptual illustration of using graph rewrite rules that formalize detailing steps of the graph-based representation of a shield-tunnel model. Each instance of the graph can be evaluated to create an actual model in a parametric CAD-system.

transformed by applying predefined rewrite rules. An arrow "rule" indicates the application of a rewrite rule. At each stage of this process, a parametric CAD system can interpret and process the graph in order to create an editable parametric model. This model is further called the evaluated model. An arrow labeled "evaluation" marks the generation of the evaluated model out of the graph. Note, that the graphs in Fig. 1 do not actually represent the respective geometry. They merely illustrate the presented concept.

In this paper, we will show how this approach can be refined and developed further in order to enable the representation and formal generation of more complex models. In the case of shield-tunnel models we extend the method towards the additional support of nonlinear (meaning "not based solely on the alignment") geometry parts, such as fire exit shafts or crosscuts. Furthermore, we will introduce a possibility to use the graph-based method for the semi-automatic parametric model generation in the scope of high-rise construction, namely steel connections (Figure 2). To achieve this, we will show how we can refine our graph rewrite system to allow the representation of procedural models comprising assemblies and constraints on assembly level.

Figure 2: Detailing of a steel connection.

The paper is structured as follows: Subsequent to the introduction, Section 2 will give an overview of previous and related research as well as the theoretic background of parametric modeling and graph rewriting. Section 3 will introduce our method of graph-based description of parametric modeling and show how this method is further refined. Additionally, it will summarize our implementation work and possible use cases of our extended method. The paper concludes with a summary.

2 Background and related work

The benefits of the computer-aided or (semi-)automated creation of designs and models have been addressed by researchers before. This section puts the presented approach in context of a short overview of existing approaches. It further presents the theoretical background of the proposed methodology in terms of parametric and procedural modeling and graph rewriting.

2.1 Modeling support

Computers successfully support the process of generating technical drawings or product models and parametric CAD software is widely used and enormously valuable in the building sector [7]. However, the main purpose of such software is to assist an engineer in his creative design work, which is one of the most complex human tasks, as it depends on the consideration of various constraints to obtain satisfactory solutions [8]. Therefore, a further step is the development of methods and tools, which actively support a designer by automatically generating whole sets of design variants or by the automation of repetitive and trivial tasks in the design process. As the concept presented in this paper contributes to this field of research, major approaches, which also utilize graph representations, are summarized here.

In the field of Computational Design Synthesis (CDS), Helms [9] uses a graph grammar for the computational synthesis of product architectures. Design knowledge is captured in a port-based metamodel and the procedural design rules of the grammar. Hoisl [10] presents an approach for creating a general spatial grammar system that introduces interactive definition and application of grammar rules in the scope of CDS. It aims at actively supporting a designer in the modeling process using mechanical CAD systems. The approach by Kniemeyer [11] in the domain of biology makes use of a graph grammar to design and implement a language to support the functional-structural modeling of plants.

Furthermore, Lee et al. [12] fundamentally describe how parametric building object behavior can be specified for building information modeling systems. Their approach shows how a common method to “describe the design intent in order to share and reuse the user-defined parametric objects” between collaborating experts can be realized. This approach, however, is not intended to automate the encoding of parametric object behavior definitions.

2.2 Parametric modeling

The concept of parametric, procedural and feature-based modeling was developed in the 1990s [13] and is by now well established and used in many commercial and open source CAD applications such as Autodesk Inventor, Siemens NX and FreeCAD.

While a pure geometric model stores only the coordinates of the geometric elements, the concept of parametric feature-based modeling is to store the sequence of sketching and subsequent 3D modeling operations: The construction history of the model. Generally, a construction history has the following structure: Parametric geometric 2D models (sketches) are composed of geometric objects and parametrical constraints. During the creation of a sketch in a parametric CAD application, a system of constraints and objects is defined and forms a constraint problem. A geometric constraint solver (GCS) [14] can solve such a problem. Schultz et al. [15] define the set of parametric constraints that is implemented by all major constraint solvers as the standard geometric constraint language. It comprises the dimensional constraints for distances and angles as well as the following geometric constraints: *coincident, collinear, tangential, horizontal, vertical, parallel, perpendicular and fixed*.

A parametric sketch created in this manner can then be used as the basis for an extrusion, sweep, loft or rotation to create a 3D object, a so-called *feature*. By applying Boolean operations, several of these features are then combined to models that are more complicated and result in parts. The combination of various parts lead to the creation of an *assembly*. On assembly level, different parts are arranged by *mating conditions*, which are basically complex parametric constraints applied to points, lines or surfaces of parts.

The main advantage of a 3D model created in this manner is, that it allows changes of any operation in the construction history without losing the consecutive modeling operations. Therefore, alterations are easier, and errors can be fixed without the necessity of a complete remodeling. This modeling technique, however, relies on a deep understanding of its basics and therefore requires extensive training of possible users, as a multitude of constraints and parts lead to very complicated models that can get almost unmanaged without knowing the originator’s intentions Lee et al. [12]. Our approach therefor aims at introducing automation mechanisms into parametric feature-based modeling.

2.3 Graph rewriting

The presented approach for automating the detailing process in this paper is based on graph theory and also uses graph rewriting methodology as comprehensively described by Rozenberg et al. [16]. We employ graphs and graph rewriting mechanisms to enable the representation and the modification of procedural parametric models. An application of graph rewriting to semi-automatically create and alter parametric sketches has been presented in Vilgertshofer and Borrmann [5] and was further developed [6].

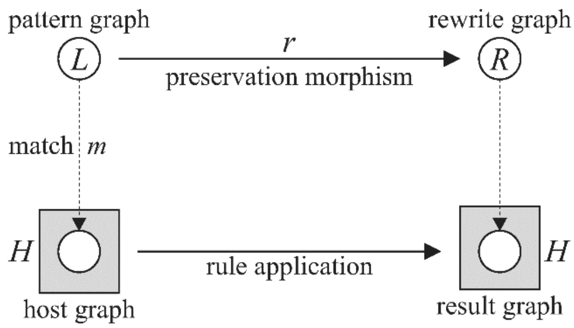

Figure 2: Graph rewriting via the SPO (inspired by Blomer et al. [19]).

Graph rewriting operations are used to create a new graph out of an existing graph by altering, deleting or replacing parts (subgraphs) of the existing graph. The changes are formalized through graph rewrite rules written as $L \rightarrow R$. A graph rewrite rule is defined by a pattern graph L and a replacement graph R. When a rule is applied to a graph (called the host graph), this graph is searched to find a subgraph that matches the graph pattern defined by L. A successful matching leads to the replacement of L with R under the consideration of a preservation morphism r. This preservation morphism controls how R substitutes or alters an instance of L in the host graph. The outcome of this rule application is called the result graph H' as illustrated in Fig. 2.

There are several different approaches to graph rewriting. Two main examples are the Single-Pushout Approach (SPO) and the Double-Pushout Approach (DPO) [17].

3 Conceptual approach

This section will give an overview of the basic concept of our existing approach and show how it was extended

3.1 Graph-based description of parametric models

In the following section, we will first give a short comparison of our work so far and discuss its limits. Thereafter, we describe how we revise and extend it to generate a wider range of parametric models.

3.1.1 Overview

Parametric modeling CAD-systems use geometric elements such as points, lines or circles as primitive planar entities. The parametric constraints as described in Section 2.2 define the topology of these entities and result in parametric sketches. Those are the basis for further procedural modeling operations, which create 3D features. To represent a procedural parametric model by means of a graph, it is necessary to define, which types of geometric elements, parametric constraints and procedural modeling operations are employed. In the scope of our research so far, we generally considered the following types:

- geometric elements: *point, line, spline circle, arc*
- parametric constraints:
  - geometric constraints: *coincident, collinear, equal, concentric, horizontal, vertical, parallel, perpendicular, fixed*
  - dimensional constraints: *dimensions of one geometric element, distances between two geometric elements*
- procedural modeling operations: *workplane, extrusion, sweep*

This listing roughly reflects the standard geometric constraint language defined in Schultz et al. [15] summarizing the most common operations provided by any parametric CAD system (see Section 2.2).

3.1.2 Formalization

For formal representation of these items, a graph metamodel describes the necessary attributed types of graph nodes and edges are. They can then be instantiated during the generation of a graph. The metamodel also forms the basis for the definition of graph rewrite rules, which formally describe modeling steps. An end user can apply those instead of manually executing the underlying procedural or parametric modeling operations. Fig. 1 in Section 1 conceptually illustrates how a graph represents a model and how the application of predefined rewrite rules transforms this graph.

The graph representing a procedural geometry model is a directed multigraph with loops $G = (V, E, T^v, T^e, s, t, lb, ty^v, ty^e, att)$. It is defined as follows:

- $V = V_P \vee V_S$ is a nonempty finite set of vertices. Elements of V_P are vertices that represent procedural modeling operations, while elements of V_S represent geometric objects in a sketch.
- $E = E_P \vee E_S$ is a nonempty finite set of edges. Elements of E_P are used to represent general relations or dependencies between the procedural operations and allocate geometric elements to a specific sketch. Elements of E_S represent parametric constraints of a geometric element or between two geometric elements.
- $V_P \wedge V_S = \varnothing$ and $E_P \wedge E_S = \varnothing$.
- $s : E \rightarrow V$ is a mapping that indicates the source node of all edges.
- $t : E \rightarrow V$ is a mapping that indicates the target node of all edges.
- Σ is an alphabet of labels of vertices and edges.
- $lb : E \vee V \rightarrow \Sigma$ is a labeling function.
- $T^v = T_P^v \vee T_S^v$ is a set of types for the vertices in V. T_P^v and T_S^v are sets of types for nodes in V_P and V_S respectively.
- $T^e = T_P^e \vee T_S^e$ is a set of types for the edges. T_P^e and T_S^e are sets of types for nodes in E_P and E_S respectively.
- $ty^v : V \rightarrow T^v$ is a typing function for the vertices, such that $ty^v(V_P) \wedge ty^v(V_S) = \varnothing$.
- $ty^e : E \rightarrow T^e$ is a typing function for the edges, such that $ty^e(E_P) \wedge ty^e(E_S) = \varnothing$.
- At is a set of attributes of vertices and edges.
- $att : E \vee V \rightarrow At$ is an attributing function.

The metamodel describes the possible set of types T^v and T^e of the graph entities V and E. They can then be instantiated to execute a rewrite rule to create or alter the graph. Additionally, the metamodel defines the attributes of a certain type as well as conditions that control which nodes and edges may be incident or which node types can be adjacent. As the type of a graph entity clearly determines which attributes that entity has, an attributing function is not given.

Instead of using separate graphs to represent sketches and subsequent procedural operations we concluded that combing all information needed for the representation of a particular model should be embedded in a single graph. This is realized by integrating graphs that represent a sketch into the procedural graph. The benefits of this method are presented in [6] in detail. We still conceptually separate the subgraphs representing sketches and the procedural operations that subsequently create 3D features and therefore use the terms *sketch graph* and *procedural graph*.

3.1.3 Limits

While the presented method enables the automated generation of basic shield tunnel models, based on the alignment, limitations occur. This is especially the case, when we approach the question of non-linear geometry or use cases in other domains. Creating and placing various features in a model proves quite difficult when there is no possibility to arrange them without altering the position of the sketches. In the parametric feature-based modeling theory, so-called assemblies remedy this problem. One or more features are combined into one part, whereas an assembly consists of multiple parts. While each part has its own local coordinate system to position one or more features (each sketch has its own local coordinate system, too), the assembly itself defines yet one more coordinate system in which the different

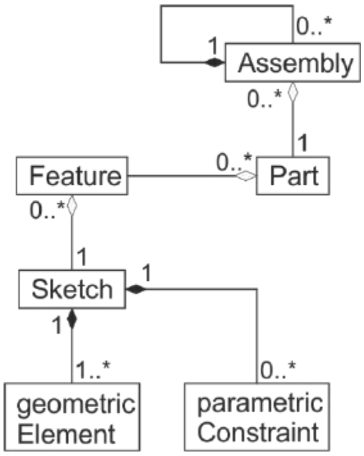

Figure 4: Structure of a model consisting of sketches, features, parts and assemblies.

parts are positioned. This placement is achieved by using either fixed coordinates (which is usually the case for the first part to be positioned) or by placing one part relatively to another one. The relative positioning works quite similar to the parametric constraints, which define the topology of the geometric elements in a sketch. In this context, however, the term mating conditions is used. Basic mating conditions define points, lines or faces of a part to be constrained to those of another part in terms of being coincident (points), collinear (lines) or on the same plane (faces).

In this regard, we also encountered the problem of referencing geometric entities that are the result of a

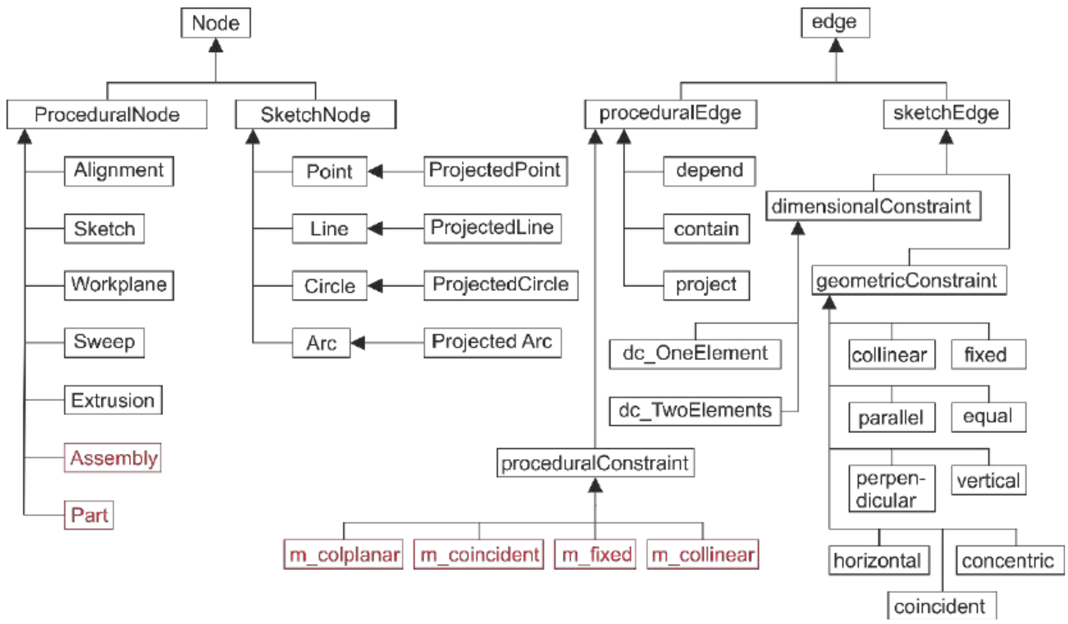

Figure 5: Extended version of the graph metamodel.

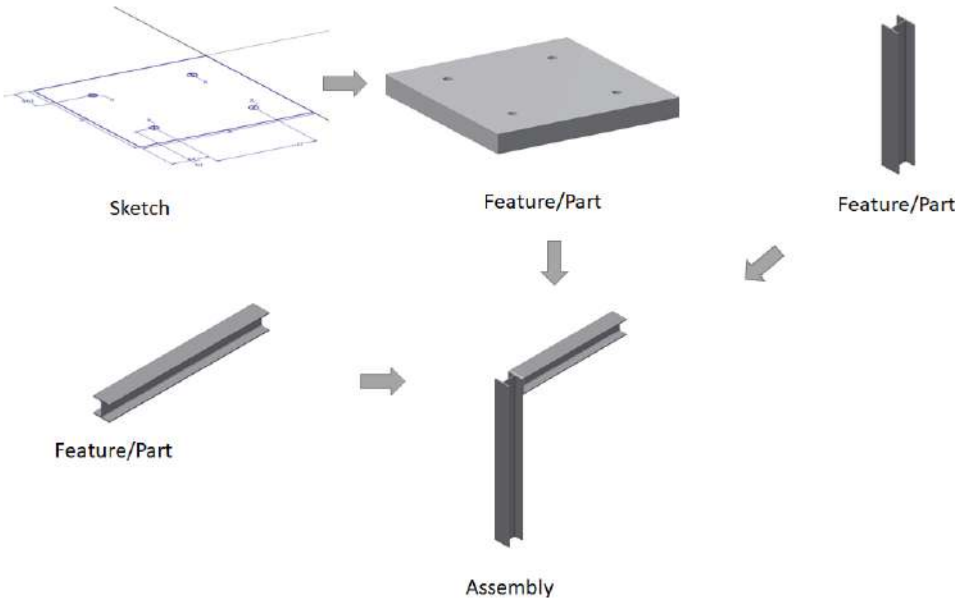

Figure 6: Modeling of a steel connection with the use of features/parts as an assembly.

procedural operation in the graph. The extrusion of a rectangle, for example, forms a cuboid. Here, the four points and four lines that the sketch describing the rectangle contains, are represented in the graph. Another eight lines, however, bound the resulting cuboid. Additionally, four new points connect those lines and the cuboid itself comprises six faces. However, the graph does not represent these 18 new entities and it is therefore not possible to reference them in subsequent graph transformation operations. Therefore, we need to refine the rules creating subgraphs that represent feature objects to comprise such geometric entities, if they objects need to be referenced by consecutive rewriting operations.

The necessary extensions to our graph metamodel in order to include assemblies and mating conditions are described in the following subsection.

3.2 Extension of the approach

As the graph metamodel is the formal description of types of graph nodes and edges that can be instantiated, it has to be extended in order to cover the representation of the described modeling operations on an assembly level. Figure 5 depicts the previous version of the metamodel in black color, while the necessary extensions are drawn in red color.

Most important extensions are the new node types *part* and *assembly*. They are used in a similar manner as sketch nodes are used to group the geometric elements of a sketch: Part nodes group one or more features created from sketches, whereas assembly nodes group one or more parts. Furthermore, constraints in the procedural context are added, to define the relative positioning of the parts in an assembly.

While this refinement is not extensive in terms of new node and edge types, it allows us to model more complex geometry than in the previously presented approach. We are now able to construct a model consisting of more than one part and to position these parts relative to one another. This decomposition of the model allows us to generate subgraphs representing model parts that are either completely independent from one another or only related by mating constraints.

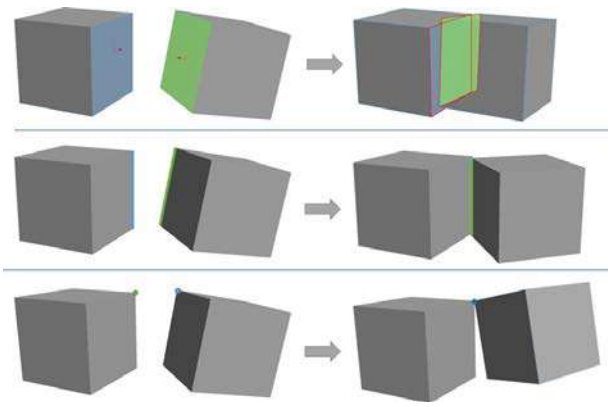

Figure 7: A model before and after applying three different types of mating constraints: coplanar, collinear and coincident.

These mating constraints are much better suited to the relative positioning of three-dimensional objects to one another than parametric constraints, as we do not have to consider the positioning of workplanes or the projection

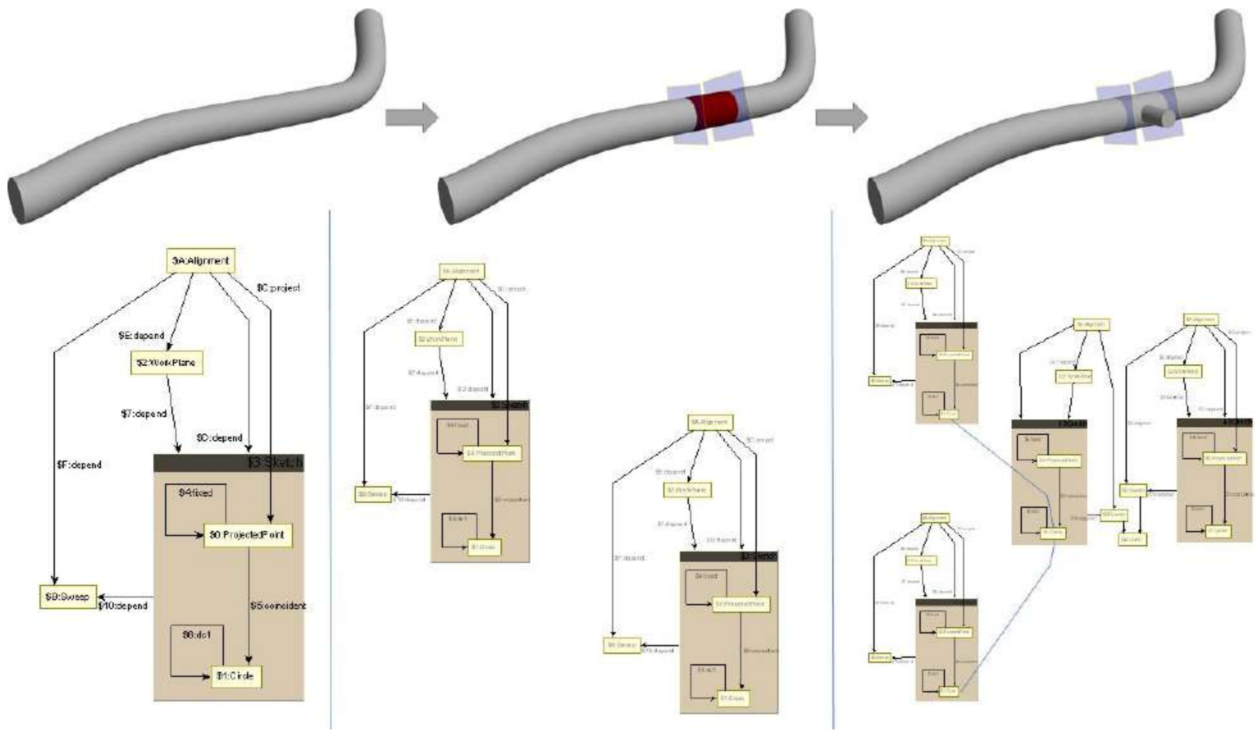

Figure 8: Process of adding a crosscut to a tunnel model. Bottom: States of the graph representing the model. Top: Geometric result of the graph transformation process.

of existing geometry between sketches. During the modeling of parts those operations are still necessary and helpful, though. When positioning parts in an assembly they can also be rotated via the application of mating conditions. As this is not the case with features combined in a part without using a procedural operation, this also gives us more freedom in the positioning process. The graph is in its definition now much more conform to the general concept of parametric feature based modeling.

As described before, the entities that mating constraints link to one another have to be present in the graph in order to apply those constraints. We concentrated on two possible solutions for this problem: We can either define a rewrite rule in a way that all new entities (points, lines and faces) are also created within the representing graph and can be referenced by further rewrite rules. Another possibility is to only create those entities that are necessary for later rewriting operations. This, of course, is only reasonable if we know at that point, which entities this will be. We are still considering which of these solutions is more constructive or if they should both be implemented simultaneously.

3.3 Use cases and implementation

For the definition and extension of the graph rewrite system consisting of a metamodel and appropriate graph rewrite rules, the graph rewrite generator GrGen.NET [18] has been used while the generation of the evaluated sketch is performed with the commercial parametric CAD application Autodesk Inventor. Inventor contains a geometrical constraint solver, which interprets the constraint problem defined by the graph. A software prototype was developed to utilize both the functionalities of GrGen.NET and of Autodesk Inventor to apply rewrite rules and perform the consecutive creation of the evaluated model.

In order to verify the improvements made to the graph rewrite system we examined two test scenarios. First, we employed the graph system to model the connection of two steel beams (Figure 6). Here, the connecting plate is designed from extruding a sketch to create a 3D feature. A part consisting only of this feature is then combined with two other predefined parts (the beams) in an assembly. To position those three parts in accordance with each other, several planes of the respective parts were constrained by mating conditions.

In the scope of modeling non-linear geometry of shield-tunnels, a crosscut was added to an existing model of a tunnel. We also realized this by using the introduced assembly nodes. While the tunnel model without the crosscut would be modeled as only one part, we now cut the alignment at both sides of the future position of the crosscut. As we now have three alignment sections, we use them as basis for three different parts. The two outer parts are created by reapplying the existing rules that rewrite the graph to create the linear 3D geometry. The inner part however is represented by a new subgraph. This subgraph is created by executing a corresponding rewrite rule that creates the representation of a tunnel section comprising the opening for the crosscut. This process is graphically illustrated in Figure 8. Thereby we create three rather independent subgraphs representing the three model parts shown in the figure. Mating constraints are then used to combine them to a consistent model. In the graph representation the subpgraphs are therefore connected by edges representing those mating constraints. For example, they are used to mate the faces of two tunnel parts that have to align in order to keep those parts in position respective to each other.

4 Summary

The presented research introduces and extends a concept for the graph-based representation of product models and their automatic generation and detailing by performing graph rewrite operations based on formal rules defined in a graph rewriting system.

It has already been successfully applied to the product models of shield-tunnels and the automatic creation of consistency preserving multi-scale versions of such models. The main contribution is the further elaboration of the underlying graph rewriting system that enables the generation of more complex graphs covering the representing of a larger variety of parametric representations. To prove the feasibility of our approach, the graph rewriting system has been implemented in the graph rewriting tool GRGEN.NET.

Further research will focus on creating a larger set of rewrite rules, which enables end users to create more diversified models in different contexts.

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Performance Comparison of Pretrained Convolutional Neural Networks on Crack Detection in Buildings

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Abstract –

Crack detection has vital importance for structural health monitoring and inspection of buildings. The task is challenging for computer vision methods as cracks have only low-level features for detection which are easily confused with background texture, foreign objects and/or irregularities in construction. In addition, difficulties such as inhomogeneous illumination and irregularities in construction present an obstacle for fully autonomous crack detection in the course of building inspection and monitoring. Convolutional neural networks (CNN's) are promising frameworks for crack detection with high accuracy and precision. Furthermore, being able to adapt pretrained networks to custom tasks by means of transfer learning enables users to utilize CNN's without the requirement of deep understanding and knowledge of algorithms. Yet, acknowledging the limitations and points to consider in the course of employing CNN's have great importance especially in fields which the results have vital importance such as crack detection in buildings. Within the scope of this study, a multidimensional performance analysis of highly acknowledged pretrained networks with respect to the size of training dataset, depth of networks, number of epochs for training and expandability to other material types utilized in buildings is conducted. By this means, it is aimed to develop an insight for new researchers and highlight the points to consider while applying CNN's for crack detection task.

Keywords –

Crack Detection in Buildings, Convolutional Neural Networks, Transfer Learning

1 Introduction

Architectural artefacts and civil infrastructures are exposed to loss of structural performance due to both deterioration of materials in time and structural challenges such as natural disasters. Structural monitoring and assessment of buildings have utmost importance for both sustaining the lifespan of structures and predict possible failures.

Visual crack inspection and detection is a widely used method for gaining insight into the condition of the architectural artefacts and structures. While the majority of the inspection is conducted by means of manual observations, several disadvantages of manual observation process are documented in literature such as being time-consuming and subjectivity of the evaluation. [1,2]

Advancements in robotics and image capturing hardware make autonomous data capturing possible while machine learning methods and deep learning algorithms in image processing show promise in the fully autonomous inspection of structures. Utilization of deep learning in these tasks not only provides reduction of computational time but also enables precise measurement of features to be inspected without human error.

On the other hand, autonomous conduction of visual crack detection is a challenging task for all image processing methods due to three major practical reasons caused by nature of the subject matter as:

1. discriminative crack features are low-level which is easily confused with noise in the background texture or foreign objects (such as hair or vegetation)
2. inhomogeneous illumination of the surface endangering the conservation of crack continuity [3]
3. irregularities in the application such as exposure of jointing

These practical challenges mentioned above are illustrated in Figure 1.

Resolving the practical challenges of images based crack detection in the course of autonomous inspection is an active field of study.

Convolutional neural networks (CNN's) are adequate frameworks with their high accuracy predictions in image classification and recognition tasks. There are several studies on crack detection on buildings and civil infrastructures with the use of CNN's. Within the scope of this study, it is aimed to investigate the relationship between the performance of CNN's and the affecting parameters.

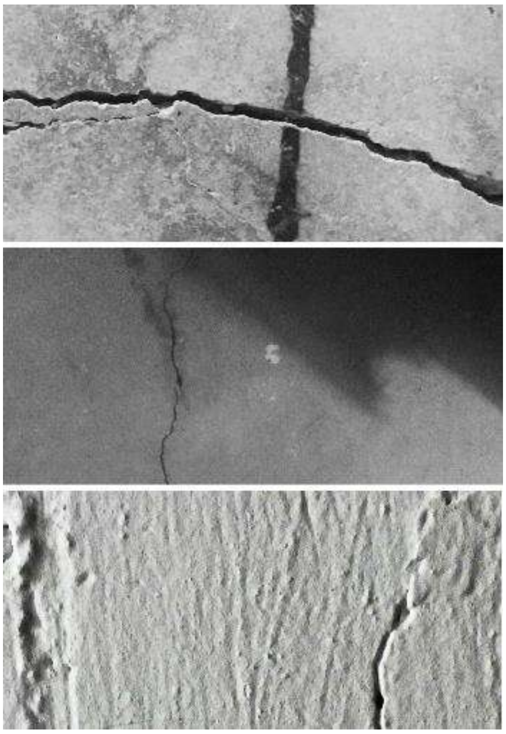

Figure 1. Practical challenges for crack detection, 1) the painting as the noise at the background (top), 2) shadow obfuscating crack and present noise (middle), 3) jointing at left presents noise (bottom)

2 Background

Visual crack detection task can be evaluated as a classification problem of crack presence in essence. Two types of methodological approaches are observed in the course of autonomous visual crack detection. The first type of studies is based on the sequential operation of feature extraction and classification by means of machine learning classifiers [4, 5]. In such studies, adaptive filters, transformations and/or morphological operations are utilized for extraction of features which are to be used for discriminating crack images from non-crack images. These features are then fed to machine learning classifiers to conduct classification. Studies of Adhikari *et al.* on pavement cracks [2] and Wu *et al.* and Sinha *et al.* on pipe defects [4,5] can be given as exemplary studies of this group. The second type of methodological approach is observed in studies utilizing deep learning (e.g. convolutional neural networks) which the feature extraction stage is conducted within the black box algorithm. In such a workflow, the input data is provided as raw images without the specification of features to search for, and algorithm finds patterns among the image data to conduct the desired task. As the features to be used for the classification of crack presence are determined by the system, human bias/error is avoided but replaced with the error of the system. In this sense, the workflow has a data-driven approach rather than knowledge-driven approach. Even though the adaptability and extensibility of the framework are more promising than sequential workflow, the errors and the factors affecting should be understood to further progress the potentials of deep learning based implementations.

Following studies are exemplary studies employing CNN's. It should be noted that it is not aimed to make a complete list but rather provide a baseline for the present study. The studies are compared in terms of number of convolutional layers utilized, number of images used for training and reported accuracy for crack detection. On the other hand, the classification accuracies of the inspected studies are highly dependent on the training and test datasets and not directly comparable.

Studies of Zhang *et al.* [6] and ASINVOS developed by Eisenbach *et al.* [7] can be given as example studies regarding the application of convolutional neural networks on crack detection on roads. Zhang, *et al.* uses a CNN with 6 convolution layers to conduct binary crack detection task on roads. Authors used 600K images for training and 200K for testing and got 0,8965 F_1 scores. The framework utilized in Eisenbach *et al.*'s study 11 convolution layers. Authors used 4,9 M image patches and tested the network with 1,2M images. ASINVOS is reported to score slightly better than the network developed by Zhang, *et al.* by scoring 0,7246 F_1 score compared to 0,6707 Zhang, *et al.*'s network on the dataset provided by Eisenbach *et al.* Similarly, Wang *et al.* [3] utilizes CNN with 5 convolutional layers for classification of asphalt pavement cracks but differently from the studies mentioned above, Wang *et al.* utilizes 3D data input including depth with 1mm resolution. Authors used 640K training image cells, 128K test image cells and scored 0,9429 accuracy. Pauly, *et al.* [8] also focus on crack detection on pavements and investigate the relation between the number of layers in CNN (deepness of network) by comparing performances of 6 layered and 7 layered networks. Authors also worked on two different subsets with the first subset contains 200K training images versus 40K test images, and the second subset contains 40K training images versus 60K testing images which are collected from different locations compared to training images. Study scored 0,913 accuracy with CNN containing 7 convolutional layers on the first subset. As the studies mentioned above are trained from scratch, they require a considerable amount of images for training which can be a limiting factor in terms of layers utilized in the network.

The study conducted by Cha, et al. [9] uses deep learning for crack damage detection for structural health monitoring. In that sense, the study is significant as it is implemented on building scale which the illumination conditions and forces which the material is subjected to show more variations compared to pavement and road inspections. Authors used a framework with 4 convolutional layers for concrete crack detection. The network is trained with several datasets with varying sizes from 2K to 40K images and testing is done with 54 full resolution images. Based on validation accuracies it is advised to use more than 10K images for training a network from scratch. For test results, mean accuracy of 0,9683 scored.

Availability of the pretrained networks eases the applicability of CNN's in new tasks without the requirement of high computational cost and deep knowledge on how CNN's operate. AlexNet developed by Krizhevsky, et al. [10], VGG networks developed by Oxford Visual Geometry Group [11], GoogleNets [12], and ResNet networks developed by Microsoft [13] can be given as examples for highly acknowledged pretrained networks which are used as the basis for application to new tasks. Study of Gopalakrishnan *et al.* [14] can be given as an example which uses transfer learning to utilize a pretrained network for pavement distress detection and employs the VGG16 network trained on ImageNet data. The study compares different classifiers in conjunction with VGG16 network. Authors used 760 images for training and 212 images for testing purposes and achieved the highest accuracy of 0,90 with the single-layered neural network classifier. When compared to studies which CNN's are trained from scratch, a similar accuracy is obtained with considerably fewer data with the use of transfer learning which is promising in terms of fast and easy implementation to new tasks.

All of these studies are concluded with accuracies above 90% for detecting cracks in images. On the other hand, performance of the mentioned studies based on several factors such as selection of data, number, and type of layers utilized other than convolutional layers, choice of filter sizes. Hence, these studies don't provide any indication of how deepness of networks and size of image datasets affect the performance of these frameworks.

Within the scope of this study, a comprehensive analysis on the applicability of CNN's on crack detection in building-oriented applications is conducted by means of transfer learning. In this regard, the influence of training dataset size, number of epochs used for training, number of convolution layers and learnable parameters on the performance of CNN's are inspected. In addition, transferability to new material types are investigated.

3 Data Preparation

In the present study, datasets utilized are explained in three categories as training, validation and test sets. The base dataset is obtained by extracting 40K image patches with the dimensions of 224 to 224 pixels, from 500 full resolution (4032 pixels to 3024 pixels) images taken from walls and floors of several concrete buildings in METU Campus. These images are taken approximately 1m away from the surfaces with the camera facing directly to the target. Even though the concrete surfaces have variation in terms of surface finishes (exposed, plastering and paint), the images are captured on the same day with similar illumination conditions. No data augmentation in terms of random rotation or flipping is applied. Image samples for training and test cases are shown in Figure 2. The base dataset is publicly shared [15].

The preparation of these datasets are explained as below:

Training dataset: As a convention, %70 of randomly selected images from the base dataset is used for training while %15 is used for validation throughout the training and %15 is used for testing. As a result, the biggest training dataset consists 28K images. The size of training dataset is then randomly reduced from 28K to 21K, 14K, 7K, 3,5K, 1,75K, 0,7K and 0,35K to imitate grid search for investigation of the relation between performance and size of the training dataset. All of the datasets are balanced in terms of classes, containing an equal number of positive and negative images.

Validation dataset: Validation dataset is used throughout the training to monitor the learning curve of the networks. The number of images used for validation is chosen with regard to the size of the respective training dataset size. The %70-%15 ratio between the training set and validation set is conserved for all training cases

Figure 2. Training and test image samples. Positive training samples (top left), Negative training samples (top center), Possible false-positive training samples (top right), Concrete test samples (bottom left), Pavement test samples (bottom center), Brickwork test samples (bottom right)

Test datasets: Four distinct cases are chosen for testing purposes. The first case uses 6K images which are randomly chosen from the 40K base dataset. This partition corresponds to the %15 of the 40K dataset which is not utilized in either training or validation. All networks which are trained with varying sizes of training datasets are subjected to the same test dataset in order to observe the effect of training dataset size and performance in predicting visually similar images.

The second, third and fourth cases focus on the performance of the trained networks to investigate the transferability of learned features to new cases in terms of both physical conditions, such as illumination or camera angle, and material variations. The cases are respectively crack detection in pavements with concrete material, in buildings components with concrete material, and in buildings with brickwork material. 50 full resolution images are used for obtaining 500 test images per test case. All images are taken from different buildings and locations compared to the ones used training and validation at different times of the day.

The number of images used for training, validation, and tests is shown in Table 1 and Table 2.

Table 1. Number of images in datasets used for training, validation

	Training		Validation	
	Positive	Negative	Positive	Negative
28K	14000	14000	3000	3000
21K	10500	10500	2250	2250
14K	7000	7000	1500	1500
7K	3500	3500	750	750
3,5K	1750	1750	375	375
1,75K	875	875	188	188
0,7K	350	350	75	75
0,35K	175	175	38	38

Table 2. Number of images in datasets used for testing

Cases	Testing	
	Positive	Negative
15% randomly selected from base dataset (Test1)	3000	3000
Concrete Pavements (Test2)	250	250
Concrete Buildings (Test3)	250	250
Brickwork Buildings(Test4)	250	250

4 Performance Comparison

Within the scope of this study, the performance of seven highly acknowledged pretrained networks; namely, AlexNet [6], VGG16, VGG19 [7], GoogleNet [8] and ResNet50, ResNet101, and ResNet152 [9] on crack detection of concrete surfaces are inspected in relation with the size of training dataset size and number of epochs to obtain best results. In addition, the effect of complexity and depth of CNN's are investigated. The number of convolutional layers and number of learnable parameters which gives an insight into the number of filters used by networks is shared in Table 3.

Table 3. Pretrained networks, number of convolution layers and learnable parameters

	# of Convolution Layers	# of Learnable Parameters
AlexNet	8	60M
VGG16	16	138M
VGG19	19	144M
GoogleNet	22	7M
ResNet50	50	25.6M
ResNet101	101	44.5M
ResNet152	152	60.2M

The networks utilized in the scope of the study are pretrained on ImageNet data and obtained from MatConvNet website [16]. All tests are conducted using MatConvNet and Matlab on a desktop workstation with 2 Intel Xeon E5-2697 v2 @2,7 GHz CPU cores, 64GB RAM and NVIDIA Quadro K6000 GPU. While batch size is bounded with the GPU memory, other hyperparameters are determined as provided by MatConvNet website. On the other hand, the approach followed for the comparison is extendable to any pretrained network on any dataset with varying hyperparameter values.

Each of the pretrained network mentioned above is trained with training datasets shown in Table 1 for 10 epochs. It is observed that 10 epochs are sufficient for convergence of all network and after 10 epochs performance of networks fluctuate. Training on 7 pretrained networks on 8 different sizes of training datasets for 10 epochs yields 560 trained networks corresponding to all combinations of parameters taken into account in the comparison. After obtaining trained networks, the performance of these networks is evaluated with four cases resulting in 2240 scores which can be represented as 7x8x10x4 (network, dataset, epoch, test case respectively) matrix. For performance evaluation metrics, accuracy and F-scoring are used.

It is observed that the accuracy and F-scores of best-performing networks are compatible with each other. Even though the discussion regarding the performance of networks is advanced mentioning accuracy scores, the same remarks can be made for F-score results. For the sake of simplicity, the maximum accuracy and F-score results obtained per network are shown in Table 4 together with training dataset and epoch information. The results per row are discussed below.

Table 4. Maximum validation and test accuracies of pretrained networks

	AlexNet		VGG16		VGG19		GoogleNet		ResNet50		ResNet101		ResNet152	
	Mean Acc.	F-Score	Mean Acc.	F-Score	Mean Acc.	F-Score	Mean Acc.	F-Score	Mean Acc.	F-Score	Mean Acc.	F-Score	Mean Acc.	F-Score
Test1 Epoch1 0,35K	0.896	0.890	0.996	0.996	0.991	0.990	0.900	0.899	0.810	0.794	0.860	0.853	0.610	0.715
Test1 Epoch1	0.999 28K	0.998 28K	0.999 21K	0.999 21K	0.999 28K	0.999 28K	0.998 21K	0.997 21K	0.999 14K	0.997 14K	0.999 21K	0.992 21K	0.995 14K	0.998 14K
Test1	0.999 28K E6	0.999 28K E8	0.999 21K E1	1.000 21K E1	0.999 28K E3	1.000 28K E10	0.999 21K E9	0.999 21K E9	0.999 28K E2	0.999 14K E2	0.999 28K E6	0.999 28K E6	0.998 21K E10	0.998 21K E10
Test2 Concrete - Pavement	0.800 28K E2	0.752 28K E2	0.970 21K E2	0.966 21K E2	0.980 3,5K E1	0.982 3,5K E1	0.980 0,35K E7	0.987 0.35K E7	0.900 0,35K E1	0.896 0,35K E1	0.770 7K E9	0.783 1,75K E8	0.620 7K E1	0.669 28K E9
Test3 Concrete - Building	0.860 0,7K E1	0.856 0,7K E1	0.980 1,75K E6	0.977 1,75K E4	0.960 3,5K E1	0.963 3,5K E1	0.920 1,75K E7	0.916 1,75K E9	0.640 0,35K E1	0.695 0,7K E7	0.740 0,7K E1	0.746 0,7K E1	0.540 14K E6	0.681 0,7K E10
Test4 Brickwork -Building	0.870 7K E1	0.855 7K E1	0.960 1,75K E4	0.955 1,75K E4	0.880 3,5K E5	0.890 3,5K E5	0.900 1,75K E9	0.912 1,75K E9	0.690 0,35K E1	0.739 0,35K E1	0.720 21K E10	0.741 3,5K E7	0.620 21K E10	0.696 14K E2

E: Epoch

4.1 Test Results

AlexNet, VGG16, VGG19 and GoogleNet networks converge quickly by scoring over 0,90 accuracy at the first epoch with 350 training samples while ResNet family achieved poorer scores at first iteration with the smallest training dataset. At second epoch all networks scored over 0,9. However, it is observed that higher test scores are obtained from higher epochs and larger datasets.

All networks benefitted from larger datasets achieving the best test score with more than 14K training samples. While ResNet50 and ResNet152 achieved best scores with 14K training set, VGG16, GoogleNet, and ResNet101 obtained best scores with 21K training dataset. Yet, the accuracy differences between results obtained with 14K, 21K, and 28K are barely noticeable and it is not possible to make an inference regarding the performance comparison of networks by solely inspecting maximum scores for test 1 which is based on the images similar to training dataset. Following test cases, which shows diversity in terms of illumination, camera orientation and distance with respect to the surface and material, are conducted to examine whether the networks overfit or prominent to learn generic crack features for further cases.

As can be seen from Figure 2, crack images on pavements are visually more discernable due to homogeneous illumination conditions and high contrast between cracks and background textures with respect to building application. As a result, all networks except AlexNet scored higher or similar scores with respect to third and fourth test cases. Low scores of ResNet101 and ResNet152 networks show that these networks are subjected to overfitting even with 350 training images. While both networks scored 0,99 accuracy in test 1 case, the maximum score obtained for test case 2 is below 0,8. The mismatch between the networks showing best performance for accuracy and F-score metrics also indicate that the networks are not stable.

Also, ResNet50 achieved the highest score with smallest training size and first epoch showing tendency to overfit. This tendency is evaluated as a mismatch between ResNet’s high capability of classifying objects with high-level features and cracks’ low-level features.

GoogleNet and VGG19 networks achieve over 0.95 accuracies with relatively limited training data. For VGG16, even though the obtained highest score is with the 21K dataset, it achieved 0.96 accuracy with 0,35K dataset at first and second epochs which are also comparable with successful counterparts.

Similar to the pavement case study, VGG networks, and GoogleNet were able to transfer learned features to building case scoring over 0,92 accuracy with at most 3,5K training dataset. While VGG networks are barely affected by the variations in illumination, background texture and camera orientation with respect to the surface, GoogleNet is subjected to 0,06 performance loss. On the other hand, ResNet networks show overfitting with decreasing scores regardless of the size of training data and number of epochs.

Brickwork images are relatively the most challenging case among the four test cases as brickwork jointing and background textures are challenging noises. Among the tested cases, VGG16 and GoogleNet achieved more than 0,90 accuracy. Especially 0,96 accuracy performance of VGG16 is promising in terms of achieving a generic crack detection framework regardless of material with limited dataset size.

4.2 Discussions

Regardless of the test case and utilized network, the performance of training datasets with fewer samples are comparable to counterparts with a high number of samples. While obtaining test 1 accuracy with the highest number of training samples, training datasets with 3,5K were sufficient for obtaining the best scores for other test cases. One exception can be given as the ResNet family performance for Test 2, Test 3, and Test 4 where the performance scores significantly drop indicating overfitting. In the case of the training data and test data being similar, size of training dataset positively influences accuracy. On the other hand, when the networks are used for varying cases in terms of illumination or spatial relations between camera and surface, then the increasing the size of dataset pose a risk of overfitting. This analysis is also valid for training epochs. As the number of epoch for training increase, accuracy for test data with similar conditions increases while for diverse test cases, the networks have a tendency to overfit or have a bias towards the training dataset with the increased number of epochs. For future studies, it is advised to start with few hundreds of images per class for training and gradually increase the number of training samples until overfitting is observed. It is also noted that the level of variance in the dataset is more important than the number of samples. Yet, variance among the training dataset is highly case specific and should be evaluated with respect to representation level of real-life cases.

Regarding the influence of network complexity in terms of the number of convolution networks and learnable parameters, it is observed that the influence of the number of convolution layers is more dominant than the number of learnable parameters. Best performing pretrained networks have 16-22 convolution layers (VGG16, VGG19, and GoogleNet). While AlexNet with 8 convolutional layers has difficulties in transferring learned features to new cases, ResNet networks with more than 50 convolutional layers have a tendency to overfit the training data. It should be noted that the layer configuration (GoogleNet having inception module and

ResNet being based on residual units) is disregarded within the scope of this study. In order to examine the influence of different layer configuration ResNet family networks are required to be truncated to obtain the same number of convolution layers. On the other hand, similar layer configuration of AlexNet, VGG16, and VGG19 shows that increased number of convolution layers contributes to the performance of networks in crack detection task for VGG16 and VGG19 compared to AlexNet. Another deduction can be made considering the number of fully connected layers. Simple CNN's having hierarchical layer connections (AlexNet and VGG networks) have shown resilience in varying test cases while DAG networks (GoogleNet and ResNet networks) have difficulty in transferring learned features to new cases. Even though the number of fully connected layers is not the only reason for the performance drop, hierarchical networks have proven themselves to adapt to new cases.

The number of learnable parameters, on the other hand, does not have a direct relationship with the performance but plays a significant role in computation time. GoogleNet, having almost five percent of VGG parameters scored a similar score. This can be linked to the low number of features defining cracks.

The computational time required to train 28K dataset per epoch for all networks are shared in Table 4.

Table 4. Computational time for training 28K dataset per epoch

28K dataset | per Epoch	Training Time (s)
AlexNet	133
VGG16	2827
VGG19	2943
GoogleNet	1227
ResNet50	1666
ResNet101	2447
ResNet152	3789

It should be noted that the majority of the learnable parameters are used by the fully connected layers of VGG networks. Hence, the trade-off between computational time and performance emerges as a trade-off between the number of fully connected layers and training time. On the other hand, it is possible to limit the number of filters to reduce the number of learnable parameters, thus the computational time while conserving the number of convolution layers for developers constructing the network from scratch.

5 Conclusion

Within the scope of the study, the performance of highly acknowledged pretrained networks on crack detection task is evaluated for buildings. The relations between training dataset size, number of epochs for training, number of CNN layers and learnable parameters are thoroughly investigated. It is shown that the pretrained networks can be fine-tuned for crack classification task with a limited number of training samples when the variance among data is provided or the test case constitutes images similar to the training samples. In the absence of variance among training images, increasing number of image samples not only contributes to the computational time without enhancing performance but also increases the risk of overfitting as the number of images with similar features analyzed per epoch increases. In the case of test case being visually incompatible with respect to training samples, it is advised to train the network with a limited number of samples and observe the tendency to overfit with the increasing number of training dataset size.

Regarding the effect of the number of convolutional layers to accuracy, even though the study does not involve a grid search for an optimum number of layers for the task, networks with 16 to 22 convolutional layers scored highest compared to both AlexNet with 8 convolutional layers and ResNet networks with more than 50 layers. In addition, networks with hierarchical layer connections and multi fully connected layers are observed to perform better in varying conditions and show promise in the course of achieving a generic crack detection framework regardless of material.

In conclusion, the pretrained networks have high applicability on crack detection even if they are trained on completely different datasets due to the low-level features shared with cracks and any objects with more abstract features. It is observed that the features learned in the course of training are transferable to other materials with high accuracy. In addition, the required number of less training samples and fast convergence networks make pretrained networks a favorable option for implementing CNN's for crack detection task.

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From the Pyramids via Modern CE to Automation & Robotics: Progress or Regress?

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Abstract –

Construction management courses are currently mostly based on frontal lectures, homework and exams – where the exams comprise of questions similar to the ones that the professor showed in the lectures & later the student is asked to solve at home. In practice, construction engineers are required to be able to quickly resolve unstructured complex problems, under conditions of uncertainty, by finding, collecting and integrating information from different sources and providing creative solutions. We propose that a learning-centered approach to the education of the construction management student, in which s/he is confronted with the need to find solutions for such complex problems, and to identify the relevant data, will better prepare the future engineer for the profession. Moreover, the students have to be exposed to the fact that there is more than one correct solution and none of the solutions is perfect. Ethical dilemmas in particular may require construction managers to resolve problems for which they cannot rely on simple formulas. An elective course in construction management, which has been developed over the past four years, in which these principles have been incorporated, will be described.

Keywords –

Construction management; Education; Learning-centered approach; Problem solving; Ethics.

1 Introduction

Most of today's students will still be professionally active in the 2060-70s (!). Hence, the curriculum and teaching methods of the previous century, which still prevails, will not be sufficient to provide the engineers of the future with the appropriate skills. Very early in their career they will find their education irrelevant. In fact, we already hear from young engineers and their employers that this is the situation.

With this in mind, we believe that the main objective of academic studies is not merely to provide technological and engineering knowledge. Instead, they should focus on EDUCATING students and developing their CREATIVE THINKING and their analytical skills. However, Construction Engineering & Management (CEM) studies currently focus mostly on a very particular type of quantitative analysis, which does not prepare the student well enough for the actual challenges of the profession.

The framework within which CEM students are educated has changed very little over the past decades. CEM courses are still mostly based on the use of frontal lectures, homework and exams. Moreover, in most of those courses the data required to solve assignments is given to the students in advance. Not only that, but the assignment normally has ONE "correct solution". As a result, many of those courses seem similar to students, and their content becomes merely a series of technical assignments. Such assignments are generally solved through well-structured procedures, as described in generic terms in Figure 1. This paradigm does not encourage creative thinking at all. In fact, it often even inhibits thinking altogether. With such an approach it is no wonder that many construction engineers and their employers ask questions, such as the ones quoted above.

The need to engage students and encourage learning and creative thinking has been recognized by some when it comes to engineering design courses, including civil engineering (e.g. Stouffer et al. [7]). We argue that the need for such an approach is just as clear when it comes to educating CEM students, as it is for gearing Civil Engineering students toward a career as design professionals who will concentrate on the engineering design work.

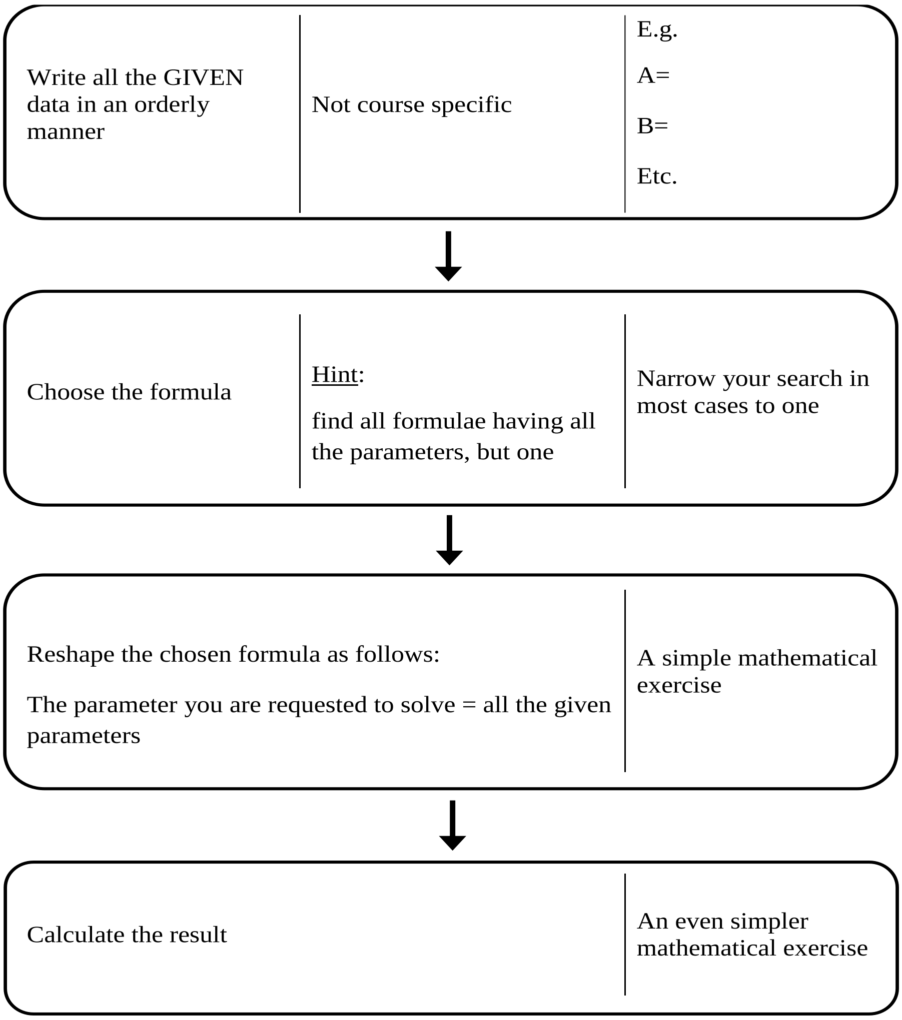

Figure 1. A typical procedure to solve assignments and exams in CEM

Construction engineers will concentrate in their professional career on project management aspects such as construction procedures, methods, and people management, which may appear to some to be more technical than creative design processes. In practice, however, construction engineers are required to be able to quickly resolve complex unstructured problems, under conditions of uncertainty and in “no time”, by collecting and integrating information from different sources and providing creative solutions.

A clear example of a situation in which construction managers have to resolve a complex problem for which no simple formula exists, is when they face ethical dilemmas. Such dilemmas may occur when an engineer needs to quickly solve a complex problem while adhering to the project schedule– the customary solution for which may conflict with engineering ethics. The complexity is amplified because such dilemmas not only do not have easy solution, but in many cases, if not the majority of them, they are not even RECOGNIZED by the engineer. This is possibly why construction engineers focus more on the technical issues, and in turn, the civil engineering schools align with current practices of the industry instead of serving as the beacon, indicating what the practice SHOULD be.

Many of the colossal accidents in Israel, if not all, were caused because of such a situation. Areas in construction management in which such a situation may occur range from accounting practices to onsite worker safety, as well as others. A limiting paradigm, which can address only specific technical problems, will obviously not prepare the student to deal with such issues.

We, therefore, propose that a learning centered approach to the EDUCATION of the CEM student, in which they are confronted with the need to find not only solutions for such complex problems, but also to select the data from databases containing partial, excess and often conflicting data, will better prepare them for their profession.

Consequently, the objective of this paper is to discuss the prevailing paradigm in CEM education, and to present an alternative model, which seeks to engage the students and encourage them to think creatively in order to provide solutions to the types of problems that they are likely to encounter in their professional careers. This model was implemented in a course that has been developed by the first author over the past four years.

2 Enabling Student Learning

A number of educational methods that stimulate student learning have previously been proposed. These include: interdisciplinary focus, collaborative learning and active experiential learning, and more [6].

Kolb and Fry [3] have argued in this context that experiential learning entails a cyclic process containing four different steps:

1. Concrete experience.
2. Reflective observation.
3. Abstract conceptualization.
4. Active experimentation.

This integrated process begins with here-and-now experience (1), followed by the collection of data about that experience (2). The data regarding the immediate concrete experience is then analyzed in order to form abstract concepts and generalizations concerning the experience that is studied (3). Finally, the implications of these concepts are tested in new situations through active experimentation (4), leading to a modification of behavior and choice of new experiences when returning to the first step of the cycle. Immediate concrete experience is thus the basis for observation and reflection that lead to a theory from which new implications for actions can be deduced.

Two common strategies that have been used to engage students and encourage learning and creative thinking are problem-based learning and group learning.

<u>Problem-based learning</u> uses real-world problems to encourage critical thinking and problem-solving skills (e.g. [1,5]). The main difference between problem-based learning and other types of active, student-centered learning processes is in that it introduces concepts to students by challenging them with problems related to their future profession. It thus reverses the conventional model, by using problems before the content has been introduced, in order to initiate learning. Problem-based learning also focuses on problems that are open-ended, unstructured and do not have only one “correct” answer.

<u>Group learning</u> is a term used for exercises in which students learn to work together in small groups on a task, which usually mimics a real-life project [4]. Students carry out realistic tasks, without direct supervision, in order to acquire through experience knowledge and skills. The aim of these exercises is to give students a chance to experience group dynamics, to learn project and time management, prioritizing and to enhance their inter-personal skills. It is clear that construction engineering graduates will need high levels of such teaming and communication skills to be successful in their work places.

3 A Practical Implementation

An elective course in CEM has been developed by the first author over the past four years, in which the above mentioned principles and methods of a learning centered approach have been incorporated. The objectives were to create a course in which the students are actively engaged, and are required to think creatively in order to tackle real-world problems. These objectives were determined for the course despite the fact that its domain was construction management, rather than structural engineering design in which such an approach has more often been implemented.

The course involved the four steps of experiential learning that were defined by Kolb and Fry [3]. These are reflective observation, abstract conceptualization, active experimentation and concrete experience:

1. <u>Reflective observation</u> was attained by holding class discussions based on topics that were presented in lectures. Students were expected to reflect upon those topics, and to take an active part in the discussions. The outcome of those discussions was usually not a single authoritative conclusion regarding the topic discussed. Instead, students were encouraged to form their own individual opinion, even if it differed from that of the lecturer.
2. <u>Abstract conceptualization</u> was attained by assigning the students an academic paper to read, to interview an industry expert on the same topic, and finally to compare the findings obtained from both sources. This required the students to confront differing opinions, from an academic and from a professional point of view, on a single topic. Despite these differences, the students were expected to form concepts and generalizations of their own concerning the topic investigated. The students presented their findings in a short presentation (a very important by-product on its own).
3. <u>Active experimentation</u> was carried out by iteratively preparing a bid for a tender, based on data that they collected themselves from different sources (e.g. the statistical analysis of data, interviews with industry experts, an analysis of plans, etc.). The students were required to follow the entire process of preparing a tender

for the execution of a real-life BOT project, based on a real call that had been issued at the time. The process started with an analysis of the existing planning conditions, proposing alternative programmatic solutions, carrying out feasibility studies, and investigating financial and contractual aspects. A key to this process was the fact that it had to be carried out through a number of iterations, as previous decisions were revisited based on additional information that was gathered.

4. Concrete experiences were gained through the simulation of team work and multi-team exercises. The students were required to carry out all the exercises in teams in the classroom, in a studio environment. The preparation of the tenders was competitive, with only one team eventually winning the bid. In some exercises, a multi-team experiment was conducted, in which different teams were required to negotiate with each other and to reach a consensus.

The attitude of the students often changed considerably during the course. Bernold [2] has observed that in practice, most people are not equally proficient in all four of the abilities that are part of Kolb and Fry's framework [3]. Similar to the findings in Bernold [2], it was clear from informal exchanges with the students participating in the course, that they were initially not all equally comfortable with the different components of the course. In particular, all students found it challenging to deal iteratively with an open, ill-structured problem. This was for them the first time they experienced dealing with such a problem in their studies, having previously had to solve mostly well-defined assignments, as described in Figure 1, for which all the information required to solve the assignments was given to the students in advance. Many expressed concerns on this when given the assignments. However, whereas Bernold [2] reports findings according to which most Civil Engineering students do not consider active learning as being effective, the overall opinion of the students, once they had participated in the course, was very positive.

Anonymous on-line survey was conducted, the results of which showed a general satisfaction with the course. When asked to rate on a 5-point Likert scale whether they had acquired new knowledge, tools and an understanding of the subject that provided them with new analytical abilities, the average response was 4.6, with a standard deviation of 0.6 (where 1 indicated "very little" and 5 "very much"). When asked whether they had felt that they needed to invest a significant effort in the course, the average response was 4.3, with a standard deviation of 0.8. But when asked whether they had encountered difficulties completing the course the average response was 2.8, with a standard deviation of 1.2.

4 Conclusions

Whereas the experience in this particular course was positive, it does raise the question of how the proposed approach can be expanded to other courses, or even to the entire curriculum. In particular, this course was an elective course, in which relatively small groups of students (on average 15-30 students) participated, in the fourth year of their studies. It could therefore be a challenge to apply a similar learning-centered approach in courses with larger groups of students, and at an earlier stage of their studies. Nevertheless, we believe that this is vital in order to make CEM studies an experience that will be more valuable and relevant for students.

One possible solution for working with a larger number of students, which has already been partly explored in the existing course, is to use multiple-team exercises, in which multiple teams of students work on a single project, with each team responsible for a specific part of the project. Such exercises simulate the more complex real-life work environment, in which large engineering projects are often executed by multiple teams. Such projects require not only the coordination of the work of individual team members, but also some form of organizational structure that ensures the coordination of the work of different teams. Multiple-team exercises are therefore also an opportunity to allow students to become familiar with different project management structures and roles.

Another possible solution in order to engage students more actively in courses at earlier stages of their studies is the use of IT solutions. Technologies such as online learning platforms can be used during lectures, even in introductory courses, in order to ask the students to answer questions during the lecture, display their answers to the class immediately afterwards, and promote discussions. The introduction of such innovations in the classroom can be an inherent part of the effort to bring about a paradigm change in CEM education.

The second author is currently leading the development and establishment of a new Civil Engineering Department in ORT Braude College of Engineering. The proposed departmental curriculum, submitted to the Council for Higher Education, is based on principles such as the one described above. We will be reporting the progress in this area in the next paper.

Lately we conducted a very limited pilot study, in which the students had to do two things:

1. IDENTIFY a dilemma in given scenario which we described to them.
2. Evaluate the optional solutions in a structured manner.

This pilot study will be described and demonstrated in the presentation.

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An Ontology of Control Measures for Fall from Height in the Construction Industry

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Abstract

Fall from heights (FFH) has been a major contributor towards both minor and major work-related injuries in the construction industry of many countries. In order to facilitate knowledge reuse/sharing and the development of knowledge-based systems for working at height, this paper aims to develop a lightweight ontology of control measures for fall from height (FFH) in the construction industry. The FFH-Onto is developed based on a generic ontological framework which consists of nine concepts: actor, task, building element, hazard, construction method, constraint, safety resource, hazard control measure, and residual risk. These nine concepts are categorized into three main parts: problem, context, and solution. The FFH-Onto can be used to facilitate knowledge re-use and sharing among the end-users (e.g., designer, engineer, safety professional, supervisor, and site manager. It also forms an important basis for developing knowledge-based systems for automated and intelligent fall protection engineering and management in the construction industry. Future efforts can be made to upgrade the proposed lightweight ontology to a heavyweight one which includes axioms and constraints. In addition, ontologies of other key hazards (e.g., struck by objects) are to be developed.

Keywords –

Construction safety; Fall from height; Ontology; Knowledge engineering

1 Introduction

While the overall safety performance in the construction industry has improved over the past decades, fall accidents and injuries in some countries have increased [1]. Fall from heights (FFH) has been a major contributor towards both minor and major work-related injuries in the construction industry of many countries and regions, such as Singapore [2,3], UK [4], US [5], Hong Kong [6]. For example, FFH accounted for over 20% of the major injuries in Singapore workplaces over the past five years.

To prevent or control the effect of a fall, a combination of control measures is often adopted. Based on the hierarchy of control [7], the control measures usually include elimination, substitution, engineering controls, administrative controls, and personal protection equipment (PPE). A large number of work-at-height (WaH) standards, best-practice, and guidelines were developed to help key stakeholders manage fall hazards on sites. However, similar fall injuries constantly occur [8, 9]. This is in part attributed to the fact that control measures for fall hazards are often not well designed and implemented and the information/knowledge is not communicated to workers. Due to the highly fragmented construction environment, lack of safety knowledge sharing and reuse is another critical reason for high fall accident rates [10].

Last two decades have seen a rapid growth in the use of Building Information Modeling (BIM) to facilitate communication, collaboration, and cooperation between key stakeholders of a construction project. Different information is integrated into BIM models for better cost management, scheduling, and facility management. However, the integration of safety information (e.g., fall hazard and control measures) into BIM models has been rather limited. Current safety practices are largely manual, paper-based, and therefore time-consuming and highly inefficient.

The integration of safety into BIM requires a formal knowledge base of construction safety domain. Developing an ontology is often considered an important starting point to construct the knowledge base [11]. The concept of "ontology" comes from philosophy, which is concerned with the nature of being and existence [7]. Gruber provided a popular definition of ontology: an ontology is an 'explicit specification of a conceptualization' [12] (p. 908). A "conceptualization" refers to an abstract model of a domain of interest based on relevant concepts, relations, and axioms within the domain. Ontology is an important means for knowledge representation, interoperation, and integration. It often plays key roles in the development of knowledge base and intelligent systems. Previous effort was made to develop an ontology for the design of active fall protection system (AFPS) [7]. Note that AFPS is only a part of control measures for fall hazards. There is no common ontology describing the knowledge of the domain of FFH in the construction industry and therefore more effort is needed to develop a more comprehensive ontology for fall from height by incorporating other fall control measures.

Thus, this paper aims to develop a lightweight ontology of control measures for fall from height in the construction industry. According to [13], lightweight ontologies only include concepts, concept taxonomies, relationships between concepts, and properties that describe concepts. An ontology must formally represent the domain knowledge that can serve for its purposes. In this study, a main purpose of the FFH-Onto is to facilitate selection, implementation, and maintenance of fall hazard controls. It also aims to facilitate the modeling and visualization of fall hazard controls in building information models and thus improve safety engineering and planning.

2 Literature review

Fall from height has received significant attention from researchers in the construction industry. For example, Hinze [14] investigated the root causes of fall accidents based on the data from OSHA. A number of contributing factors were identified, including lack of safety training, human error, and inappropriate use of controls. Similarly, Chan [15] identified twelve common contributing factors by analyzing twenty-two fatal fall injuries in Hong Kong. They suggested five strategies to reduce fall accidents, including (1) provide and maintain a safe system of work, (2) provide a suitable working platform, (3) provide safety information, training, instruction, and supervision, (4) provide suitable fall arresting system/anchorage; and (5) maintain safe workplace. Wong [16] adopted the Human Factor Analysis Classification System (HFACS) to identify and classify the root causes of fatal fall accidents. Goh and Binte Sa'adon [17] investigated the unsafe behavior of scaffolders based on the theory of planned behavior. They suggested that subjective norm was a key variable influencing a worker's decision-making.

In order to facilitate safety knowledge sharing/reuse and intelligent safety management, a number of safety-related ontologies were developed. For example, in order to improve safety knowledge sharing and reuse, Le et al. [18] developed a social network system using semantic wiki web and an ontology approach. Three main components (i.e., safety information module, safety knowledge module, and safety dissemination module) were constructed to represent construction safety knowledge based on safety semantic wiki template. In the meantime, efforts are made to develop ontology-based framework for job hazard analysis. For example, Wang and Boukamp [19] developed an ontological framework which represents knowledge about activities, job steps, and hazards. The framework can be used to conduct job hazard analysis based on ontological reasoning and document evaluation mechanism. This pioneering work has demonstrated the utility and importance of ontology in intelligent safety management. They suggested that the ontological framework be integrated into BIM tools to enable more automated site safety management. In addition, in order to reduce the level of human effort in job hazard analysis, Chi et al. [20] applied ontology-based text classification to identify hazard controls for specific unsafe scenarios. The ontology developed by them is based on three main text resources: CPWR construction solution database, the NIOSH FACE reports, and the OSHA standard. The ontological framework consists of nine concepts: task, activity, hazard, CPWR unsafe scenario, NIOSH fatality case report, safe approach, OHSA standards for construction industry, subpart, and standard. However, the ontological framework, as well as the ontology, may not be suitable for modeling and visualizing hazard controls in BIM tools, as it appears that there is no obvious links with BIM data model (e.g., Industry Foundation Classes (IFC) data format).

Information technologies have been used to help reduce fall accidents and injuries. For example, Navon and Kolton [21] developed an automated model that can identify dangerous work-at-height activities and areas. The schedule is integrated into the model which enables it to produce both textual and graphical reports that correspond to the schedule. The automated model was implemented in a prototype written in Visual Basic (VB), AutoCAD, and MS Project. Zhang et al. [22] explored the automation in modeling and planning fall hazard controls based on BIM models. The tool they developed can detect unprotected slab edges and holes and install guardrail system automatically. A limitation of this study is that the fall hazard controls modelled in BIM are not comprehensive (limited to scaffold and guardrail systems). Other important fall hazard controls such as active fall protection systems are not included. More recently, Qi [23] developed a PTD (prevention through design) software tool to help designers implement best practices to prevent fall accidents. Using the PTD tool, automatic safety checking can be performed by using BIM technology and a knowledge base that was designed based on best practices. These efforts were aimed at reducing fall accidents by improving building design and optimizing production planning. Supported by these advancements, a part of fall hazards could be either eliminated, substituted, or managed by engineering and administrative controls. However, personal protection equipment, including AFPS, is still required as a last line of defense to protect workers in many situations [24].

More recently, Zhang et al. [25] developed a construction safety ontology to facilitate automated safety planning by formalizing job hazard analysis (JHA) knowledge. The ontology consists of three ontological models: construction product model, construction process model, and construction safety model. The ontology is in part based on IFC data schema and the link between the ontology and BIM is bridged. However, the ontology is aimed at job hazard analysis and does not capture high levels of detail for selection, design, and implementation of hazard control measures.

In order to better facilitate safety engineering and hazard control design in the construction industry, Guo and Goh [7] developed a generic ontological framework which can be used as a harmonization framework for developing sub-domain ontologies. Based on the ontological framework, they developed an ontology for the design of active fall protection system (AFPS). The ontology (i.e., AFPS-Onto) provides a formal and shared knowledge base for the design of AFPS and forms an important part of the domain knowledge of FFH. Using the AFPS-Onto, Goh and Guo [26] designed a online knowledge-based system, *FPSWizard* to support the design and selection of AFPS.

3 Method

A number of methodologies for ontology building have been developed by researchers since the early 1990s, including the Grüninger and Fox [27] approach, the Uschold and Gruninger [28] approach, CO4 [29], METHONTOLOGY [30], and SKEM [31]. This study adopted the METHONTOLOGY to build the FFH-Onto. The METHONTOLOGY consists of seven main steps: specification, knowledge acquisition, conceptualization, integration, implementation, evaluation, and documentation (see Fig. 1).

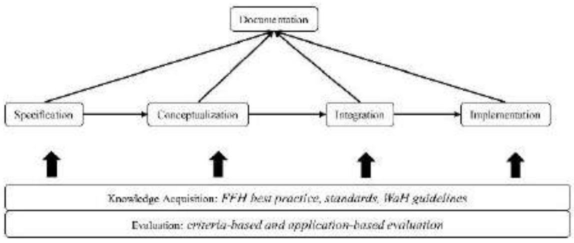

Fig. 1 Development process of FFH-Onto

Specification focuses on determining the purpose, scope, level of formality, intended uses, and end-users of the FFH-Onto. A set of competency questions were established in this step (see Table 1). These questions include, but are not limited to, “What are the purposes of the ontology?”, “Who are its end-users?”, “What information should be captured in the ontology?”, and “What design criteria should be followed?”. By answering all competency questions, this step produced an “Ontology requirements specification”, which severed as guidelines for the whole ontology building process.

Table 1 Key ontology requirements

Competency questions	Answer
What are the purposes of the ontology?	• Represent knowledge of fall protection in the construction industry • facilitate safety engineering and hazard control design in the construction industry • facilitate modelling and visualization of fall protection in BIM tools
What is the scope	All control measures for fall from height in the construction industry
Who are its end-users?	Designer, engineers, safety professional, supervisors, site managers
What information should be captured in the ontology?	Information that is important for the selection, implementation, engineering, and maintenance of fall hazard controls
What design criteria should be followed?	Clarity, extendibility, completeness, coverage

In order to acquire knowledge for the ontology development, a number of knowledge sources were collected and studied to elicit the domain knowledge, including industry standards, WaH best practice guidelines, fall accidents, CPWR construction solution database, and NIOSH FACE reports (see Table 2). These knowledge sources capture structured expert knowledge and industry norms of fall protection in the construction industry.

Table 2 Knowledge sources

Corpus	Title
Industry standards	AS/NZS 1576 series Scaffolding
	AS/NZS 1577 Scaffold decking components
	AS/NZS 1892 Portable ladders
	AS/NZS 4389 Safety mesh
	AS/NZS 4576 Guidelines for scaffolding
	AS/NZS 4994 Temporary roof edge protection for housing and residential buildings
	AS/NZS 5532 Manufacturing requirements for single-point anchor device used for harness-based work at height
	AS/NZS selection, use and maintenance for fall arrest equipment
Best practice guidelines	Preventing falls in housing construction [32]
	Safe use of safety nets
	Best practice guidelines for working

	at height in New Zealand
	Best practice guidelines for working on roofs
	Managing the risk of falls at workplaces
	Scaffolding in New Zealand
Fall accidents	OSHA accident database
Other knowledge base	CPWR construction solution database
	NIOSH FACE Reports

A comprehensive list of fall protection systems and tools were collected and categorized according to their hazard control mechanism. Key attributes of each system were extracted from industry standards and guidelines. A main purpose of using multiple databases is to reduce or eliminate conceptual and terminological confusion and reach a shared understanding of the domain of interest.

4 FFH-Ontology

The FFH-Ontology is developed based on the generic ontological model designed by [7] (see Figure 2). The ontological model consists of three main parts: problem (i.e. specific hazards that need to be managed), context (i.e. the situation in which the problem exists), and solution (i.e. hazard controls).

The problem includes five concepts: hazard, actor, task, IFC building element, and construction method. These five concepts and their relations and attributes describe a safety problem or an unsafe scenario. Context is composed of two concepts: constraint and safety resource, which are aimed at providing information about the context in which safety problems exist and solutions are designed. Solution is composed of two concepts: hazard control measure and residual risk.

From a global perspective, the three parts are interconnected: a problem is solved by solutions which, in turn, are constrained by the context in which the problem occurs.

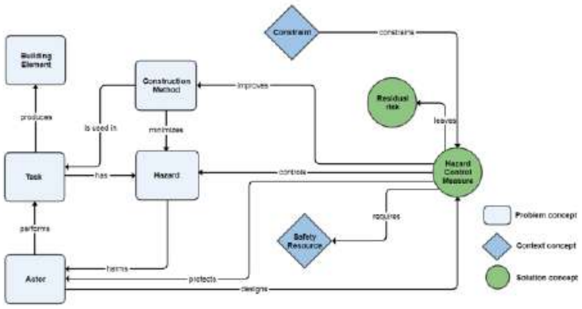

Fig. 2 The generic ontological model

The components (i.e., concepts and relations) of the FFH-Onto is presented as follows.

4.1 Concepts

4.1.1 Task

Task is used to represent the hierarchy of construction process. Being consistent to the AFPS-Onto [7], the FFH-Onto adopted types of task defined by the Industry Foundation Classes (IFC), which consist of 12 main tasks: attendance, construction, demolition, dismantle, disposal, installation, logistic, maintenance, move, operation, removal, and renovation. Different sub-tasks (e.g., floor laying, wall framing, and installing prefabricated roof trusses) can be grouped into the 12 main tasks according to their nature. Note that this is not the only way to model task. Other ways can be referred to [19].

4.1.2 Actor

Actor defines all actors or human agents involved in hazard management. Compared to the AFPS-Onto which only defines workers and professional engineers, the FFH-Onto expands the concept by defining other key actors, including “a person conducting a business or undertaking (PCBU)”, “officer”, “manufacturer”, “supplier”, and “installer”. By doing so, the FFH-Onto is able to formalize richer information and knowledge such as legal duties and manufacture information.

4.1.3 IFC building element

IFC building element comprises all elements that are primarily part of the construction of a building [33]. Considering that the FFH-Onto is in part aimed at facilitating modelling and visualization of fall hazard control in BIM models, it adopts the structure of IfcBuildingElement from IFC schema. The class *Ifc Building element* include the following subclasses: IfcBeam, IfcBuildingElementProxy, IfcChimney, IfcColumn, IfcCovering, IfcCurtainWall, IfcDoor, IfcFooting, IfcMember, IfcPile, IfcPlate, IfcRailing, IfcRamp, IfcRampFlight, IfcRoof, IfcShadingDevice, IfcSlab, IfcStair, IfcStairFlight, IfcWall, and IfcWindow. By adopting the IFC building elements, the FFH-Onto is linked with BIM models and can exchange information with BIM models and other programs as an application programing interface (API).

4.1.4 Construction method

Construction method represents methods, techniques, and technologies that are used to construct a building. More often than not, a combination of safety work methods are required to perform safely a sub-task such as floor laying. Thus, safety knowledge of WaH can be meaningfully defined and formalized based on tasks, which facilitates the visualization of fall hazard controls in 4D schedule BIM models. When a robust knowledge base of WaH is developed, the FFH-Onto is potentially able to assist designers and engineers with integrating the concept of "design for safety" in building design. Examples of alternative construction methods include: (1) prefabricating wall frames horizontally before standing them up, (2) using precast tilt-up concrete construction instead of concrete walls constructed in situ, and (3) pre-painting fixtures/roofs before installation.

4.1.5 Hazard

A *hazard* is anything in the workplace that has potential to harm people. The FFH-Onto focuses only on fall hazard.

4.1.6 Constraint

The FFH-Onto adopts the taxonomy of constraint defined in the AFPS-Onto. The taxonomy consists of four main constraints: project constraint, design standard, regulatory constraint, and environmental constraint. Details of each constraint can be referred to [7].

4.1.7 Safety resource

Safety resource represents resources that are consumed and used in designing and implementing control measures for FFH. It is composed of financial resource (e.g., money), human resource (workers, safety professionals, and project managers), physical resource (e.g., existing fall prevention and fall arrest devices and equipment), safety knowledge, and safety item (fall protection plan, best practices, and rescue plan and procedure). This component covers important information and knowledge that can justify the selection of control measures for FFH.

4.1.8 Hazard control measure

Control measures for fall hazards are categorized into nine main groups, including: (1) guardrail, (2) temporary work platform, (3) harness system, (4) safety mesh, (5) mechanical access plant, (6) safety net, (7) soft landing system, (8) access/egress, and (9) administrative control (see Figure 3).

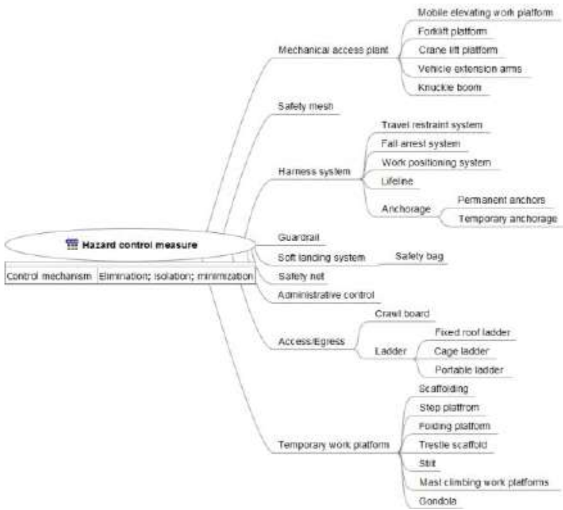

Fig. 3 Main control measures for fall hazards

According to [32], control measures for FFH can also be categorized into a 5-level hierarchy.

Level 1 controls aim to eliminate the risk of a fall by either carrying out tasks on the ground or platforms (e.g., flat roof) with edge protection (e.g., parapet).

Level 2 controls represent fall prevention devices and equipment, such as temporary work platforms (e.g., scaffold, elevating work platforms, step platforms, mast climbing work platforms, and ladders), guardrails, and safety mesh.

Level 3 controls include any work positioning systems that can restrain workers within safe areas.

Level 4 controls are used to arrest a fall when it is not reasonably practicable to prevent a fall. For examples, catch platforms, and active fall arrest systems are common measures to arrest a fall. Safety net should be used when it is not practicable to provide scaffolds or temporary guard railing.

Level 5 captures all administrative controls such as safety training.

4.1.9 Residual risk

Residual risk refers to hazards and risks remaining after the inherent risks have been reduced by hazard controls. Any implementation of a specific hazard controls may bring about new risks or leave some risks unaddressed. For example, the design of active fall arrest system may leave some residual risk such as poor installation, inadequate training and supervision.

4.2 Semantic relations

Semantic relations are defined as "meaningful associations between two or more concepts, entities or sets of entities" [34]. Semantics refers to the meaning of the concepts within an ontology. Semantics play important roles in information modelling and knowledge representation. There are five main semantic relations:

(1) Hyperonym-hyponym relations: they refer to the relations between a broader and narrower concept.
(2) Meronym-Holonym relations: they refer to the relations between a concept and its constituent parts.
(3) Concept-object relations: they refer to a class and its instances.
(4) Cause-effect relations: they refer to cause-effect relations between concepts using causative verbs.
(5) Locative/spatial relations: they are used to specify how a concept is located in space in relation to other concepts.

Examples of semantic relations are provided in Table 3.

Table 3 Semantic relations

Type	Relation	Example
Hyperonym-hyponym relations	"is_equivalent_to" "is_disjoint"	Horizontal Lifeline System <is_disjoint> with a Vertical Lifeline System
Meronym-Holonym relations	"is_subsystem_of" "is_part_of"	Longitudinal Wire <is_part_of> Safety Mesh
Concept-object relations	"is-instance-of"	Installing prefabricated roof trusses <is_instance_of> Construction
Cause-effect relations	"performs", "produces" "harms" "minimizes" "designs"	Hazard <harms> Worker
Locative/spatial relations	works_on	Worker <works_on> Roof

4.3 Attributes

According to El-Gohary and El-Diraby [35], an "attribute" is defined as "*a characteristic that describes a thing*". Modelling and visualizing fall hazard controls without information about attributes is less meaningful and useful. Attributes should cover information that is important to end-users of an ontology. For example, it is not enough to model and visualize a safety net without any information about its size, material, class, energy absorption capacity. The information is significant for selection and implementation of safety net on site. Note that attributes of the concepts of active fall protection system are not presented here. Details can be referred to [7].

"Hazard control mechanism" is an attribute of hazard control measure and it is inherited by all sub-classes of hazard control measure. The attribute has three values: elimination, isolation, and minimization, which are consistent with the traditional hazard control hierarchy.

Key attributes of other main concepts are presented in Table 4.

Table 4 Key attributes of main concepts

Concepts	Key attributes
Fall hazard	• fall scenario; • fall height; • severity; • likelihood
Safety net	• material; • maximum fall distance; • minimum clearance below the working area; • class; • energy absorption capacity; • mesh configuration; • mesh size; • manufacturer; • data of manufacture; • net's unique identify or serial number (ID); inspection status
Scaffold	• intended use; • dimension; • duty loading; • weight; • height; • bay length; • lift height; • base-to-height ratio; • load-bearing capacity of the supporting foundation; • inspection status;
Safety mesh	• dimension; • the supplier and country of manufacture; • diameter of safety mesh wires; minimum • tensile strengths of safety mesh wires; • dimensions of the mesh aperture; • width of the mesh; • nominal weight of the mesh; • UV stabilization rating; • initial sag;
Guardrail	• span; • material; • rail height; • portability; • collapsibility; • free-standing-ability; • inspection status
Roof	• slope; • length in the direction of its slope; • material; • strength;

Values of attributes take different data types, including Integer, Float, String, and Boolean. These attributes in the ontology are grouped as slots attached to specific concepts. These attributes carry importance information for selection, implementation, and maintenance of fall hazard controls.

4.4 Coding

The FFH-Onto was coded using Protégé 5.2.0, as shown in Figure 4. Protégé is a free, open-source ontology editor and framework for building intelligent systems [36]. In protégé, “Classes”, “Object properties”, and “Data properties” are used to model concept, relations, and attributes, respectively. Some plug-ins (e.g., OntoGraf) can be used to present key classes and their relationships (see Fig. 5).

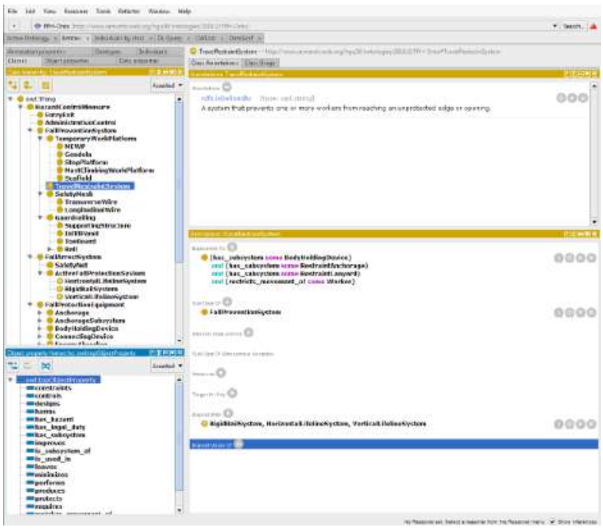

Fig. 4 Screenshot of the ontology editor Protégé.

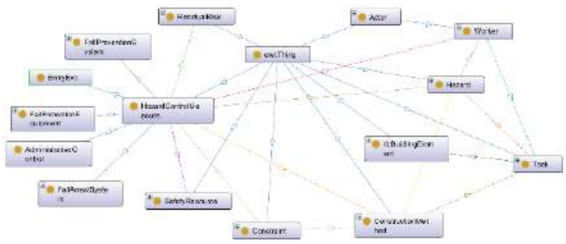

Fig. 5 Key classes and their relationships

5 Ontology evaluation

Ontology evaluation is essential for the development of ontologies. It represents a “*judgement of the ontology content with respect to a particular frame of reference*”. [35]. The paper only aims to develop a lightweight FFH-Onto which does not include axioms and constraints. As a result, it is not possible to conduct automated consistency checking using logic reasoner such as Pellet. FFH-Onto is initially evaluated using a criteria-based evaluation approach.

5.1 Criteria-based evaluation

Four key criteria which match the objectives of FFH-Onto were adopted from past studies [12, 37, 38], including clarity, extendibility, completeness, and coverage.

Clarity refers to whether an ontology effectively communicates the intended meaning of defined concepts, relations, and attributes without ambiguity [37]. To ensure the clarity of the FFH-Onto, all concepts and their definitions were extracted directly from the knowledge sources presented in Table 2. The knowledge sources were developed by groups of safety experts and are deemed to capture unambiguous concepts with clear definitions. Standards developed in different countries may use different concepts with similar meaning. For example, “Professional engineer” used in SS 607 [39] is a synonym of the “Qualified engineer” used in Z259.16-15. To clarify, synonyms of a given concept were listed in the Protégé through the use of <rdfs:comment>, an instance of <rdf:property> that may be used to provide a human-readable description of a resource.

Extendibility refers to an ontology’s ability to expand itself to “*describe specific application domains in a way that does not change the current definitions within the ontology*” [37]. The authors made effort to capture the majority of concepts and their attributes underlying the generic ontological framework. The FFH-Onto is scalable so that new relevant concepts and attributes can be integrated without changing the current structure of the ontology.

Completeness means whether definitions of concepts are complete. Although the completeness cannot be proven, the incompleteness of the ontology was detected by considering its reference to the real world itself, as suggested by Yu et al.[37]. For example, “ladder” is not only a subclass of temporary work platform, but also can be a kind of entry and exit.

Coverage refers to the coverage of the concepts over the domain of fall from height in the construction industry. In order to improve the coverage of FFH-Onto, a combination of knowledge sources were collected (see Table 2) and core concepts and attributes were manually extracted from these industry standards, best practice guidelines, etc.

Despite these efforts, it is acknowledged that more efforts should be made to further evaluate the FFH-Onto when it is upgraded to a heavyweight ontology which includes concepts, concept taxonomies, relationships between concepts, properties, axioms, and constraints.

6 Discussion, conclusions and future study

This paper developed a lightweight ontology for the domain of fall from height in the construction industry. It represents an effort to develop the global ontology for construction safety hazard management (CSHM-Onto), as suggested by [7].

The FFH-Onto builds itself on the generic ontological framework designed in [7]. A major consideration is that a hierarchy of hazard control measure ontologies (FFH-Onto, AFPS-Onto, and struck-by-objects ontology) can be built and combined based on the harmonization framework. The lightweight ontology captures the vocabulary (i.e., concepts, attributes of and relations between the concepts) in the domain of fall from height in the construction industry. In particular, nine groups of fall hazard controls were categorized, including (1) guardrail, (2) temporary work platform, (3) harness system, (4) safety mesh, (5) mechanical access plant, (6) safety net, (7) soft landing system, (8) access/egress, and (9) administrative control.

Compared to previous safety-ontologies developed for job hazard analysis, the FFH-Onto is more comprehensive, powerful, and flexible. It servers purposes beyond conducting job hazard analysis. By unifying multiple databases in the FFH domain, it can be used to (1) promote knowledge reuse and sharing, (2) facilitate the development of knowledge-based systems, and (3) improve the modeling and visualization of fall hazard controls in BIM tools.

The ontology can be used to facilitate knowledge re-use and sharing among the end-users (e.g., designer, engineer, safety professional, supervisor, and site manager. As a foundation of knowledge engineering, ontologies represent effort to engineer domain knowledge into a high level of human expertise [40].

The FFH-Onto formalizes empirical experience, standards, best practices in the domain of fall from height in the construction industry. Specific fall protection systems and devices are explicitly defined and thus it promotes modeling and visualization of fall protection in BIM models. Engineers and safety practitioners can demonstrate the design and installation of hazard controls (e.g., active fall protection system and guardrail systems) in BIM models and therefore improve communication and safety planning.

Recent years have seen a growing interest in developing knowledge-based systems for construction safety engineering and management. Building these intelligent systems poses special requirements for interoperability. Thus, establishing agreements about domain knowledge becomes critical. The FFH-Onto captures consensual the domain knowledge in a generic way and as such facilitates interoperability of formal knowledge across computer programs. By organizing objects (e.g., workers and scaffold) into categories, semantic networks, rules, and logic can be designed and integrated into computer programs for certain tasks. For example, by capturing a working at height scenario using concepts like actor, task, building element and their relations and attributes, it is possible to write rules that enable automatic hazard recognition and classification based on additional information extracted from BIM models. Intelligent hazard control recommendation systems could also be designed based on the temporal-spatial relationships between building objects, materials, tools, process, practices, and workers.

The ontology developed in this paper has the following limitations. First, the proposed lightweight ontology needs to be further developed by including axioms and constraints. Second, FFH-Onto is by no means a "perfect and only" ontology to represent the knowledge of FFH domain. Other representation strategies are possible. Future efforts should be made to develop ontologies for other key hazards such as struck by objects. Once local ontologies are developed, they can be mapped and integrated into a global ontology of construction safety hazard management. The success of these efforts would significantly promote automation in construction safety engineering and management.

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Compound Movement Support by an ULSS Based on a Bioelectrical Signal for Upward High Load Works

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Abstract –

Upward high load works such as the installation of ceiling boards are severe work. We have developed an upper limb support system (ULSS) for the works. The purpose of this study is to develop compound movement support algorithm for the ULSS, and to confirm the effectiveness of the ULSS with the algorithm. The installation of the ceiling boards is compound movement. The workers move a tool vertically with one arm while holding the heavy board with another arm. The ULSS is a powered exoskeleton and has enough range of motion (ROM) for the works. The developed algorithm controls each arm part of the ULSS separately and achieves the compound movement support based on a bioelectrical signal (BES). The BES is detected on the surface of the human skin covering the muscle when the human is going to move their muscle. Volunteers perform the compound movement simulating the actual work in the evaluation experiments. As a result, the ULSS with the algorithm had a positive effect on the support. The average number of the compound movement with the ULSS increased 2.0 times compared to the average number without the ULSS.

Keywords –

Compound movement; Upward high load works; Powered exoskeleton; Bioelectrical signal

1 Introduction

At demolition or construction sites, workers have to perform upward high load works. Examples are installation of ceiling boards, cutting of metal pipes, and chipping of cement [1]. The workers hold heavy loads overhead, and move heavy loads vertically. It is difficult to sustain such the upward high load works, and working environment will be severe. For this reason, actual working time of whole working time decreases, and work efficiency will be reduced. In addition, the severe working environment causes decrease of the workers in the construction industry [2]. Therefore, It is necessary to improve the working environment, and movement support for upper limbs is required.

A wearable system with a sufficient degree of freedom (DOF) and support power will be effective to sustain these upward high load works for a long time. Many wearable systems for the movement support have been researched and developed [3]-[9]. However, these studies focus on the high power support for the works performed under the wearer's head, or light power support for the works performed on the wearer's head. In this study, we focus on the upward high load works, and have developed an upper limb support system (ULSS) [10]. The ULSS is a powered exoskeleton and follows complex movements of the wearers by redundant DOF. In the actual work sites, it is necessary for the ULSS to perform voluntary movement support by following motor intention of the wearers. Estimation of the motor intention is important for the voluntary movement support. In this study, we adopt a bioelectrical signal (BES) as the method for estimating the motor intention [11]-[16]. The BES contains nerve command signals and myoelectrical signals. The BES is detected on the surface of the human skin covering the muscle when the human is going to move their muscle. The BES is effective for voluntary movement support because this electrical signal reflects muscle activity and the motor intention directly. A movement support algorithm for the ULSS based on the BES is required to achieve voluntary movement support.

In previous research, we have developed a static movement support algorithm for the holding movement such as the cement chipping work, and dynamic movement support algorithm for the vertical movement such as the pipe cutting work [17][18]. These algorithm supports simple static or dynamic movement. In the simple work such as the chipping work or cutting work, the workers treat tools and materials by their both hand. However, the workers perform compound movement of the static holding movement and dynamic vertical movement in the actual work sites. The installation of ceiling boards is compound movement. This work is one of the most demanding types of the work in terms of the weight of the tools and materials. The workers move a nailing machine vertically with one arm while holding the heavy ceiling board with another arm. During this work, required support power changes according to the movement of each arm. Thus, it is necessary to develop a new compound movement support algorithm for the upward high load works such as the installation of ceiling boards.

The purpose of this study is to develop a new compound movement support algorithm for the ULSS based on a BES to achieve continuous upward high load works. In addition, we confirm the effectiveness of the ULSS with the algorithm through evaluation experiments. In the evaluation experiments, we assess the voluntariness of the ULSS, and the effectiveness of the ULSS for the compound movement.

2 Material and Method

2.1 Upper Limb Support System (ULSS)

Figure. 1 shows an overview of the ULSS. The ULSS is a powered exoskeleton. Basic points of the movement of the arms are shoulder joints. When the workers raise their arms, the clavicles and the scapulas of the wearers which hold the humeruses tilt to upward [19]. In addition, the spine moves three-dimensionally. Consequently, the positions of the shoulder joints move significantly. The ULSS has the middle joins, and this joint is redundant with respect to the structure of the wearer in the sagittal plane. The wearers of the ULSS can move smoothly through the middle joints. Moreover, Japanese adult males, who have dimensions of the human body between 5%tile to 95%tile, can wear the ULSS by the shoulder width adjusting mechanism.

A total of six power units are installed on the arms of the ULSS. The ULSS supports the wearer's upper limb movement by moving independently on the left side power units and the right side power units. The shoulder joints and middle joints are connected by the parallel link mechanism to reduce the required support force [20]. The ULSS is attached to the wearer by belts. There are cuffs that transmit support forces to the wearer. Each joint has a mechanical angle limiter. The lumber load support unit transmits the reaction force of the support force to the iliac horns of the wearer. The total weight of the ULSS is 8.3 kg. The minimum safety factor for the breaking strength is over 2.0 in a state of maximum load. In order to ensure safety, the wearers only handle tools and materials that they can handle without the support of the ULSS. In addition, the wearers have enough training and explanation before the evaluation experiments.

Figure. 2 shows a system configuration of the ULSS and the method for measurement of the BES. Power units in each joint have angle sensors and actuators. There is a control unit in the back part of the ULSS that consists of a main-computer, BES sensing unit, A/D converters, absolute angle sensor, and motor drivers. The reset switch is within reach of the jaw of the wearer. There is a battery unit in the lumbar load support unit, and the battery unit supplies electricity to the power units and each unit circuit. The BES sensing unit

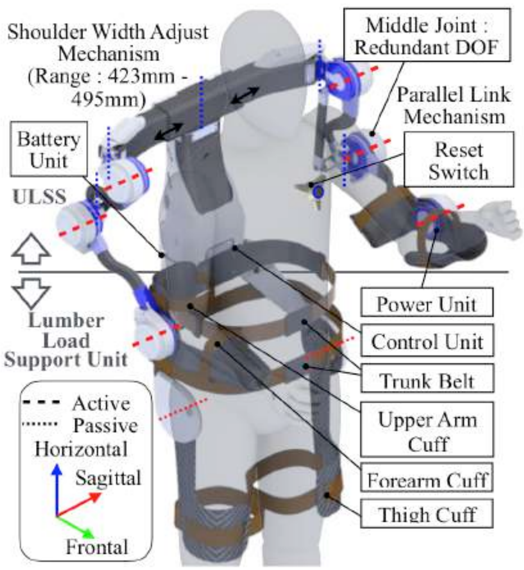

Figure 1. Overview of the ULSS. The ULSS is a powered exoskeleton and has redundant DOF for smooth movement of the wearer.

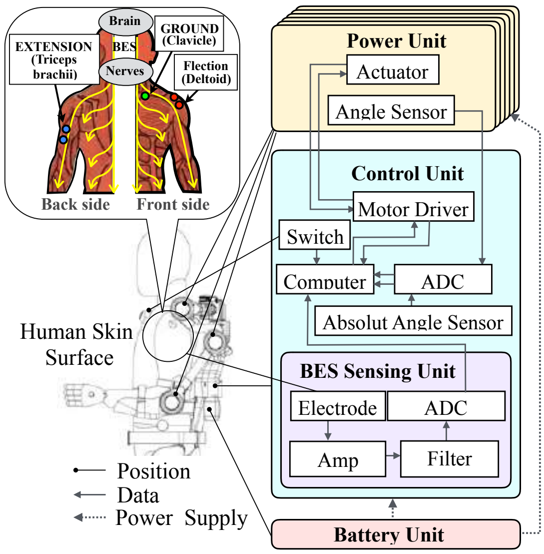

Figure 2. System configuration of the ULSS and the method for measurement of the BES.

measures the BES for the estimation of the motor intention by the wet type electrodes. The BES contains nerve command signals and myoelectrical signals and reflects muscle activity and the motor intention directly. The BES is detected on the surface of the human skin covering the muscle when the human is going to move their muscle [11]-[16]. The electrodes are attached on the deltoid, the triceps brachia, and the roots of the clavicle. The ULSS performs calibration process of the BES before the movement support.

2.2 Compound Movement Support

During the upward high load works, required support power changes according to the movement of each arm of the wearer. The ULSS supports the wearer by the compensation of gravity and viscosity according to the control phase. The developed algorithm achieves the compound movement support by shifting control phases. The support torque in each drive joint is

$$\tau = MgL + \tau_S + \tau_W + \tau_V \tag{1}$$

The M is the assumed weight which is held by the wearer in wearer's hand. We treat M as the known value because the weight of tools and materials will not change particularly in one upward high load work. It is considered that the method can support the actual works by inputting the weight value of the tools and materials. The ULSS achieves the compound movement support by changing the M according to the control phase. The g is the acceleration of gravity. The L is a moment arm of the position of M and each drive joint. The τ_S is the self-weight compensation torque around each joint, and the τ_W is the wearer's arm weight compensation torque around each joint, The τ_V is the viscosity compensation torque around each joint. It's possible to reduce the required gravity compensation torque around the shoulder joint by the parallel linkage [20].

The algorithm is compatible with the compound movement such as the installation of the ceiling boards. The workers move a tool vertically with one arm while holding the heavy material with another arm in such the work. The algorithm distinguishes between whether the movement of the wearer is the holding movement or the vertical movement based on the BES.

Figure. 3 shows a state transition diagram of the control phase. The control phase decides support power. This diagram illustrates the control phase of a single arm of the ULSS. The symbols in parentheses are equivalent to the M of the equation (1). The MH simulates the weight handled in holding movement, and the MV simulates the weight handled in vertical movement. In most cases, the MH is heavy than the MV in the compound movement such as the installation of ceiling boards. After the calibration, the control phase shifts to the NO-LOAD phase. When the reset switch was pressed, the control phase shifts to the WAIT phase. After that, the control phase shifts voluntarily based on the BES. The flection side BES is the fl, and the extension side BES is the ex. The control phase does not shift, when the co-innervation of the flexor muscle and extensor muscle occurs. The decision condition is

$$THR_{CO} < | fl - ex | \tag{2}$$

The THR_{CO} is the threshold value of the decision condition.

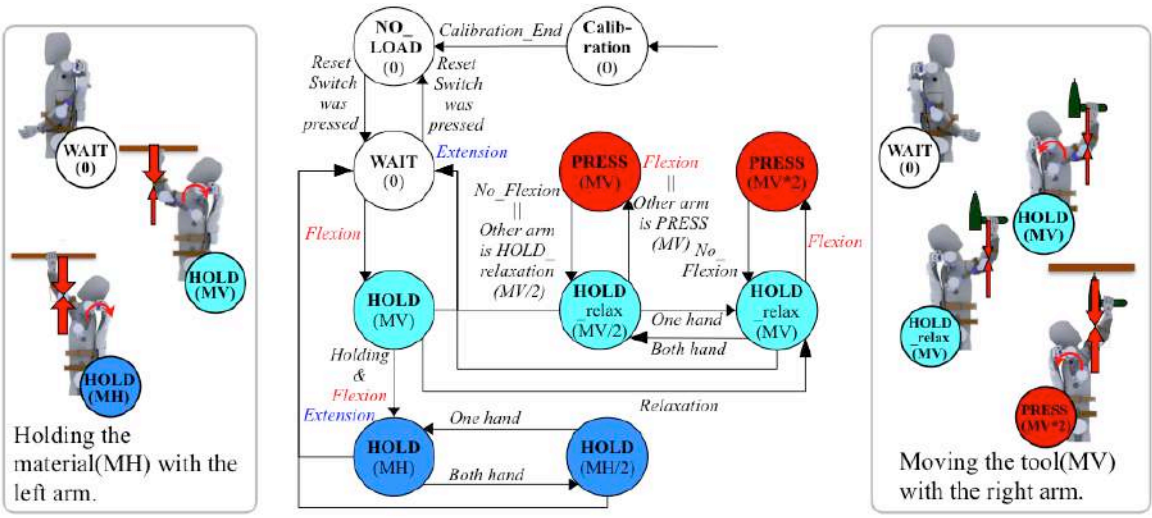

Figure 3. State transition diagram of the control phase for one arm part of the ULSS. When the reset switch was pressed, the control phase shifts to the WAIT phase.

The shift of the control phase in the vertical movement is shown below. The Flection indicates that the fl exceeds the threshold value THR_{FH}. The Extension indicates that the ex exceeds the threshold value THR_{RE}, and fl goes below the threshold value THR_{FL}. The THR_{FH} is larger than THR_{FL}. When the wearer holds the MV with his one arm, the state of the BES changes to the Flection. In addition, the WAIT phase shifts to the HOLD(MV) phase. At this time, the arm of the wearer can relax by the support of the ULSS. The decision condition of the relaxation is

$$(fl < (fl_{max} - THR_{FR})) \,\&\, (fl - THR_{FL}) \tag{3}$$

The fl_{max} is the maximum value of the fl, and the THR_{FR} is a threshold value of the relaxation. After the relaxation, the control phase shifts to the HOLD_relaxation(MV). When the wearer presses the MV upward, the state of the BES shifts to the Flextion, and the control phase shifts to the PRESS(MV*2). When the state of the BES shifts to the No_Flextion, the control phase shifts to the HOLD(MV). The No_Flextion indicates that the fl goes below the threshold value THR_{FL}. When the wearer pulls down his arm, the state of the BES shifts to the Extension, and the HOLD phase shifts to the WAIT phase.

The shift of the control phase in the holding movement is shown below. When the wearer holds the MH with one arm, the state of the BES changes to the Flection, and the WAIT phase shifts to the HOLD(MV) phase. At this time, the gravity compensation for the weight in the wearer's hand is less than the support required for the MH. Thus, the BES keeps the Flection. At this time, the joint angular velocity shifts the Holding state and goes below the threshold value. For this reason, the control phase shifts to the HOLD(MH). When the control phases of both arms are the HOLD(MH) or the HOLD_relaxation(MV), the ULSS estimates that the wearer handles the heavy load by both arms. In this case, the control phases of both arms synchronize, and the assumed weight of the single arm becomes a half. Thus, the compound movement algorithm can support the holding movement and vertical movement voluntarily.

3 Experiment

3.1 Outline

Evaluation experiments were conducted to confirm the effectiveness of the system with the developed algorithm. The experiments were a random instruction experiment and a movement support experiment conforming to the installation of ceiling boards. Figure. 4 shows the pattern diagram of the experiments. A weight of 15 kg simulated the ceiling board, and a weight of 5kg simulated the nailing machine. Another weight of 5 kg simulated the reaction force, and this heavy load was passively moved vertically. The volunteers were five healthy adult Japanese males who had heights below the 95%tile value. The volunteers moved the two heavy loads of 5kg vertically with the dominant hand while holding the heavy load of 15kg with the non-dominant hand in synchronization with an instruction. The instruction was performed by a beep sound. The volunteers wore protectors.

3.2 Random Instruction Experiment

The random instruction experiment was conducted in order to confirm that the control phase changes by following the motor intention. The volunteers wore the ULSS and moved the heavy loads vertically. At first, the volunteers waited 5 s. Next, the volunteers gripped both of the below head height heavy loads at random intervals of 1 - 4 s. Next, the volunteers moved the upper heavy load vertically 3 times with dominant hand while holding the heavy load with the non-dominant hand. At this time, the rise of the two heavy loads of 5kg was performed for random intervals of 1 - 4 s, the descent of the heavy loads was performed for 1 s, and each vertical movement was performed after random intervals of 1 - 4 s. Next, the volunteers put the heavy loads on the pedestal after random intervals of 1 - 4 s, and pressed the heavy loads down. Finally, the volunteers waited 5 s. We measured the timing of the instructions, the movement of the wearers, and the shifts of the control phases.

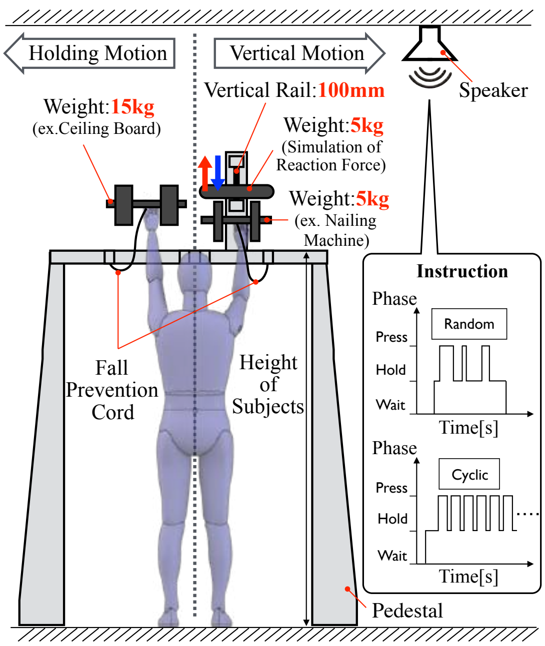

Figure 4. Pattern diagram of the experiments.

3.3 Movement Support Experiment

The movement support experiment was conducted in order to confirm that the ULSS with the developed algorithm had a supportive effect for the compound movement. The volunteers performed the compound movement in synchronization with cyclic instructions. The volunteers continued the movement to the limit of the physical strength without and with the ULSS. At first, the volunteers waited 5 s. Next, the volunteers gripped both of the below head height heavy loads for 5 s. Next, the volunteers moved the upper heavy load vertically with the dominant hand while holding the heavy load with the non-dominant hand. At this time, the rise of the two heavy loads of 5kg was performed for 4 s, and the descent of the heavy loads was performed for 1 s. When the volunteer could not continue this compound movement, they put the heavy loads on the pedestal and pressed the heavy loads down. Finally, the volunteers waited 5 s. We measured the number of the compound movements. Moreover, we conducted a dependent t-test to compare the number of compound movements without and with the ULSS, and the level of significance was 5 %. The volunteers took a rest between both of experiments to recover.

4 Result

Figure. 5 shows results of the holding movement in the random instruction experiment. The control phase of all volunteers followed the instruction with a delay. In addition, the control phase shifted in the order of the WAIT(0kg), the HOLD(5kg), and the HOLD(15kg).

Figure. 6 shows the results of the vertical movement in the random instruction experiment. The control phase of the volunteer A, B, and E followed the instruction with a delay. As for the volunteer C, the HOLD(5kg) shifted to the PRESS(10kg) 2.25 s faster than the instruction. As for the volunteer E, the number of phase shift is smaller than the number of vertical movement instruction. In addition, when the instruction phase shifted from the PRESS(10kg) to the HOLD(5kg), the control phase didn't shift from the PRESS(10kg) to the HOLD(5kg) once in a while. As for the control phase of all volunteers, the control phase shifted in the order of the WAIT(0kg), the HOLD(5kg), and the HOLD(10kg).

Figure. 8 shows the state of the movement support experiment. Figure. 9 shows the results of the movement support experiments. In the experiment without the ULSS, the average number of the compound movement repetitions was 9.4 sets, and the 95%CI was 11.7 - 7.1 sets. In the experiment with the ULSS, the average number is was 19.0 set, and the 95%CI was 23.4 - 14.6 sets. The number of all the volunteers increased with the ULSS. The average number of the compound movement repetitions with the ULSS was 2.0 times higher than without the ULSS. The result of the t-test was that the number of compound movement repetitions with the ULSS was significantly large higher.

5 Discussion

The volunteers performed holding movement and the vertical movement in the random instruction experiment. The results of the holding movement showed that the control phase of all volunteers followed the instruction with a delay. From this result, the volunteers performed the holding movement as per the instruction, and the developed algorithm voluntarily shifted the control phases by following motor intention of the wearers who perform the holding movement. In addition, the control phase shifted in the order of the WAIT(0kg), the HOLD(5kg), and the HOLD(15kg).

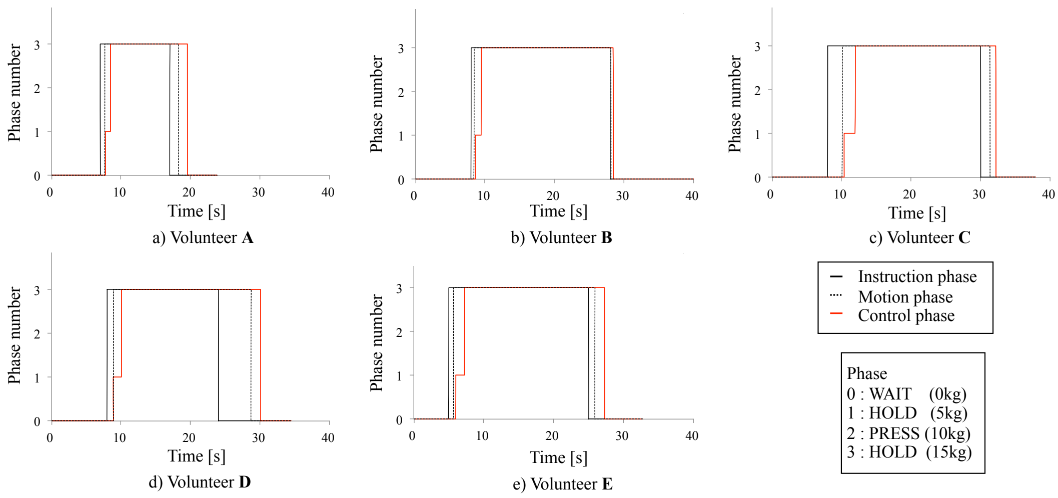

Figure 5. Results of the random instruction experiment (holing movement).

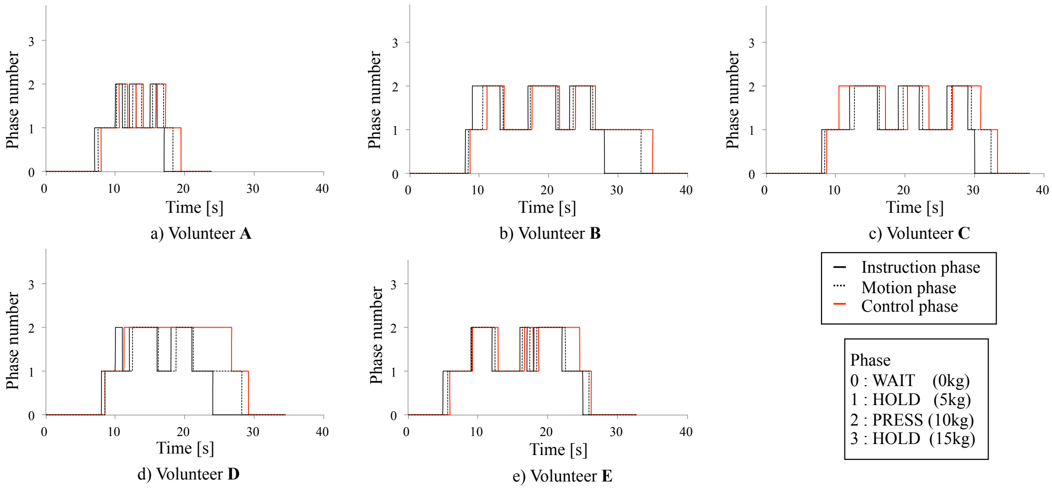

Figure 6. Results of the random instruction experiment (vertical movement).

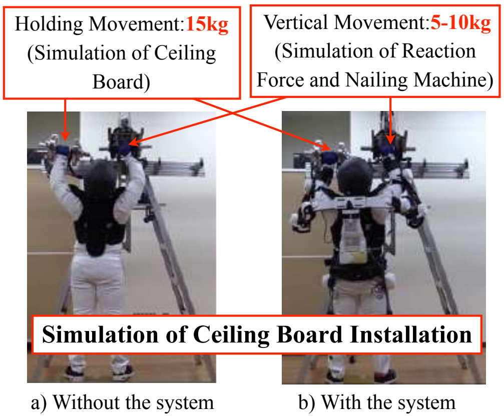

Figure 7. State of the compound movement experiment.

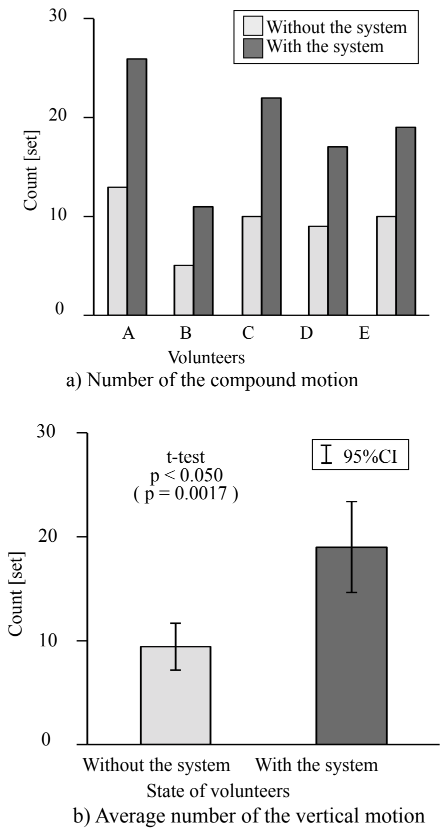

Figure 8. Results of the movement support experiments. The number of compound movement repetitions with the ULSS is significantly greater.

Thus, the developed algorithm detected the lack of the support power based on the BES, and switched the control phase adequately.

The results of the vertical movement showed that the control phase of the volunteer A, B, and E followed the instruction with a delay. From the result of the vertical movement, the volunteers A, B, and E performed the movement as per the instruction. As for the volunteer C, the HOLD(5kg) shifted to the PRESS(10kg) 2.25 s faster than the instruction. When the control phase of the vertical movement side shifted to the PRESS(10kg) from the HOLD(5kg) for the first time, the control phase of the holding movement shifted to the HOLD(5kg) from the WAIT. For this reason, we could assume that he moved both of his arms as per the instruction for his one arm.

As for the volunteer E, the number of phase shift is one smaller than the number of vertical movement instruction. We could assume that he couldn't react to the first instruction for the PRESS(10kg) because the instruction was performed for a short time. In addition, when the instruction phase shifted from the

PRESS(10kg) to the HOLD(5kg), the control phase didn't shift from the PRESS(10kg) to the HOLD(5kg) once in a while. We could assume that the volunteer E supported the heavy loads while performing the descent of the heavy loads. For these reasons, the developed algorithm voluntarily shifted the control phases by following motor intention of the wearers who perform the vertical movement having a large personal deviation. Thus, the control phase changes by following motor intention of the wearers who perform the compound movement.

The volunteers performed cyclic compound movement in the movement support experiment. The number of the compound movement repetitions of all the volunteers increased with the ULSS. The average number of the compound movement repetitions with the ULSS was 2.0 times significantly-higher than without the ULSS. From the result, the ULSS with the developed algorithm had a supportive effect for the compound movement consist of the static holding movement and the active vertical movement. We could assume that the support torque of the ULSS reduced the joint torque of the volunteers for the compound movement. For this reason, the volunteer could perform the more continuous compound movement.

The developed algorithm changed the control phases by following the motor intention of the wearers, and the ULSS had the effect of support for basic compound movement. Because of that, the ULSS with the algorithm was effective for the continuation of compound movement. When the control phase shifted by following the wearer's movement, the delays of the phase shift were large in the random instruction experiment. The volunteers performed the movement without a problem and had the effect of the support, but there is room for improvement for the delay of the phase shift. It is necessary for the algorithm to develop a function adjusting the threshold values automatically. In the evaluation experiment, the basic compound movement conforming to the installation of ceiling boards was performed. This movement is the one of the most demanding types task in terms of the weight of tools for heavy overhead task. For this reason, we can apply the ULSS with the developed algorithm to other construction sites using lighter tools and materials.

6 Conclusion

In this study, we developed a novel compound movement support algorithm for the ULSS based on the BES to achieve the continuous upward high load works. The developed algorithm achieves the compound movement support by voluntary shifting of the control phase in response to a change of the BES. In the random instruction experiment, the algorithm voluntarily shifted the control phases of the ULSS by following the motor intention of the wearer. In addition, the algorithm had the effect of the support for the basic compound movements, conforming to the actual work. Therefore, we could confirm that the ULSS with the algorithm had effectiveness for the compound movement. In our future work, we will improve the delay of the phase shift. We can expect that the ULSS with the algorithm increases the work efficiency, and improves environment of the actual work sites.

7 Acknowledgment

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Automatic Inspection of Embankment by Crawler-type Mobile Robot

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Abstract –

In this paper, we report a method that a mobile robot operates automatic inspection of embankment. The mobile robot KENAGE, which has been developed by Japan Aerospace Exploration Agency, tows a truck with an inspection instrument and is basically controlled by Robot Operating System. From the result of way point navigation experiment, it is confirmed that the mobile robot is able to go through several way points and to inspect the embankment automatically.

Keywords –

Mobile Robot; Self-localization; Inspection of Embankment; Automatic Inspection

1 Introduction

Construction demand is keeping high not only in modern times but also expected to grow in the future because of reconstruction of buildings and maintenance management of the infrastructures such as bridges and tunnels. However, decrease of the working population in the construction industry is becoming a severe problem especially in America and Japan. For example, in Japan, the population in construction was 3.4 million in 2014 which is estimated to become 2.2 million in 2025. Despite of the population problem, the construction demand is predicted to rise. Therefore, shortages of workers are exceedingly concerned, so young workers on construction are desired.

For the problem about shortages of workers, it is necessary to take measures not only to employ young workers but also to create more efficient construction methods. It is considered that one of the methods is bu introduction of construction robots. The robots which work autonomously or support human workers lead to more efficient constructing. Many researches and developments on the construction robot are in progress. Menendez et al. developed tunnel structural inspection and assessment robot which detects defects of tunnel by using computer vision system and ultrasonic sensor[1]. Cebollada et al. are on research of a robot which sprays foam insulation in underfloor[2]. SAM (Semi-Automated Mason) produced by Construction Robotics company in America which lays bricks faster than human[3]. BIM (Building Information Modeling) will also become one of support technology for automatic constructing robots.

In this paper, we propose the automatic embankment inspection robot system for manpower saving in construction site.

2 Inspection Procedure of Constructed Embankment by using Radio Isotope

Quality of constructed embankment is checked by an instrument using radio isotope in Japan. For developed embankment, density and moisture content is measured at several points by the placing the instrument. A selection method of the measuring points is ruled by MLIT (Ministry of Land, Infrastructure, Transport and Tourism) Japan. The rules are as follows. [4]

1. Embankment is divided into several units. It is necessary that quality is checked and recorded at each unit.
2. It is ruled that unit size is one layer of embankment area constructed for one day. Standard unit size is 1500m2. If embankment area size is over 2000m2 a day, the area is necessary to be divided into 2 units.
3. Each unit is inspected at 15 points in principle and an average of them is calculated and recorded. If embankment area size is smaller than 500m2, At

least 5 points inspection is required.
4. The inspection is executed on the constructed day in principle.
5. If several layers of embankments are constructed in a day, an unit area doesn't cover the layers.
6. When the nature of soil used for filling changes, the area in where the corresponding soil is used becomes another inspection unit.

Fig. 1 Embankment inspection instrument ANDES[5]

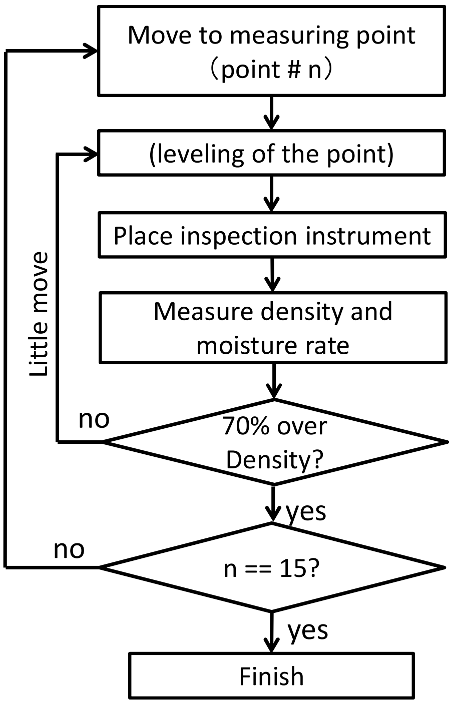

Fig. 2 Embankment inspection procedure

Fig. 1 and Fig. 2 show the instrument of inspection and inspection procedure respectively. The weight of the instrument is 10.5kgw. Additionally, 2kgw steel stick with radiation source is attached. Although the inspection procedure includes calibration before measurement strictly, explanation of the calibration is omitted because of low importance in this paper. Detail of inspection procedure is as follows: density and moisture content are measured 1 time per second at each point and averages of them are recorded. For avoiding defective measurement, the recorded data that shows smaller than 70% density is removed. With changes of measurement points, this procedure is operated 15 times in principle.

3 Hardware of inspection system

3.1 Multi-crawler type Mobile Robot

In this research, we used a multi-crawler type mobile robot which was developed at JAXA (Japan Aerospace Exploration Agency) and called KENAGE[6][7]. Fig. 3 shows overall view of the robot and electric equipment. Specification is shown in Table 1. The robot has four crawlers and eight passive links structure. By utilizing this structure, the robot is able to climb over an about 450mm wall and a slope of 45 degrees. Because of the ability, we considered that the mobile robot is useful in construction site.

Additionally, the mobile robot equips with 2 dimensional LIDAR, GNSS module and IMU (inertial measurement unit) as sensors for self-localization.

3.2 Towing truck with inspection instrument

For accomplishing unmanned inspection, the mobile robot equipped with embankment inspection instrument goes around the measuring points and inspects at each point automatically. To carry the instrument, a towing truck is developed.

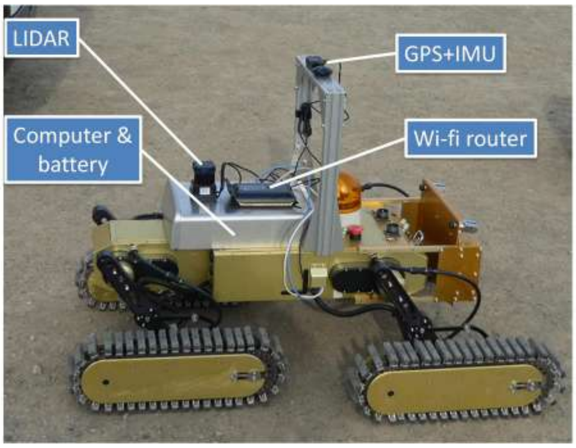

Fig. 3 Multi-crawler type mobile robot KENAGE

Table 1 specification of the mobile robot

External dimensions	1115L x 780W x 250H
weight	45kg
equipment	4 crawlers
Power source	Li-ion battery(54V/6Ah)
sensors	GNSS, IMU and LIDAR

Fig. 5 Mobile robot and developed towing truck

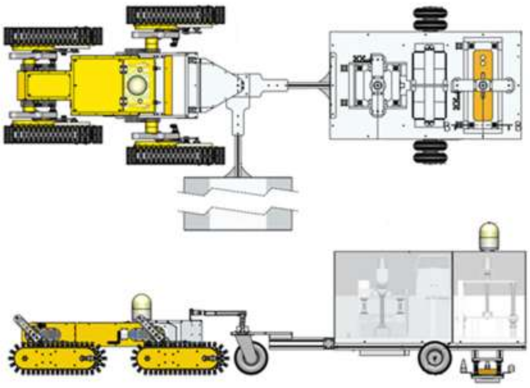

Fig. 4 Top and Side view of towing truck

Fig. 4 shows top and side view of robot and towing truck CAD images. Fig. 5 shows overall system picture which captured on construction site. The inspection instruction is equipped in the truck. A micro-controller is also placed. By sending signal from the micro-controller, the instrument goes up and down. When measuring density and moisture content of embankment, the instrument goes down and is placed on the ground. After finishing the measurement, the instrument goes up and the robot moves to next point. Furthermore the battery for the truck and the mobile robot is equipped inside the truck. The towing truck is connected by link joint, so the truck follows the robot same as a trailer.

4 Autonomous mobile system

The mobile robot is necessary to move automatically for the unmanned inspection. To achieve it, the autonomous mobile system is required, which consists of self-localization, path planning and obstacle avoidance. For applying the developed system on the construction site in a short period, we used ROS (Robot Operating System) for robot control in this research[8].

4.1 Control program structure

Program packages for robot control are provided by ROS. Combination of several packages leads rapid prototyping of robot control system. In this research, we used mainly two packages called robot localization package and navigation stack. Connections and data flow of each function are shown in Fig. 6.

Datum from GPS and IMU modules are inputted to robot localization package and self-localization is calculated by using them. The obtained self-localization data is lead to local planner which is a part of navigation stack. The role of navigation stack is path planning and trajectory generation. Global planner and local planner generate rough trajectory to an inputted goal and short term trajectory to be on the rough one respectively.

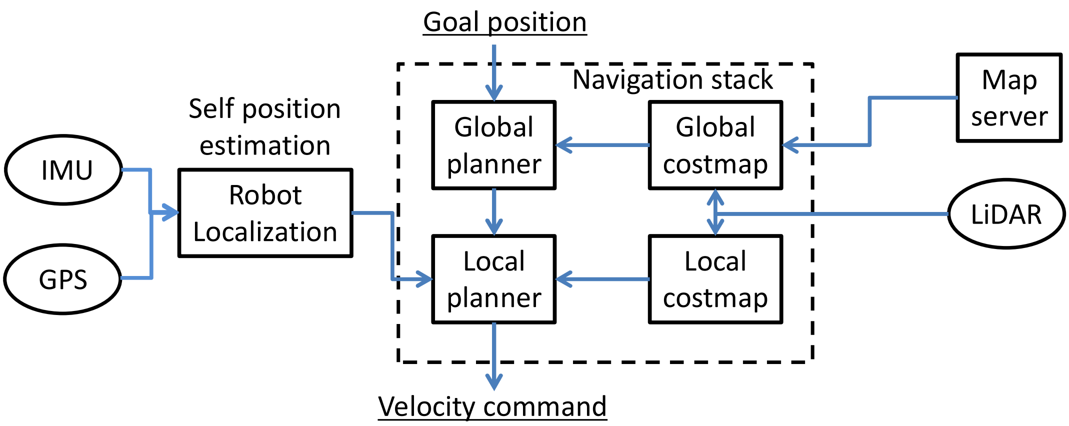

Fig. 6 Connections and data flow of each function

Inputs of global planner are the goal point data and costmap data. In local planner, difference between predict position in only navigation stack and estimated self-localization data from localization package is calculated and local trajectory is corrected.

On the other hand, LIDAR data and static map information which is set in advance make global costmap. Although the static map is usually used for showing floor plan of buildings, it is used for assigning entry permitted area in this research. It depicts in right side of Fig. 4. In contrast, local costmap only uses LIDAR data. When an obstacle appears on the planned trajectory, costmap is updated and obstacle avoiding trajectory is generated. Finally, navigation stack outputs velocity command of the robot and the command is sent to motor drivers hardware.

In this research, the goal information as input data to navigation stack corresponds measuring point, so after arriving the goal the mobile robot starts to measure density and moisture content of terrain. As mentioned before, there are 15 measuring points, so the robot begins to move next point after finishing the each measurement.

4.2 Evaluation of automatic driving of robot

For evaluating the developed system, we tested how accurate the robot moved on planned path to consist of several way points. The way points are supposed to be the measuring points in the construction site. The evaluation procedure is as follows.

7. Assign several points by mouse clicking on Google map.
8. Input the assigned points to the computer of the mobile robot
9. Start the robot to move to first way point
10. After arriving first way point, set the second way point as a next goal and the robot aims there
11. Repeat #4 several times

As supplemental information, the ROS program judges arrival at the goal when the robot completes travelling in a circle of goes into a 2 meter in diameter with the center as the way point. An Experimental field is selected to be outdoor environment for receiving GNSS signal. The size of the experimental field is about 50m by 50m square. The 7 way points are set in the field so as to form hexagonal shape based on the above procedure. For checking whether or not the robot goes out of entry permitted area, only one way point is set outside of the experimental area. Fig. 7 shows trimmed captured screen image when way points are setting.

4.3 Experimental result

Fig.8 shows the result of automatic moving experiment. Star marks represent assigned way points and continuous line shows connected GNSS signals.

As a rough analysis, the mobile robot went through assigned way points. However there is an error of several meters. It is considered that the reason of the error caused by the accuracy of the GNSS signal and judging requirement of arriving which is to go into the 2m diameter circle.

Concerning about the evaluation that the robot didn't go out of permitted area, the robot canceled corresponding point and aimed to next way point.

Fig. 7 Captured screen image when setting way points

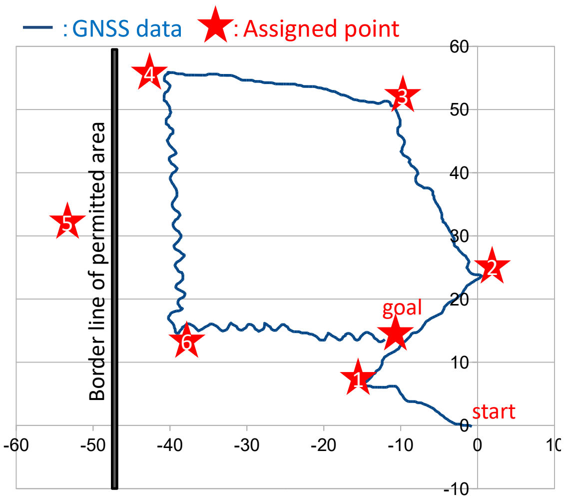

Fig. 8 Obtained self-localization data

Therefore the global planner functions performed correctly. A part of the continuous line is seen to have wave form. Posture measurement of IMU sensor seems to have an error on the way of moving, so it is required to prepare a more accurate posture sensor.

4.4 Evaluation of automatic inspection of embankment

Based on the inspection procedure mentioned in section 2, we evaluated automatic inspection of embankment. A procedure of inspection by using autonomous mobile robot is as follows.

1. GNSS coordinates data of 15 measuring points are acquired in advance
2. Input the coordinates data to the mobile robot
3. The mobile robot tows truck and aims to the measuring point
4. After arrival, the mobile robot takes down the instrument, places on the ground and starts to measure
5. After finishing measurement, the instrument is lifted up and the mobile robot start to move to the next point
6. Back to iv and repeat procedure

According to the above procedure, the automatic inspection was evaluated. The size of the experimental field was about 30 meter by 200 meter. The 15 measuring points were assigned at an interval of 10 meter. Same as experiment at section 4, the mobile robot judged arrival to the goal when the robot traveled into a 2 meter diameter circle of which center was the measuring point. Just after placing the instruments, the robot waited 1 minute for measurement.

Fig. 9 shows a picture of the experiment. X mark in Fig. 9 represents the measuring point. Furthermore the inspection instrument is seen to be taken down from bottom of the towing truck and placed on the ground. Table 2 shows the density and moisture content derived from the experiment. The data represents the average of 15 times measurement and includes standard existing method and automatic inspection method which is proposed in this paper. The results are much the same and 2% difference of measured value which is less than measurement error. This result proves that the proposed automatic inspection is feasible.

5 Conclusion

In this paper, we propose the automatic inspection of embankment system which consists of the crawler-type mobile robot and towing truck. The mobile robot goes through several way point as measuring point. The evaluation experiment indicates that the robot accurately goes on the planned trajectory. Furthermore through the other experiment, we show automatic placing of the instrument and measurement work fine for the reason that the measured value is within the measurement error. As a future work, we will make the system practicable.

Fig. 9 Field test of inspection

Table 2 comparison of density and moisture content

Inspection method	Automatic	Existing standard	Difference
Density(g/cm^3)	2.192	2.242	0.05
Moisture content (%)	7.0	6.9	-0.1

Acknowledgement

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Integration of Imaging and Simulation for Earthmoving Productivity Analysis

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Abstract –

Earthwork productivity varies depending on a unique geologic condition, types of earthwork equipment, and an equipment allocation plan. For this reason, it is difficult to accurately estimate the productivity of an earthwork. To address this issue, this paper develops an imaging-to-simulation method in which a real jobsite data is automatically collected and used for analyzing the earthwork productivity. Object existence and its location in image data are identified by convolutional networks, and they are used to infer the earthwork context. The context information is transformed into the simulation input by the context reasoning processes. A productivity report is produced by using the WebCYCLONE simulation. The developed method was tested in a tunnel construction site, providing a new equipment allocation plan, which minimize the cost and time compared with the original plan.

Keywords –

Productivity Analysis, Vision-Based Monitoring, Simulation, Earthmoving, Context Reasoning

1 Introduction

Since earthwork in construction involves various types of construction equipment, establishing the optimal equipment allocation plan is a primary concern of site managers. Construction process simulation can be used to generate a productivity report to a given earthwork plan, thereby enabling comparison among different earthwork plans [1,2]. However, even with the simulation results, the optimal plan is not easily established due to a unique geologic characteristic and dynamic working conditions in jobsite. These issues cause the simulation input to deviate from the real jobsite working status. As a result, the reliability of the productivity report is degraded, because a small deviation of the simulation input significantly affects the simulation results. Previous studies proposed vision-based productivity analysis methods, which provides the cycle time of earthmoving [3-5] or concrete pouring operations [6]. Ham, et al. [7] presented an imaging-to-simulation framework to detect hazards related to strong winds. However, integration of construction simulation and vision-based monitoring for productivity analysis has not yet been proposed.

To address these issues, this study proposes an imaging and simulation integrated method to analyze an earthmoving process productivity, as shown in Figure 1. This method automates the process of jobsite data collection for productivity analysis, thereby improving the reliability of the simulation results. An earthmoving process in a tunnel construction site was selected for validating the proposed method. The initial idea of this study was presented in [8].

2 Vision-based context reasoning

A tunnel site, construction under the new Austrian tunneling method (NATM), was selected to apply the proposed method. In the tunnel construction site, the amount of muck produced daily was 680 m^3, and a closed-circuit television (CCTV) was installed at an elevated position to monitor muck-loading tasks by a single excavator and seven dump trucks. The maximum amount of muck that can be stored in the temporary

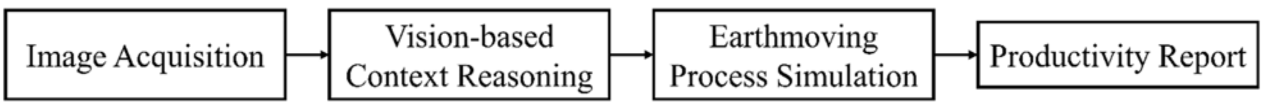

Figure 1. Overview of the proposed method

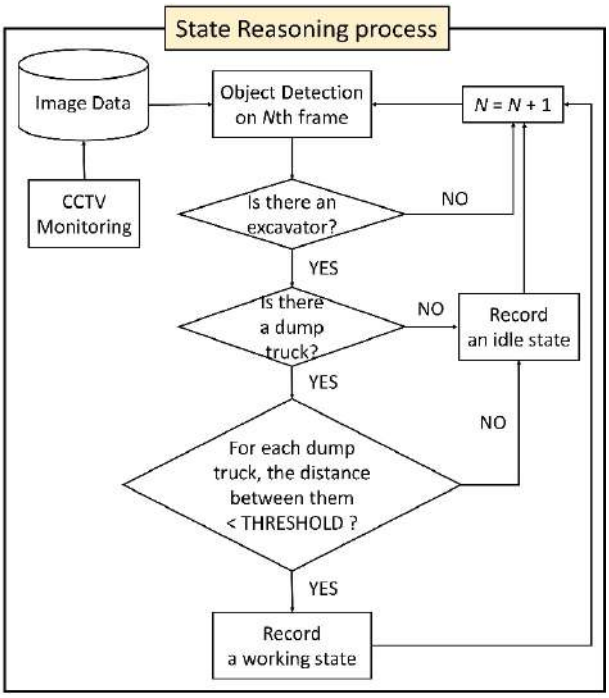

Figure 2. State reasoning process

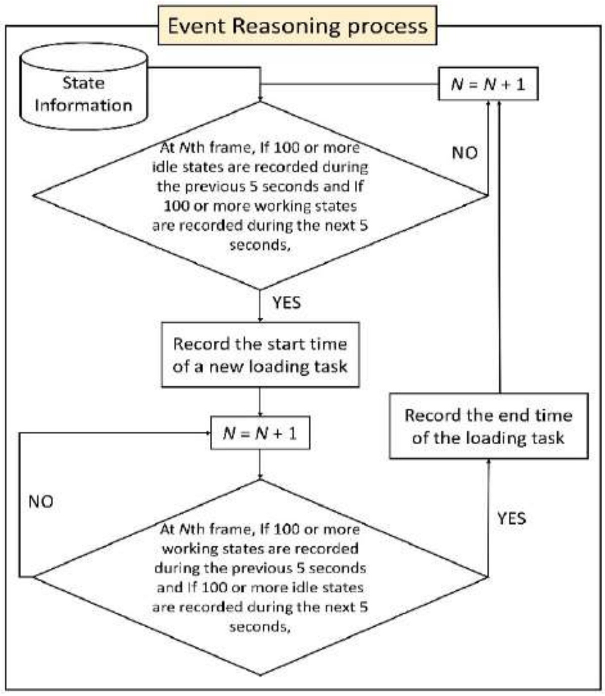

Figure 3. Event reasoning process

disposal area was 1,500 m^3. To detect the target objects in tunnel CCTV image data, a region-based fully convolutional networks (R-FCN) proposed by Dai, et al. [9] is utilized. Using R-FCN, construction equipment such excavators and dump trucks can be detected with the high accuracy at a short processing time [10]. R-FCN comprises three main modules for object detection, which are the feature extraction layers, region proposal network, and the position-sensitive score maps for determining the object class and location in image data. Refer to Dai, et al. [9]'s work for details.

For producing the simulation input, object class and location information from image data can be converted into the context information [3-6]. The context information includes the state and event information. The state information denotes a working or idle state of an excavator and dump trucks in regard to loading or hauling tasks. Figure 2 illustrates the state reasoning process. The event information denotes the time to complete a single loading or hauling task. It records the start and end time of a loading task, following the process illustrated in Figure 3. The start and end time of a hauling task is recorded by the site access information of a dump truck.

2.1 Earthmoving Process Simulation using WebCYCLONE

For the construction process simulation using the WebCYCLONE [11], the earthmoving process should be modelled as a form of discrete event elements used in WebCYCLONE such as NORMAL, COMBI, Q NODE, and ARROW. The target earthmoving process includes eight elements, which are "Loading", "Excavator Idle", "Hauling", "Loaded Truck Queue", "Dump", "Dump Spotter Idle", "Return", and "Dump Queue". The elements constitute the earthmoving process structure, representing loading and hauling cycles of an excavator and dump trucks.

3 Experiments and Results

The proposed method was performed on the Intel i7-6700 CPU and the GTX1080 8GB GPU with the Ubuntu 16.04 operating system. The R-FCN model [9] pretrained with the ImageNet data was re-trained using the AIMdataset [10] and the tunnel image data. The length of the tunnel video for the test was 8 h 11 m. The video resolution was 720 × 480. To evaluate R-FCN for object detection, the evaluation criterion of the PASCAL VOC [12] was used. The experimental results of object detection and vision-based context reasoning are shown in Table 1. R-FCN trained with the AIMdataset and the tunnel image data recorded the mean average precision (mAP) of 99.09% for detecting an excavator and dump trucks. The samples of the detection results are shown in Figure 4. The errors of the context reasoning processes were 0%, 1.6%, and 0.12% for estimating the number of task cycles, average duration of loading tasks, and average duration of hauling tasks, respectively.

Figure 2. Samples of the detection results

Table 1 Performance of equipment detection and vision-based context reasoning

Detection performance (mAP)		99.09%
Error rates of context reasoning	Number of task cycles	0%
	duration average of loading tasks	1.60%
	duration average of hauling tasks	0.12%

Table 2 Productivity report

Daily muck output	680m^3
Capacity of disposal storage area	1500m^3
Current resource allocation	1 excavator, 7 dump trucks
Current productivity	100.88 m^3/hour
Current unit cost	5.59 $/m3
Optimal resource allocation	1 excavator, 10 dump trucks
Optimal productivity	141.78 m^3/hour
Optimal unit cost	5.45 $/m^3
Cost savings (for 600 days)	$310,858

To validate the simulation model, the simulation result was compared to the actual earthmoving process. The deviation of the total working time between the actual earthmoving process and the simulation result was only 2.23% for the 44 task cycles, confirming that the simulation model was correctly modelled as the actual earthmoving process. The productivity report indicates that the current earthmoving process can be improved by changing the number of dump trucks to 10 from 7, as shown in Table 2. The equipment operation costs are $523.33 and $566.94 for each dump truck and excavator, respectively. The payload of a dump truck was 17m^3. With the new equipment allocation plan, the idle time of the excavator can be reduced to 21.12% from 43.97%. Moreover, the total earthmoving cost can be saved by $310,858 (12.25%) for 384 working days of earthmoving in the NATM process of 600 days.

4 Conclusion

This study presents an imaging and simulation integrated method for analyzing the earthwork productivity based on the actual jobsite data. Image data was process by R-FCN to identify the location and class of a target object. The context information was automatically interpreted by the context reasoning processes. By using the actual construction site data, the reliability of the construction process simulation results was enhanced. Integration of imaging and simulation enables rapid generation of a productivity report under changing geologic conditions. This capability allows site managers to optimize the resource allocation for the current geologic condition. Currently, the proposed model is suitable for analyzing a single earthmoving process. The developed model should be further improved to analyze a complex interaction among various jobsite work processes as well as the earthmoving process.

Acknowledgments

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Applying BIM and visualization techniques to support construction quality management for soil and water conservation construction projects

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Abstract –

Constructing soil and water conservation (SWC) facilities is crucial to protect soil and water resources, maintain natural ecology and landscape, and prevent erosion, landslide, debris flow, and other disasters. Due to the existence of mountainous terrain in Taiwan and the frequent prevalence of extreme climate changes, thousands of SWC construction projects are built or renovated all over the island in each year. The responsible central governmental entity (home bureau) in Taiwan continuously seek for solutions to improve their current database management system which collects only numbers, texts, and two-dimensional photos to monitor the construction progresses of these projects. This study applies the building information model (BIM), augmented reality (AR) and virtual reality (VR) to develop a new construction management system that can visualize each construction project on a three-dimensional model and access the project information promptly in a cloud environment to support both home bureau and local bureau (the actual project owner). The proposed system is applied to a case project to demonstrate its benefits in supporting construction quality management. The application results suggest that the governmental bureau should provide sufficient incentives to encourage those middle- or small-size designers and contractors to apply the proposed system to the SWC construction projects.

Keywords –

Soil and water conservation construction projects; building information model; augmented reality; virtual reality; construction quality management

1 Introduction

Soil and water conservation (SWC) facilities are used to protect soil and water resources, maintain natural ecology and landscape, and prevent erosion, landslide, debris flow, and other disasters [1]. Due to the existence of mountainous terrain in Taiwan and the frequent prevalence of extreme climate changes, thousands of SWC construction projects are continuously built all over the island in each year.

From the government's viewpoint, the management of each SWC construction project can be classified into two parts, including the one from the branch bureau and the other from the home bureau (that is, the Soil and Water Conservation Bureau, Council of Agriculture, Taiwan). While the branch bureau is the project client in managing the construction project, the home bureau is responsible for monitoring the progresses of all construction projects in an integrated manner.

Currently, both branch and home bureau uses a database management system to collect project data that are in a form of texts, numbers, and a few jobsite photos (and even without drawings) to describe the construction progress and site conditions of each project. That is, the current system has a weakness in helping engineers to visualize a project. Consequently, the governmental engineers must frequently visit the jobsites (with eyes) to get familiar with the projects so that they can manage them accurately on quality, safety and schedule control. Without in-depth understanding about those projects, the bureau engineers would have little sense of the project conditions (in terms of construction quality and safety, for example) and may pay wrong attention to the projects with high vulnerability to an in-coming disaster (e.g., typhoon).

Moreover, these SWC construction projects are often located in mountains or at the places where transportation is not convenient. Hence, engineers would need to carry heavy hardcopies of design drawings and specifications to find project data to support their quality and safety inspections in the construction jobsite.

Enhancing the visualization ability on the SWC construction projects and improving the efficiency in retrieving project data have been identified by both home- and local-bureau engineers as a solution to reduce extensive engineer's laborious work and improve the management of these construction projects. This study proposes to apply the building information model (BIM), augmented reality (AR) and virtual reality (VR) to develop a new construction management system that can visualize each construction project on a three-dimensional (3D) model and access the project information promptly in a cloud environment.

2 Literature review

2.1 Soil and water conservation construction projects

A soil and water conservation (SWC) construction project is related to civil engineering, hydraulic engineering, agronomic/planting engineering; and, it usually exists in slope areas. Additionally, the treatment work of torrent, river, and landslide is the main work scope of SWC construction project [2].

According to the SWC design handbook [3], the major SWC facilities include: sediment storage dam (check dam), slit dam (comb dam), groundsill works, and revetment. Their usages are described as follows:

1. Sediment storage dam (check dam): A check dam helps reduce channel velocity, prevent erosion, and trap small amounts of sediment by intercepting flow along a channel. See Figure 1 for example.
2. Slit dam (comb dam): Depending partly on the spacing of the posts, the slit dam can keep larger clasts (cobbles and boulders) behind the dam, thus preventing damage downstream [4]. See Figure 2 for example.
3. Groundsill works: A groundsill work is constructed across the waterway to prevent riverbed degradation. See Figure 3 for example.
4. Revetment: Revetment are sloping structures placed on the banks of a river in such a way as to absorb the energy of incoming water. See Figure 4 for example.

Figure 1. Concrete gravity dam

Figure 2. Slit dam

Figure 3. Groundsill works

Figure 4. Revetment

2.2 BIM applications in Civil Engineering

BIM has been mostly used in building projects. Only very few BIM applications are in Civil Engineering. For example, considering that BIM remains a relatively underutilized tool in horizontal construction, Fanning, et al. [5] implemented BIM on bridge construction projects. In their study, BIM may have provided approximately 5–9% cost savings during construction by contributing to reduced change orders and rework. Additional and potentially significantly greater benefits may be realized through future BIM-enabled operation and maintenance of such infrastructure.

2.3 Augmented reality (AR) and BIM

Augmented reality (AR) and Virtual reality (VR) and are two categories of visualization techniques. AR preserves the user's awareness of the real environment by integrating the real world and the virtual contents in a mixed 3D space, while VR replaces the user's physical world with a totally synthetic environment and isolates the user's sensory receptors from the real physical world [6].

There are two types of simple augmented reality: marker-based which uses cameras and visual cues, and marker less which use positional data such as a mobile's GPS and compass [7].

Wang et al. [8] provided examples how BIM and AR can be integrated and used on site. In general, AR can visualize as-planned BIM facility information right in real-world jobsite to enable project participants to review the as-built progress against as-planned.

2.4 Virtual reality (VR) and BIM

Visualization can improve a user's cognition and help communication in discussing an abstract concept or physical object to real-world situations. Virtual reality (VR) is an immersive multimedia technology that uses VR headsets to create realistic images, sounds and other sensations to simulate a user's physical presence in a virtual environment and interact with digital objects in real time.

As indicated by Du et al. [9], most VR applications in design and construction problems must start with an established design deliverable in a form of CAD or BIM. Considering that there is a lack of automated data transfer approach between BIM and VR, Du et al. [9] proposed a BIM-VR real-time synchronization system to update BIM model changes in VR headsets automatically and simultaneously.

3 Proposed system

The proposed system aims to integrate BIM, AR and VR to provide 3D visualization and information accessibility to facilitate the branch- and home-bureau engineers in managing SWC construction projects. Additionally, the proposed system is operated in a mobile device and cloud environment.

Figure 5 presents the framework of the proposed system which consists of four parts: (1) developing SWC facility BIM model and terrain BIM model, (2) integrating BIM and AR, (3) integrating BIM and VR, and (4) developing construction management modules (including quality and safety management modules).

3.1 Developing SWC facility BIM model and terrain BIM model

Executing a SWC construction project consists of the construction of main SWC facilities (such as check dams, slit dams and ground sills) and other appurtenant construction work (such as drainage facilities) which are all located in the jobsite. Thus, a complete BIM model for SWC construction project preferably integrates both SWC facility BIM model and terrain BIM model. This study applies the Autodesk Revit software package to build the BIM model for the SWC facilities (such as slit dams and ground sills). The level of development (LOD) of this BIM model is LOD 300 [10]. That is, each BIM model element (such as slit dam, groundsill work, and revetment) of SWC facility is graphically represented in terms of quantity, size, shape, location, and orientation. Additionally, non-graphic information (such as specifications and unit prices) can be also attached to each element.

In developing a terrain BIM model is comparatively complex. This study uses the digital surface model (DSM) (representing the earth's surface in which the construction project is located) to build a terrain BIM model. To do so, this study write a series of matlab equations to support the transfer of the DSM data (representing the coordinates and elevation for each location point) which are in ASCII format to the data which are in comma separated values (CSV) format. Such a CSV format file can then be read by Revit for producing a terrain BIM model [11].

3.2 Integrating BIM and AR

This study uses a AR model to interconnect to corresponding segmented BIM model and associated information (e.g., design dimensions, quality specifications, etc) of each part (e.g., could be the part of comb dam, groundsill work, etc) of the SWC construction project. Then, the jobsite engineers can scan the AR makers (related to particular AR models) by mobile devices to visualize the 3D design objects and retrieve required information.

The above integration is carried out by the following three steps: Step 1 transfers the BIM model in .fbx format so that Autodesk 3Ds Max software can read and render. Step 2 builds the AR model by Unity 3D software and developing the relationships between the AR makers the corresponding segmented BIM model. Step 3 uses Unity 3D to attach information to the AR model and save in .apk file format so that a mobile device can read the AR model.

For reading AR model from mobile device, the camera lenses of the mobile device will catch the AR markers' 2D image, and then interpret the marker detection to create the AR model.

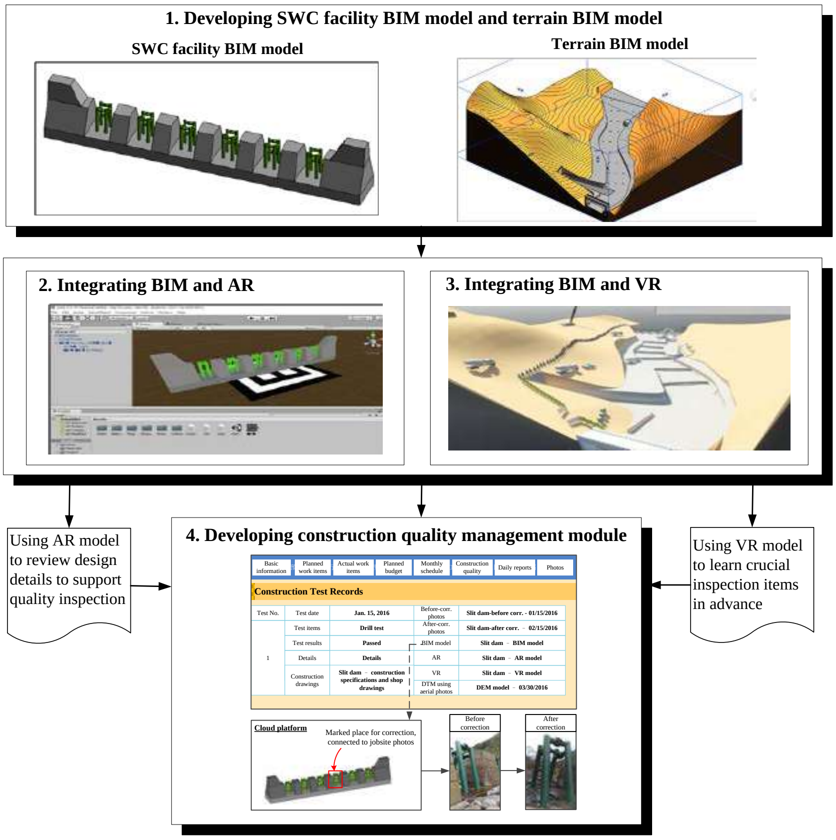

Figure 5. Framework of the proposed system

3.3 Integrating BIM and VR

The proposed system applies a 3D rendering engine called "Enscape" which can be plugged in Revit. Integrating BIM and VR is conducted by the following three steps: Step 1 is to open Revit which has possessed the Enscape functions. Step 2 activates Revit's Enscape function to transfer the BIM model into VR model. Step 3 is to view the VR model from computer screen or VR glasses.

3.4 Quality management module

The current system collects the quality management data of the "sampling inspection records" (including data of inspection date, sampling items, and results) and "quality audit records" (including data of audit date, performance score, A/E defects, and contractor defects). All these data are numbers and texts.

By integrating the current database system with the AR, VR and BIM, the proposed quality management module provides the following five functions (Q1~Q5) in supporting construction quality management: (1) using BIM model to review the quality correction results, (2) accessing information readily, (3) using AR to review design details to support quality inspection, and (4) using VR to learn crucial inspection items in advance.

4 Case study

The proposed system is applied to a case project located in Northern Taiwan. This project consists of the following main SWC facilities: a set of steel-pipe-type slit dam, six sets of arc-shape drop structure, 1,100 meter of revetments, and 1,385 square meters of masonry boulders. The contractual duration and price of the project are 300 calendar days and around US $1,248,000 US dollars (37,450,000 NT dollars), respectively. Figure 6 displays the bird view of the jobsite and Fig. 7 shows the steel-pipe-type slit dam of this project.

Notably, this case study is the after-the-fact analysis to demonstrate the feasibility of the proposed model.

Figure 6. Bird's view of case project

Figure 7. Steel-pipe-type slit dam of the case project

4.1 Developing SWC facility BIM model and terrain BIM model

4.1.1 Developing SWC facility BIM model

A complete BIM model integrates two BIM models of SWC facilities the terrain. Four steps are conducted to develop the SWC facilities BIM model. The following uses the steel-pipe-type slit dam for example.

1. Step 1: developing slit dam (or comb dam) templates. Drawing a plane section to be a template for representing the cross section of slit dam, as shown in the left of Fig. 8.
2. Step 2: defining parameters to describe slit dam. In the template, parameters, such as the height, the width on the top, the width on the bottom, the width of anti-sliding tenon, and so on (as displayed in the right of Fig. 8), and used to depict the slit dam. Thus, a user can develop a BIM object of slit dam by simply specifying the scale numbers of those parameters and the length of the slit dam.
3. Step 3: developing BIM objects of the steel pipes. That is, repeating Step 1 and 2 can build the steel-pipe templates and define parameters to depict the steel pipe.
4. Step 4: integrating the slit dam BIM objects and steel pipe BIM objects to generate the steel-pipe-type slit dam, as shown in Fig. 9.

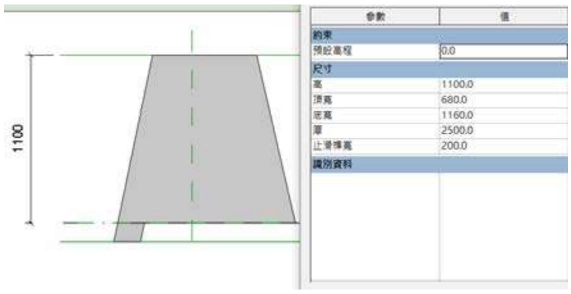

Figure 8. Using parameters to define the slit dams

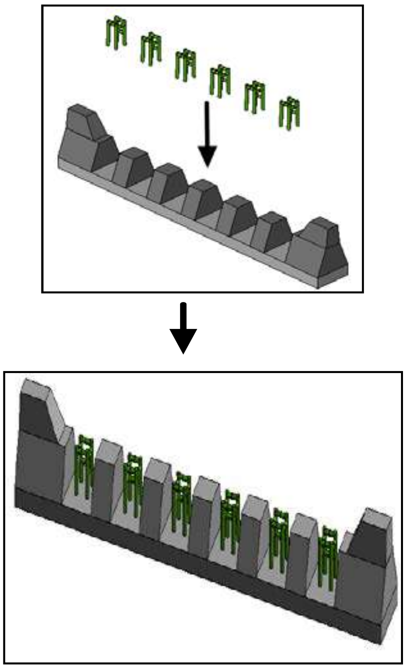

Figure 9. BIM objects of the steel-pipe-type slit dam

4.1.2 Developing terrain BIM model

Then, according to the steps described in Section 3.1, the proposed system generates a BIM model of the terrain in which the case project is located. Figure 10 presents the complete BIM model integrated with SWC facilities and terrain for the case project.

Notably, while each the SWC facility (such as slit dam and ground sill) can contain its geological information or data (such as design dimensions and construction specifications), the terrain can also carry with relevant information or data (such as the governmental regulations of the terrain, and the information of ecological sensitive areas)

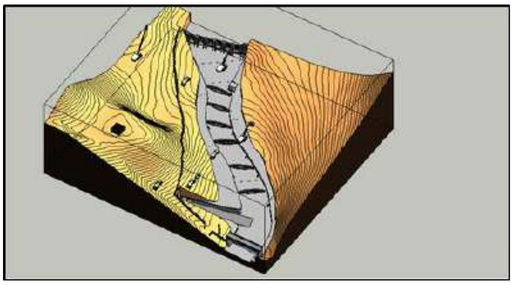

Figure 10. Complete BIM model integrated with SWC facilities and terrain for the case project

4.2 Integrating BIM and AR

After the proposed system develops the BIM model of both SWC facilities and terrain, the system follows the steps described in Section 3.2 to integrate the BIM model and AR for the case project. Figure 11 shows the BIM model that is read by Autodesk 3Ds Max software (Step 1 in Section 3.2). Figure 12 presents the screenshot of the AR model for the jobsite overview of case project.

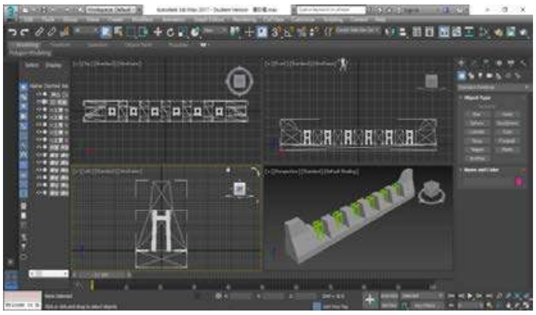

Figure 11. BIM model imported into 3Ds Max

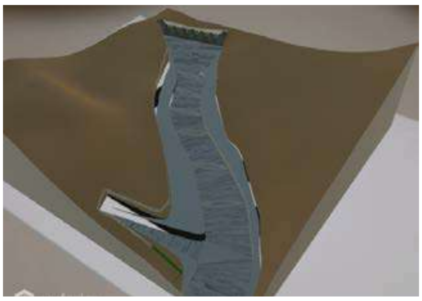

Figure 12. AR screenshot of the jobsite overview

4.3 Integrating BIM and VR

The proposed system applies a 3D rendering engine called "Enscape" which can plug in Revit. That is, the system uses Enscape to transfer the established BIM model to VR model. Figure 13 presents the VR screenshots of the jobsite overview, construction fence, and falsework of the case project, respectively.

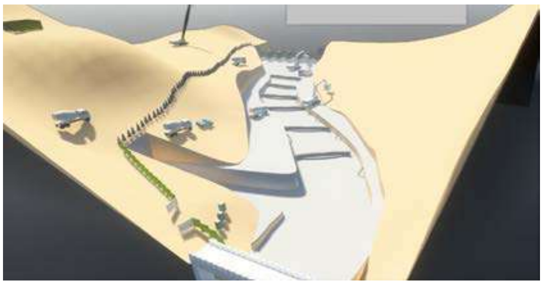

Figure 13. VR screenshot of the jobsite overview

4.4 Construction quality management module

Based on the integrated BIM model, AR model, and VR model, the construction quality management modules can support the following quality control activities:

1. Using the BIM model to support review the quality correction results. This can be carried out by evaluating the quality-correction photos, specifications, quality inspection/testing records which are retrieved from to the BIM model. See Figure 14 for example.
2. Accessing quality information readily. An engineer can visualize the 3D model and view/download project documents in the cloud device or in mobile devices for supporting communications.
3. Using AR model to review design details to support quality inspection: An AR model provide both 3D visualization and design information by scanning an AR maker for comparing the planned and actual conditions for a particular construction object in the jobsite. See Figure 15 for example. An AR model can be applied especially in the suburbs where a SWC construction project is usually located and internet is not available. This is because an AR maker represents a particular AR model which corresponds to a specified portion of BIM model and associated information (see Section 3.2). Hence, a mobile device can activate each AR model by scanning the AR marker without the need of internet.

Using VR model to learn crucial inspection items in advance: Before conducting field quality inspections, a VR model with 3D and information can be walked through freely in the office to get acquainted with the construction project and learn the crucial inspection items in advance. Such a walk though with marked notes can also be recorded in a file for educating young engineers. A recorded VR file can be viewed from a mobile device in the jobsite. Figure 16 displays the snapshot using VR for the case project.

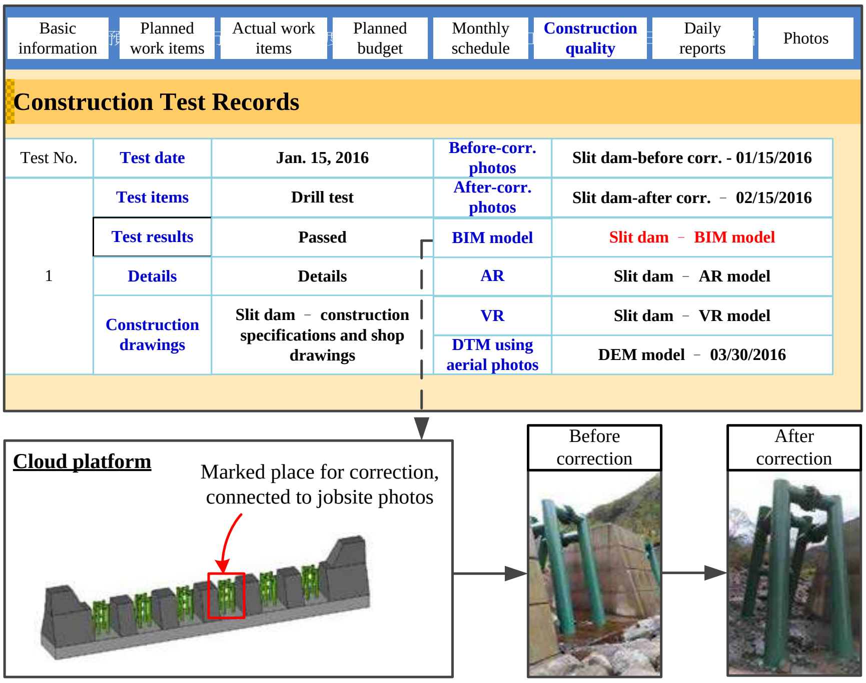

Figure 14. Using BIM model to support review the quality correction results

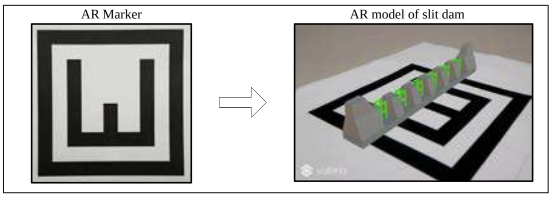

Figure 15. Using AR to review design details to support quality inspection in the field

Figure 16. Using VR to learn crucial inspection items in advance

5 Discussions

During the course of this study, several governmental engineers are appreciated of the proposed system's benefits in providing 3D visualization and easy information accessibility to support construction quality and safety management of the SWC construction projects. However, several difficulties of future implementation of the system are also raised. Their feedback can be summarized as follows:

First of all, insufficient budget available to perform new technologies for each contractor and designer is an obstacle to implement the proposed system. According to 839 SWC projects performed during 2014 and 2016 in Taiwan, the average contractual cost of each project is only about US$200,000, which is relatively small comparing with building projects. Assuming that 0.5% of averaged construction costs is budgeted for adopting these new technologies mentioned here, only US$1,000 (=200,000x0.5%) is available, which is mission impossible. Hence, additional budgets must be provided to support contractors and designers.

Secondly, insufficient capability to conduct new technologies is another obstacle herein. As can be found, most designers and contractors involving in these small-scale projects are often from small- or middle-size firms and are unacquainted with BIM, AR and VR. Thus, training those designers and contractors for using these new technologies is needed. Listing the capabilities of using these new technologies as one pre-qualification for bidding could be a solution for overcome the obstacle here.

6 Conclusion

This study applies BIM, AR and VR to develop a new construction management system to support the government bureaus in managing numerous SWC construction projects. The proposed system built in a cloud environment provides 3D visualization model and access project information from mobile devices.

The case-study results are appealing. However, additional budgets and training must be provided to encourage those middle- or small-size designers and contractors for adopting the proposed model.

Besides the future research directions discussed in Section 5, additional future research may include applying the proposed system to the maintenance/ operation project phase. Although this study focuses on the applications of construction phase, the proposed model should have greater benefits in the maintenance/ operation project phase. For instance, Moreover, the graphic and non-graphic information provided by the proposed model (integrating BIM, AR, and VR) may be useful for government officers in evaluating the conditions of SWC facilities after the occurrence of natural disasters (such as earthquakes or floods).

Acknowledgments

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Embodied Energy Assessment of Building Structural Systems Using Building Information Modeling

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Abstract

Buildings contribute to socio-economic development of the human societies, but they are also among the main consumers of energy and contributors to the greenhouse gas emissions during their lifecycles. The construction phase of building projects is typically recognized for substantial use of natural resources and energy consumption. Steel, reinforced concrete, and engineered wood are the most common structural materials used in the Canadian construction industry. The environmental impact of the structural material is typically overlooked mainly because the industry lacks a documented assessment framework. There were some research efforts that studied energy consumption of the construction phase of building projects, but they mostly used a large number of complex calculations to estimate the consumed energy and emission. This paper introduces an innovative framework for the environmental assessment of the construction of building structural systems. This method uses a building information modelling platform to automate data extraction and then links them to certain databases to calculate embodied energy and emissions. This framework considers production, transportation, wastage, and installation/construction processes to calculate the impacts. An experimental study was carried out on two residential buildings, with a similar layout but different structural systems, to evaluate the practical use of this framework. It demonstrated a straightforward method to estimate embodied energy and emission of the structural system using the BIM model of the design. Similar to other studies, the manufacturing phase has the greatest impact on the embodied energy and emission of a building structure.

Keywords –

Embodied energy; Embodied carbon; Building information modelling; Structural system

1 Introduction

Buildings use energy either directly in the construction, operation, maintenance, renovation, and final demolition, or indirectly in the initial production of the construction materials, consumables, and other embodied energies [1]. Operational energy (OE) and embodied energy (EE) are the two types of energy consumption in buildings, where the embodied energy includes the energy used in extraction, manufacturing, transportation, and construction of building elements, and the operational energy covers with range of energy types used for operation of a building (e.g. lighting, and heating and cooling). It is estimated that the direct energy used in buildings is about 30%-40% of all primary energy, which results in 40%-50% of total GHG emissions [2].

Although operational energy constitutes 80%-90% of the total energy consumption of a building in its lifecycle [3], the embodied energy of the construction phase still can have a considerable environmental impact. Structural system is estimated to have the largest portion (more than 50%) of the total embodied impact of a building [4-5]. Several selection criteria, such as cost, speed of construction, mechanical performance, and availability of the material are usually considered to choose a certain structural system; however, the environmental impact is usually ignored [6].

A number of studies investigated the embodied energy and embodied carbon while using different structural materials and systems. The scopes and viewpoints of these studies, however, were different. A research stream assessed the impact of different structural materials and systems through the entire lifecycle of buildings using lifecycle assessment (LCA) framework. They commonly reported that the energy use in the operation phase has the greatest portion [7-8]. Another group of research efforts focused on the embodied impacts of different structural systems in the construction stage. The embodied carbon (EC) of the structure can vary by up to 18% in different subclasses of steel- and concrete-framed structures with different number of floors [6]. The finding of case studies in Italy

[9] and Iran [10] revealed that the embodied energy of the steel-framed buildings is usually greater than the reinforced-framed structures. Application of high-strength concrete instead of regular concrete could also reduce energy consumption and CO_2 emission in the construction phase [11]. There was, however, a research study that showed similar embodied carbon levels in three steel and concrete-framed buildings (about 200kg CO_2/m²), and it was argued that the embodied carbon of the medium rise buildings with regular geometry and no basement is around this value. There are, however, opportunities to reduce the embodied impact through careful modifications [4]. Moreover, embodied energy of particular structural elements such as slabs [12] and beams [13] were investigated.

Although most of these studies reported a lower total embodied energy for concrete-framed buildings compared to the steel structures, on-site construction of cast-in-place concrete requires greater on-site equipment and labor efforts, which in turn results in larger amount of on-site energy consumption and emission [14-15].

Cost, speed of construction, stakeholder requirement, and availability of the material and skilled labor are typically considered during the selection process of a structural system for a building project. Embodied energy and carbon of the alternatives, however, is not usually ignored. Lack of an easy-to-use and documented assessment framework is a reason for this, because the research efforts on this subject used a large number of manual calculations for different processes to obtain the results. Building information model (BIM) of a project contains variety of information for different building components, which can be used to develop an automated embodied energy assessment system for different structural systems. Certain attributes of structural elements, such as material type, and geometrical and spatial data, could be extracted and used to estimate the embodied energy of the building components. There are a number of BIM-based systems for lifecycle assessment and modelling of the operational energy usage of buildings [16-17]; but only a few research efforts exclusively employed BIM for embodied energy estimation of the construction phase. For example, automated quantity take-offs (QTO) from a BIM model were mapped to embodied energy [18-19] and CO_2 databases [18] to estimate the embodied energy and carbon of building projects. The scopes of these methods, however, are limited to the manufacturing processes and they do not estimate the impact of transportation and on-site construction processes.

This paper presents an innovative BIM-based framework to estimate the embodied energy and carbon of the construction stage of different structural systems. The scope of this framework covers the construction phase, which includes the manufacturing of the structural material, transportation, and onsite installation/construction. This system extracts structural elements and their properties from a BIM model, and then estimates manufacturing, transportation, and onsite construction energies using a created model, defined databases, and user inputs.

2 Methodology

The architecture of the proposed system is presented in Figure 1. The first module of the system extracts the required data from a BIM model. Then the calculation model sorts elements' attributes and maps them to the corresponding energy and CO_2 inventories to estimate the impacts of production/manufacturing, transportation, and construction phases of the potential structural systems.

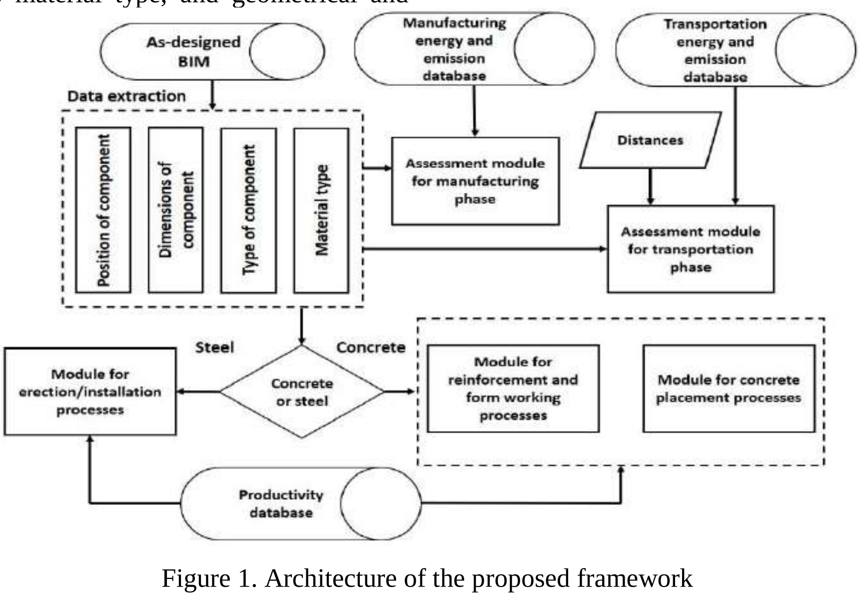

Figure 1. Architecture of the proposed framework

2.1 Data Extraction from BIM

Accurate quantity estimation from the design is essential in the construction industry [20], and this data are also necessary for environmental impact assessment. Completeness and accuracy are the most important factors in QTO and getting reliable estimates requires detailed model of a building project. Most BIM platforms have an automated QTO tool which calculates work quantities by extracting properties of building elements, such as material type, size, volume, space area, location, and weight, from the BIM model and reports them to the user-defined tables [21]. It is also possible to extract attributes of the elements' directly from an Industry Foundation Classes (IFC) file [21]. This module uses a script to extract all the main structural elements (i.e. columns, beams, bracing, floor slabs, and shear walls) and some of their main properties, including material type, and geometrical and spatial data.

2.2 Assessment Model for the Manufacturing Phase

Calculation of energy consumption during the manufacturing phase is mainly based on the embodied energy of the structural materials. The database of Inventory of Carbon and Energy (ICE) was used for the manufacturing embodied energy and carbon [22]. Table 1 shows the embodied energy and carbon coefficients of the main structural material.

Table 1. Embodied energy and carbon coefficients [22]

Materials	Embodied Energy(EE) (MJ/kg)	Embodied Carbon(EC) (kg CO_2e/kg)
Steel	20.1	1.46
Glulam	12	0.42
Concrete	0.88	0.132
Rebar	17.4	1.4
Plywood	15	0.45

The overall manufacturing embodied energy and embodied carbon of the structural system are calculated using Equations 1 and 2, respectively.

$$EE_m = \sum m_i EE_i \tag{1}$$

$$EC_m = \sum m_i EC_i \tag{2}$$

where EE_m = overall energy used in material manufacturing process; m_i = mass of elements i needed in the building; EE_i = embodied energy coefficient of material i; EC_m = overall embodied carbon during manufacturing phase; and EC_i = embodied carbon coefficient of material i.

It is common to have some level of material waste in the building construction process for various reasons, including the need to extract uniquely shaped building elements from standard-sized manufactured items, defects in products, poor handling, and damage to material during delivery. The wastage should be considered in the estimation of embodied energy and is commonly calculated as a percentage of the required amount of material. The waste factor depends on the type of building materials and the waste factors for the main material were considered as: 0.05 for steel and 0.025 for concrete and timber [23].

2.3 Assessment for the Transportation Stage

The differences in the embodied energy of material transportation are attributed to size, type, distance, and the quantity being transported [11]. The type of vehicles can also affect energy consumption in the transportation stage, which can complicate the estimation process. Some of the previous LCA studies ignored transportation or simplified the problem by assuming direct travel from the manufacturing plant to the jobsite. However, it is common for the manufactured structural materials, such as steel and timber elements, to go through several distribution centers before arriving at the construction site. Loading and unloading processes in each distribution center consume energy, which are considered in this study.

Energy consumption and CO_2 emission factors reported by Hong et al. [24] were used for the material transportation vehicles. To simplify the estimation process, GHG emission factors were converted to carbon dioxide equivalent (CO_2e), based on the global warming potential (GWP) of each form of greenhouse gas, where the GWP for carbon dioxide is 1, for Methane is 25, and for Nitrous oxide is 298 [25].

Both haul and return trips between the manufacturing plant/distribution center and construction site were considered by this system. It was estimated that the energy consumption and emissions in empty return trips is about 66% of the value of full-load trips [26]. Moreover, the energy consumed for loading/unloading in distribution centers were considered in transportation of steel, rebar, and forms, which were calculated similar to the lifting process of the erection stage (described in the next section). Energy usage and GHG emissions of transportation stage were calculated using equations 3 to 6.

For concrete:

$$E_t = 1.66 \sum m_i EE_i^t . D_i \tag{3}$$

$$GHG_t = 1.66 \sum m_i EC_i^t . D_i \quad (4)$$

For steel and Plywood (forms) products:

$$E_t = 1.66 \sum m_i EE_i^t . D_i + n. E_{LP} \quad (5)$$

$$GHG_t = 1.66 \sum m_i EC_i^t . D_i + n. EC_{LP} \quad (6)$$

where E_t = energy consumption during transportation; GHG_t = CO_2 equivalent emissions during transportation; m_i = weight of material i (including waste); EE^t_i = Energy consumption per kilometer per ton of material i; EC^t_i = CO_2 equivalent emissions per kilometer per ton of material i; D_i = Distance traveled between the origin and destination of material i; n = number of distribution centers; E_{LP} = Energy consumed for material handling process in a distribution center; EC_{LP} = Emission of material handling process in a distribution center.

2.4 Assessment Model for the Onsite Construction Stage

There are specific construction equipment and methods for onsite construction of different structural systems. Energy consumption during onsite construction, e.g. erection and installation, is represented by the energy used by various pieces of construction equipment. Mobile cranes are commonly used for material delivery in steel- and wood-framed buildings, and a concrete pump or a crane is employed for concrete pouring in low- to mid-rise concrete buildings. Mobile cranes are also used for delivering rebars and forms to the installation location in the concrete-framed structures.

Equipment working hours were the basis to estimate energy consumption and emission of the onsite construction operations. The energy consumption of the equipment is calculated using equation 7.

$$E_{equipment} = \sum E_i = \sum T_i \times ECF_i \quad (7)$$

where E_i = Energy usage of equipment i; T_i = Working hours of equipment i; ECF_i = Energy consumption factor of the equipment i (MJ/h).

The first step is to calculate the energy consumption factor of the envisioned equipment. A calculation model (see Equation 8) was adopted from Food and Agriculture Organization [27] to estimate the rate of fuel consumption per machine-hour for each equipment type.

$$LMPH = \frac{K \times GHP \times LF}{KPL} \quad (8)$$

Where LMPH presents liters used per machine hour; K is the rate of fuel consumed per hp/hour in kg; GHP is the gross engine horsepower; LF is the load factor in percent; KPL is the fuel density in kg/liter.

Given gross engine horsepower (GHP) of the selected equipment and the related values in Table 2 [27], fuel consumption of the machines (LMPH) were estimated. Then, the energy and emission conversion factors of diesel and gasoline [25] were used to estimate energy consumption and emissions (see Equations 9 and 10).

Table 2. Weight, fuel consumption rates, and load factors for diesel and gasoline engines

Engine	Weight (KPL)	Fuel Consumption(K)	Load Factor(LF)		
	kg/liter	kg/brake hp-hour	Low	Med	High
Gasoline	0.72	0.21	0.38	0.54	0.7
Diesel	0.84	0.17	0.38	0.54	0.7

$$ECF = LMPH \times Energy\ coversion\ factor \quad (9)$$

$$EF = LMPH \times Emission\ conversion\ factor \quad (10)$$

Where ECF is the energy consumption factor and EF is the emission factor.

2.4.1 Equipment Working Time

Mobile crane operations include two processes: (1) Lifting process; (2) Installation process.

There are five motion types in a lifting process: hoist down for the element, hoist up with the load, slew with the load, hoist down the load, and slew without load. One piece of structural element is carried in each cycle. The lifting time (T_{LP}) is the total duration of the five operations. Duration of each motion was calculated based on the slewing and hoisting speeds of the selected mobile crane, the lifting height, and the angle between the component loading area and the installation position (please see [28] for details). The spatial data of each structural element were used to obtain the last two pieces of information, which were extracted from the BIM model (See Figure 2).

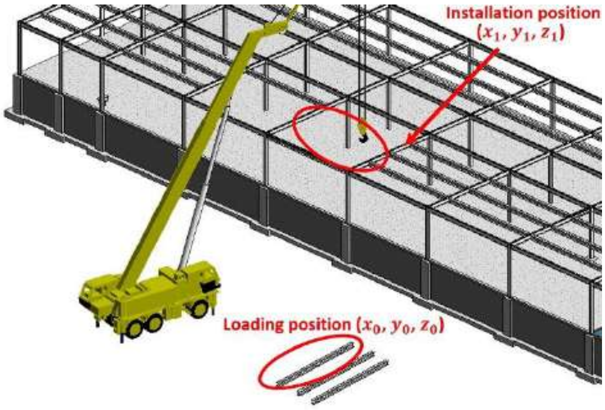

Figure 2. Sample 3D view of the spatial data for lifting of each element

Given the lifting process duration, the energy consumed in the lifting process (E_{LP}) was estimated as: $E_{LP} = T_{LP} \times ECF_{Crane}$.

In addition to the lifting time, the crane has to keep the component in its installation position until the crew initially fix it. The system calculates the installation time (T_{IP}) based on the productivity of the crew, which were obtained from RSMeans construction cost data. Given the installation process time, the energy consumed in the process (E_{IP}) was estimated as: $E_{IP} = T_{IP} \times ECF_{Crane}$.

Additional processes are required in the construction of concrete-framed structures (e.g. form working and rebars). If the reinforcement details exist in the BIM model, the system is able to extract them. Availability of such data, however, depends on the required level of details (LoD) and some BIM models might not include them. This system calculates formwork materials using the geometrical data of the structural component extracted from the BIM model. A mobile crane is considered for delivery of formworks and rebars, which has two types of processes: lifting and installation operations. The lifting efforts were estimated similar to the lifting of steel elements and the installation times were calculated using RSMeans.

A mobile concrete pump was selected for concrete placement in this model. The working time of the concrete pump (T_P) for each component was estimated by dividing the concrete volume of the element by the crew productivity (using RSMeans database). Given the concrete placement time, the energy consumed in this process (E_P) was estimated as: $E_P = T_P \times ECF_{Pump}$.

3 Case Study

A reinforced concrete and a steel-framed residential building with rather similar layouts were used to assess the developed system. Both of the buildings include three stories and ground level, where the total gross floor area of the concrete- and steel-framed buildings were 5,490.7 m^2 and 4,934.6 m^2, respectively. Concrete building had a one-way slab flooring system and the steel-framed structure had composite steel decks.

3.1 Quantity Take-off

Both designs were modelled in the Revit environment. The required element attributes, including length, width, volume, location, reinforcement volume, and customized shared parameters, namely formwork area, were extracted from the models.

3.1.1 Implementation of the Manufacturing Phase Model

Embodied energy and emission values for the manufacturing phase are calculated by multiplying the quantities of materials, including wastage, and corresponding embodied energy and carbon coefficients (see Equation (1) and Equation (2)). Figure 3 illustrates the embodied energy and emission values of the different materials used in the two studied structures. It is evident that the manufacturing embodied energy of the steel structure is larger than the concrete structure. The embodied carbon of the concrete structure, however, was larger than the steel-framed one. This is mainly due to the much greater ratio of the embodied carbon to embodied energy of concrete compared to steel (See Table 1). Because, large amounts of CO_2 are released during production of cement due to high temperature of clinker production as well as the CO_2 release in chemical reactions.

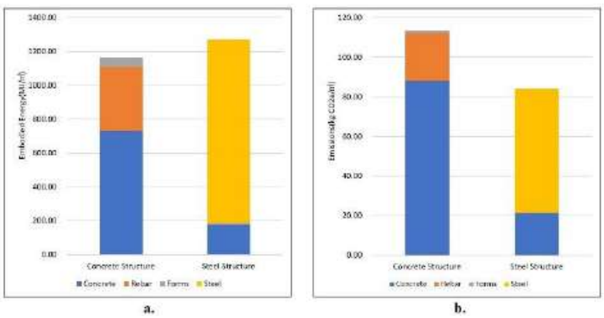

Figure 3. Results of the assessment of manufacturing phase of the studied buildings for: a) embodied energy; b) embodied carbon

3.1.2 Implementation of the Transportation Phase Model

This case study assumed 1000 km, 2000 km, and 3000 km distances for transportation of steel and rebar products, with the number of distribution centers varying from zero to three. For the concrete components, 25km transportation distance was assumed, because fresh concrete is a locally-sourced material. These numbers can be altered by the user.

Energy consumption and GHG emissions in the transportation stage were calculated by applying energy consumption and GHG emission factors of the selected vehicles and the quantity of materials in equations (3), (4), (5), and (6). Figure 4 shows the variation of the embodied energy and emissions values in the transportation stage with changes in transportation distance and the number of distribution centers. These figures show that the growth rates of embodied energy and emissions of the concrete structure are both higher than that of the steel structure, which means that the impact of the number of distribution centers for rebars and formworks on the concrete structure is greater than it is on the steel structure.

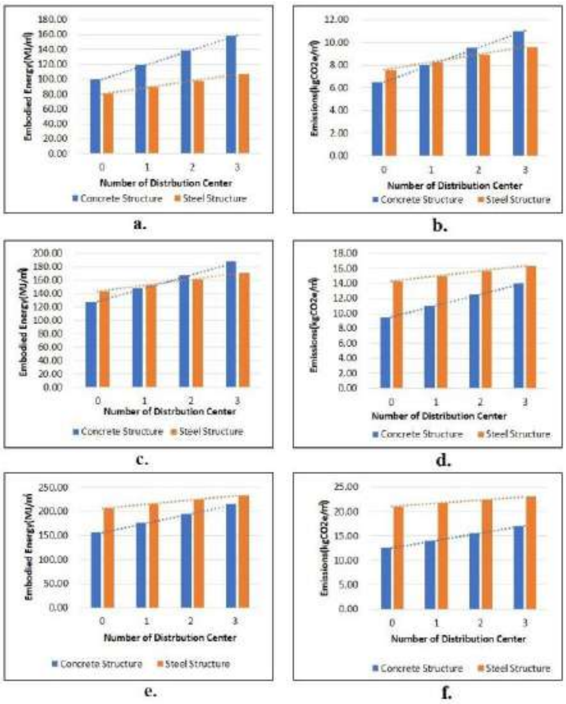

Figure 4. Embodied energy and carbon in the building structures during transportation stage: a) EE in 1000 km; b) EC in 1000 km; c) EE in 2000 km; d) EC in 2000 km; e) EE in 3000 km; f) EC in 3000 km

3.1.3 Implementation of the Onsite Construction Model

This module of the system estimates the onsite energy consumption by multiplying equipment working hours and energy consumption factor. A 30 t mobile crane with engine power of 164hp, maximum hoist speed of 136 m/min, and maximum slewing speed of 2 RPM was considered for lifting processes in this case study. A truck-mounted boom pump with a 395hp engine was selected for concrete pouring operations. The hoisting and slewing speeds were assumed between 40% and 60% of the maximum speeds. The swing angles (between loading area and installation position) of 90° to 105° were assumed for component delivery. Figure 5 shows the results of this phase, in which the concrete structure sample resulted in greater energy consumption and emissions than the steel-framed building (See Figure 5).

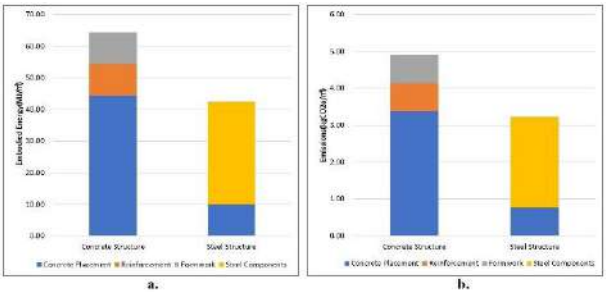

Figure 5. Results of the assessment of erection/construction phase of the studied buildings for: a) EE; b) EC

4 Discussion

The findings of this the study showed that application of different structural systems in a building project could result in different embodied energy and emissions. The manufacturing phase has the highest portion of the total embodied energy in both structural types (81%-91%). The results of this research were close to the ranges that were reported by other studies [6 and 29], but there are some differences (see Table 3). For example, the embodied energies differ from the results reported in [10]. One main reason was the difference between the energy inventories, in which their database included larger values for material and transportation. This is an important consideration, because production technologies and methods vary in different countries and should be adjusted in assessments.

Table 3. The estimated EE and EC of the concrete and steel structures studied previously

Research	Embodied energy and embodied carbon during construction			
	Embodied Energy (MJ/ m^2)		Embodied Carbon (kg CO_2-e/ m^2)	
	Concrete Structure	Steel Structure	Concrete Structure	Steel Structure
[29]	328-678	1419-2976	-	-
[6]	-	-	153-168	153-163
[10]	1720-3580	2540-4180	-	-
This study	1400-1520	1463-1624	163-175	125-142

In addition, the results were compared against the results of manual assessment by two groups of senior Civil Engineering students. The results for the manufacturing and transportation phases had the lowest difference, which were 3.8% and 4.5% for steel and concrete structures, respectively. But the estimation of the embodied energy for the erection/installation phase had larger differences, which were 7.2% and 10.7% for steel and concrete structures, respectively. These larger differences were due to large number of parameters and assumptions needed for the erection/installation process, whereas the values in manufacturing and transportation phases mainly depend on QTO and delivery distances that have less uncertainties.

This system, however, has some limitations. First, the LoD of model (e.g. reinforcement details) could have a significant impact on the accuracy of the results. Second, data inventories for material production and transportation are different in different locations, because employed technologies and methods vary in locations and they should be modified accordingly. Third, transportation data, such as the distances and the number of distribution centers might not be easily obtained in some practical cases.

5 Conclusion

A BIM-based framework was developed to estimate the embodied energy and carbon dioxide equivalent emissions of building structural systems. Different energy and emission calculation models were developed and data inventories were used for different construction phases of structural systems. This system automatically extracts required data from a BIM model and links the calculation model to the databases. A case study on a concrete and a steel-framed building showed that the type of structural system could result in a significant difference in the embodied energy and the emission of a building. It was also found that the energy consumption of the manufacturing phase has the greatest impact on the overall embodied energy of a structural system. In the transportation stage, the energy consumption is affected by the material transportation distance and the number of distribution centers. Finally, concrete-framed building consumed more energy than the steel structure in the onsite construction phase.

The future research will investigate the impacts on other building components, such as architectural, mechanical, and electrical elements.

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High Level-of-Detail BIM and Machine Learning for Automated Masonry Wall Defect Surveying

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Abstract –

Despite the rapid development of reality capture technologies and progress in data processing techniques, current visual strategies for defect surveying are time consuming manual procedures. These methods often deliver subjective and inaccurate outcomes, leading to inconsistent conclusions for defect classification and ultimately repair needs. In this paper, a strategy for monitoring the evolution of ashlar masonry walls of historic buildings through reality capture, data processing (including machine learning), and (H)BIM models is presented. The proposed method has been tested, at different levels of granularity, in the main façade of the Chapel Royal in Stirling Castle (Scotland), demonstrating its potential.

Keywords –

Terrestrial Laser Scanning; Data Processing; Surveying; HBIM; Ashlar

1 Introduction

Whilst traditional approaches to defect identification and analysis are widely utilised, their results have been empirically shown to frequently yield subjective results and mis-classification [1][2]. Attempts to enhance accuracy have been sought in the use of unifying standards and the creation of a 'common language' for the classification of masonry defects [3]. The difficulties faced by surveyors in meaningfully attempting to accurately and rapidly identify defects make the process extremely time-consuming and therefore problematic when 'upscaling' the survey operations from individual masonry units, within localised regions, to complete façades and ultimately entire buildings. On a more fundamental level, the inability of traditional survey to facilitate the labelling of individual masonry units is of significant concern. Yet, all analysis and intervention flow from accurate initial identification of individual materials and components [4]. Indeed, best practice guidance in the conservation sector [5] proposes that those undertaking visual survey and evaluation of historic masonry fabric adopt detailed pictures of the defective areas that can be supplemented by additional information such as measured dimensional survey and a rudimentary process of manually 'marking up' the images with alternative colours denoting different defects. When seen from the perspective of time, cost, accuracy and reproducibility/transferability, these proceses are increasingly untenable.

More recently, novel reality capture technologies, such as Terrestrial Laser Scanning (TLS) or photogrammetry, deliver coloured dense point clouds which can be used to support surveying activities, such as the identification and semantic labelling of the structural and non structural components. Regarding the digitisation of historic buildings, examples of the use of laser scanners include the work of Wilson et al. [6] which illustrates the potential of this technology with several UNESCO heritage sites.

Beyond the sole recording of buildings and other constructions, the unstructured point clouds produced by these devices can also be used for the generation, and subsequent management, of semantically rich digital representation of buildings [7].

In addition to reality capture technology, Building Information Modelling (BIM) is an effective digital approach to the whole lifecycle management of buildings. Besides new construction, for which BIM is used from the conception stage, BIM can be also applied to historic buildings, where it can play a particularly important role in operational maintenance and repair activities. BIM applied to the specific context of historic buildings has become increasingly accepted as HBIM [8][9].

Pronounced differences are noted between BIM and HBIM insomuch that in new projects designs are digitally conceived by means of BIM and CAD design tools, while BIM models of historic buildings need to be produced to reflect their existing (i.e. 'as-is') state, increasingly using dense point clouds as a reference. Hichri et al. [7] provide a general review of the stages to be undertaken from point cloud to BIM, in a process now commonly termed Scan-to-BIM. Similarly, Macher et al. [8] present an approach to create 3D models of historical buildings by means of point clouds. The authors divide the building in sub-spaces, model surfaces and fit primitive shapes to architectural elements.

The semantically-rich 3D models produced through Scan-to-BIM processes can subsequently be used as a reference to monitor the effects of deterioration. More specifically, decay or change of primary architectural elements or secondary components, such as walls, roofs, etc., can be tracked by means of the processing of newly acquired 3D coloured point clouds and their comparison with the previous known state of the building recorded in the BIM model, using Scan-vs-BIM processes [10].

1.1 Increasing the Level of Detail (LoD) in Scan-to-(H)BIM

Various researchers and practitioners are introducing HBIM to surveys, taking advantage of the structured digital representations of buildings provided by these models [11] [12]. Dore et al. [13] undertook a Scan-to-BIM process for sections of the Four Courts in Dublin and structural damage and decay simulations were applied for conservation analysis. In addition, Oreni et al [14], presented a case study in which HBIM models were generated for digitally surveying an earthquake affected church prior to restoration. This work is particularly interesting in highlighting their approach to the management and evaluation of ashlar columns, whose blocks are individually modelled and their dimensions considered for potential replacement operations.

However, BIM elements, such as walls, typically obtained with these Scan-to-HBIM approaches, do not contain the granularity of composition that is necessary for a detailed annotation and analysis of typical surveys, or require significant manual work to obtain such level of detail. Indeed, surveys may require delineating wall façade defects as effecting a single stone, a cluster of stones (or wall region), or even a part of a stone. There is thus a need for Scan-to-BIM approaches that can efficiently deliver ‘as-is’ semantically-rich 3D models with such higher LoD – in the case of stone walls, down to the individual stones (and mortar regions).

With the objective of automating these segmentation processes, several authors have recently proposed solutions for the computerised segmentation of images [15] or 3D data [16] of various building elements to support the identification of defective regions. Oses et al. [15] present a semi-automatic process for delineating ashlar in masonry walls in 2D images. Whereas Drap et al. [16] identify clusters of ashlar stones in 3D data. Even if these works propose solutions for dividing structural elements (i.e. walls) into smaller parts, an automated stone-level segmentation process would produce higher LoD representations of walls. Valero et al. [17] previously proposed a method for the automatic segmentation of random rubble from point clouds. However, whilst it is recognised as a significant step forward, that approach is not well suited to ashlar wall constructions for which 3D data alone may not be sufficient to robustly segment the wall data (mortar depth profiles are often too well aligned with stone profiles to easily detect the stone boundaries using this information alone).

1.2 Survey Objectivity

Whilst defects are wide ranging, they have been codified into five primary categories in the ‘ICOMOS glossary of stone deterioration patterns’ [3]. These include: Crack and deformation; Detachment; Features induced by material loss; Discolouration and deposit; and, finally, Biological colonisation. These are the broad categories that have been adopted for this research.

The heterogeneity and sophistication of these catalogued defects make their labelling process complex, even for professionals, who can differ in their analysis. For example, historic building walls are composed of hundreds, and in many instances thousands, of unique units (i.e. stones, bricks…), and can be affected by almost countless defects. Sánchez et al [18] proposed a novel strategy to identify, in point clouds, the deformation and erosion of walls and highlight unit clusters (i.e. areas) affected by decay. Valero et al. [4] have recently proposed the use of geometric and colour-related features from individual masonry units relevant to interpretation or conservation purposes, but that interpretation remained manual.

While these recent works investigate the potential of using point clouds to detect wall defects, these remain preliminary in nature. They do not fully automate defect detection and classification, or do this in a limited way, both in terms of the range of defects being detectable and the depth of the classification/analysis.

1.3 Contribution

This paper aims to address the two needs identified at the end of the previous two sub-sections. We first present a novel Scan-to-(H)BIM approach that automatically segments point clouds of ashlar masonry walls into their constitutive units, i.e. stones, and mortar regions (Section 2). Then, we propose a novel machine learning based approach to masonry wall defect classification, that considers both the geometry and colour information of the acquired point clouds, to classify a selective range of common types of masony wall defects (Section 3). The defects are found in relation to the masonry HBIM element and constitutive units, and so can be recorded in a structured manner within the HBIM model, so that the condition of all architectural components can be effectively tracked over time.

For the theoretical presentation of those two novel contributions, Section 4 reports experimental results obtained using real data. Finally, Section 5 concludes the works and proposes directions of future research development.

2 High LoD HBIM Masonry Wall Element

In this work, principal building elements, such as roof or walls, are referred to as *elements*, that can be subsequently segmented into their constitutive sub-elements, named *units*. These would include bricks or stones in the case of walls (See Figure 1). Furthermore, if several contiguous units are affected by the same defects, these should be recorded and studied as a region. Therefore, we refer to several adjoining units composing regions of interest as *clusters*. Finally, certain defects can affect only parts of a unit. We call such region a *sub-unit* region.

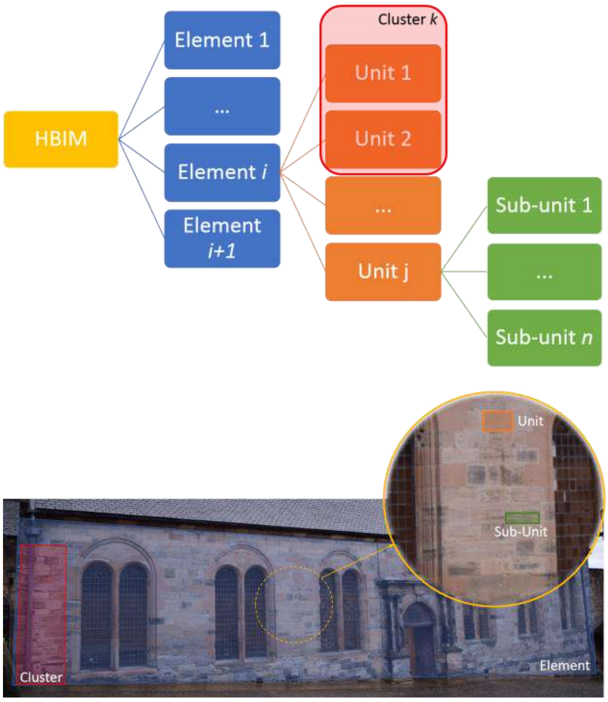


Figure 1. Proposed levels for analysis. Ilustration for a wall

To deliver the hierarchical subdivision described above, a segmentation process was developed to identify the individual masonry units composing the overall element. This method considers colour and 3D information at both local and global level and it is grounded on the analysis of data in the frequency domain. The 2D Continuous Wavelet Transform (CWT) is applied to identify the joints between units and segment individual stones (see Figure 2).

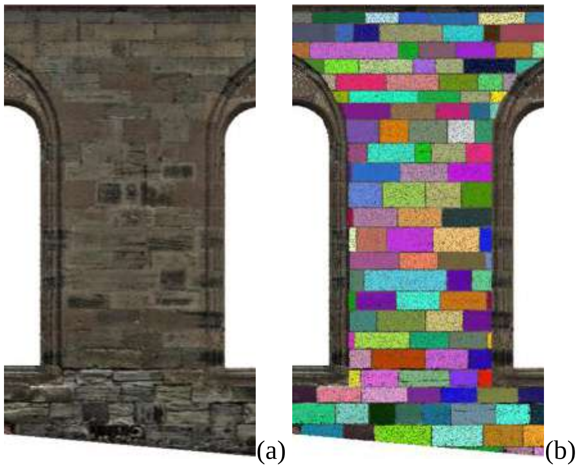


Figure 2. Ashlar masonry wall (a) Coloured point cloud (b) Segmented ashlar units

3 Identification of Defects using Machine Learning

Several geometric and colour metrics are presented in this section, that highlight stone regions potentially affected by decay, at different levels, both unit and sub-unit (Section 3.1). These are used for defects classification by means of machine learning (Section 3.2).

3.1 Metrics for the Identification of Defects

Once units are segmented and labelled, information regarding geometry and colour is extracted from each stone and several parameters are calculated to evaluate its state.

In the case of coursed ashlar, two specific parameters can play an important role to identify decayed units. Regarding geometric-based defects, the evaluation of the roughness of the stone face profile helps differentiate between flat and rough masonry units. Higher levels of roughness can suggest stones affected by deformation and detachment, related in most cases with loss of material. Roughness is calculated as the standard deviation of the distance of the profile points to the profile's mean plane:

$$Ra = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(d_i - \mu)^2}, \text{ with } \mu = \frac{1}{N}\sum_{i=1}^{N} d_i \qquad (1)$$

where N is the number of 3D points for the given stone face and d_i's are the projection distances of those points to the fitted plane.

With respect to colour-related defective areas, the analysis of the dispersion of colour in each stone, by means of the calculation of the standard deviation of the hue values within each ashlar unit (Equation (2)), can be used to highlight zones affected by discolouration or other defects associated to color, such as efflorescence or biological colonisation.

$$H_\sigma = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(h_i-\mu)^2}, \text{ with } \mu = \frac{1}{N}\sum_{i=1}^{N} h_i \qquad (2)$$

for which the Red-Green-Blue (RGB) colour data is first converted into Hue-Saturation-Value (HSV) format, using the algorithm presented in [19].

The evaluation of these two parameters can be undertaken at the unit level (i.e. stone), resulting in the generation of two colour maps as illustrated in Figure 3. Figure 3 (a) corresponds to the roughness map, while Figure 3(b) illustrates stones potentially affected by defects related to colour variation. Traffic light colour maps have been used, in which the stones coloured in green are less likely to be affected by decay and the yellow and red ones are potentially defective.

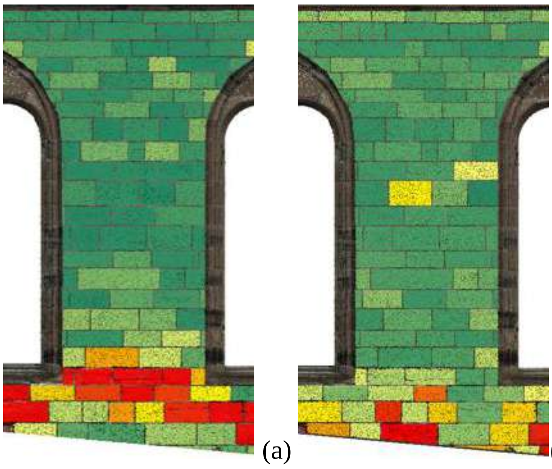

(a) (b)

Figure 3. Geometry- and colour-based parameters (a) Ra (b) H_σ

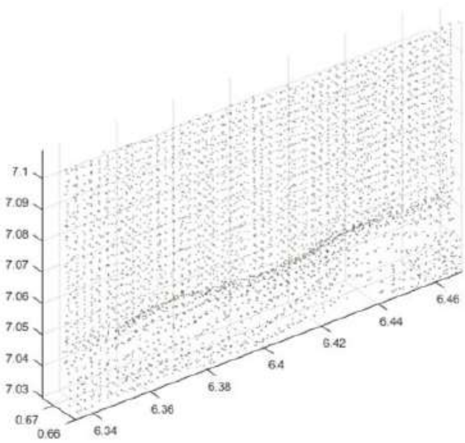
These above parameters and subsequently produced maps are of value for unit-level analysis and are useful to highlight clusters affected by decay. However, a more detailed analysis (i.e. at sub-stone scale) can deliver information about the precise defects which are affecting a specific stone.

The fine dressing of ashlar masonry, especially in polished finishes, facilitates the detection of defective areas. In these cases, the stone profile should fit a plane, with areas potentially affected by geometry-related defects can be found as those containing the outliers. Figure 4 illustrates, for each ashlar, the inliers (in green) and the outliers, which are coloured from yellow to red, according to the distance of the recorded 3D points to the fitted plane. Regions coloured in red are those with a more pronounced loss of material.

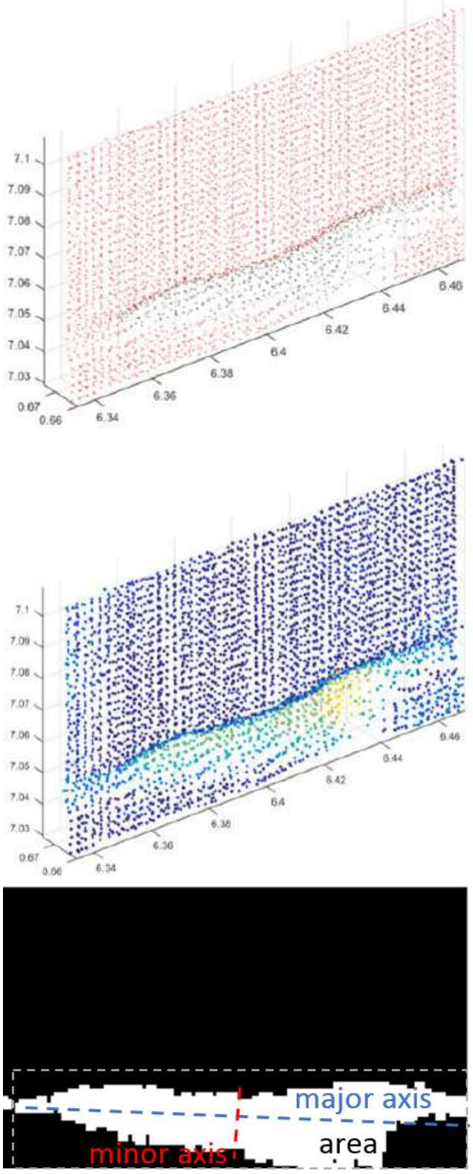
Figure 4. Sub-stone level analysis map

3.2 Machine Learning Approach for Defects Classification

An extended evaluation of the areas containing outliers can be undertaken in order to identify the particular effects affecting the material. Figure 5 (a) illustrates a decayed region of ashlar, where a plane is fitted to the stone and the outliers are considered to be part of a defective area (see darker points in Figure 5 (b)). While 3D coordinates are used to calculate the roughness coefficient (the point cloud is coloured according to their depth in Figure 5 (c)), additional metrics are calculated after the binary image obtained from the 3D point outliers (see Figure 5 (d)).



(a)



(b)

(c)

(d)

Figure 5. Process for parameters extraction (a) Original coloured point cloud (b) Inliers (red) and outliers (gray) after plane fitting (c) Depth map for outliers (d) Binary map created after orthogonal projection of outliers

From the 3D coordinates of the outliers, two metrics are extracted:

- Ra, the roughness coefficient of the defective area, (Equation (1)), and
- The median value of the normal vectors of the outliers with respect to the plane fitting the ashlar.

From the binary map obtained after the projection of the ouliers, the following parameters are considered:

- the number and area of unconnected defective areas (white segments in Figure 5(d)),
- the elongation of the defective areas, which is the ratio of the lengths of the minor to major axes and gives an indication of how ‘oblong’ a defective area is,
- the rectangleness of the defective areas, which is calculated as the fraction of the bounding box covered by the object, and
- the circularity of the defective areas, which is the ratio of the area of the projection of the defective region to the area of a circle with the same perimeter (p), as detailed in Equation (3).

$$C = \frac{4 \cdot area \cdot \pi}{p^2} \qquad (3)$$

From the colour information of the points associated to the defective area, two metrics are extracted:

- H_σ , as detailed in Equation (2).
- Colour lightness. RGB colour data are converted to grayscale [20], and the median value of g_i, (the grayscale value of each point inside the defective area) is calculated to provide information about the colour lightness.

Machine learning techniques are effective tools for classification and analysis. In this work, we propose a supervised learning algorithm to classify masonry units affected by different types of decay, and using the parameters described above. Stones labelled as ‘defective’ by professional surveyors, as illustrated in Figure 6, are used for training the classifier and producing an inferred function that is subsequently employed to automatically label new data.

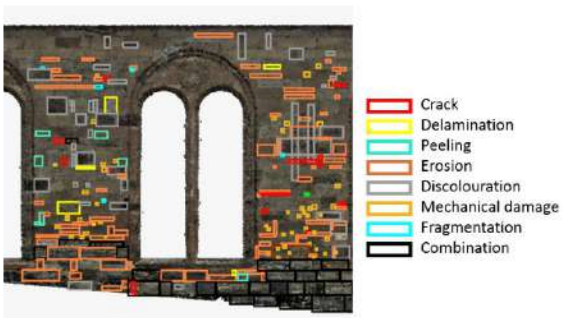


Figure 6. Defective areas labelled by surveyors

The chosen machine learning algorithm may vary depending on the number and nature of samples in the studied dataset and features [21]. In this work, after evaluating the amount of available samples and the extracted features, a logistic regression algorithm has been employed.

4 Experimental Results

The proposed approach has been tested with data from the main façade of the Royal Chapel in Stirling Castle, Scotland. A coloured dense point cloud (see Figure 7) has been produced after merging four scans acquired with a Leica P40 TLS device [22].

4.1 HBIM and Unit-level Maps

The generated point cloud was considered as a reference to create an 'as-is' 3D model of the Chapel Royal's façade. This model, that distinguishes the wall, door and windows (Figure 8) is used as the base of an HBIM model.

After removing the points corresponding to the door and the windows using a Scan-vs-BIM process, the point cloud composing the wall is segmented, producing a database with 1,116 ashlar units, as illustrated in Figure 9.

The points assigned to each ashlar unit are then automatically processed to calculate the parameters mentioned in the Subsection 3.1. Two maps, containing the values of Ra and H_{σ} can be seen in Figure 10.

As can be observed in Figure 10, the bottom part of the façade is found to be potentially affected by both geometry and colour-related defects. Also, the left and right ends of the walls have decayed regions. Physical inspection of the wall confirmed long term deterioration associated with previously defective rain water downcomers, leading to higher fabric moisture contents and subsequent increased incidence of freeze thaw decay processes. In addition, the presence of white 'blooms' were noted and are most likely attributed to salt crystallisation.

Figure 7. Dense coloured point cloud of Chapel Royal's main façade

Figure 8. Rendered 3D model of the façade

Figure 9. Segmented ashlar units

(a)

(b)

Figure 10. Colourmaps generated for the façade. (a) Roughness. (b) Standard deviation of hue values

All produced outcomes in the form of colourmaps, were subsequently added to the HBIM model (see Figure 11) adding information that can be contrasted with the status of the structural components at previous epochs.

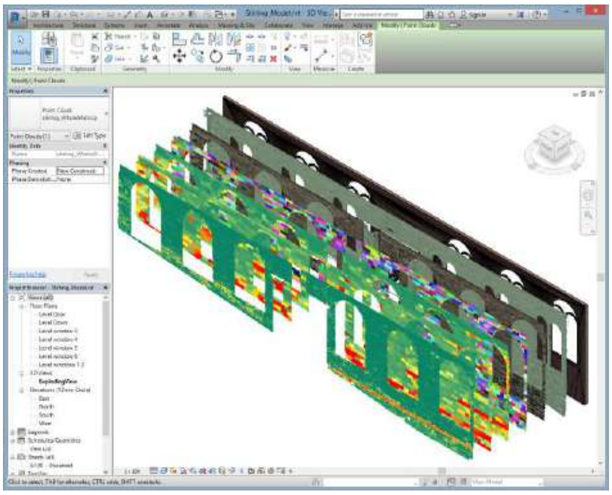


Figure 11. Datasets attached to the HBIM model

4.2 Classification of Labelled Defective Areas

To enhance the rapidity, accuracy and objectivity of labelling, machine learning techniques were developed and applied. The initial classification (i.e. labelling) of defective stones and broader areas was performed by specialist surveyors with expertise in masonry fabric repair and deterioration. The Stirling Castle Royal Chapel's ashlar façade was used and comprehensively surveyed and subsequently adopted to test the algorithms.

As previously illustrated in Figure 6, approximately 230 defective stone areas were labelled by specialist surveyors. Although approximately ten different types of defects were identified, only three of them were representative in significant numbers to be considered in this study: erosion (E), mechanical damage (M) and discolouration (D). The frequency of those most repeated defects is detailed in Table 1.

Table 1 Frequency of defects identified by surveyors in the studied area

Defect	Repetitions
Erosion	77
Mechanical damage	53
Discolouration	43

As previously mentioned in Section 3.2, the logistic regression algorithm was then employed, performing a 'one vs all' training process. For the training process, random samples of these three classes (72 from erosion, 48 labelled as mechanical damage and 38 identified as discolouration), were used as input to the algorithm. A maximum of 50 iterations has been used, with a regularization parameter applied to the cost function.

A total of 15 samples (5 of each class) were included in the test set, obtaining a global accuracy of 93.3% in the classification. More detailed results are summarized in Table 2. Additionally, Table 3 shows recall and precision values for the classification process.

Table 2 Confusion matrix for the classification of defects

	E	M	D	Predicted
E	4	0	0	4
M	0	5	0	5
D	1	0	5	6
Labelled	5	5	5	15

Table 3 Precision and recall values for the different classes

	Recall	Precision
Erosion	0.8	1
Mechanical	1	1
Discolouration	1	0.83

5 Conclusions

A strategy for monitoring the evolution of ashlar masonry walls of historic buildings through reality capture, data processing including machine learning, and (H)BIM models is presented in this paper. Different levels of magnitude are considered to perform surveying tasks: from element to sub-unit levels, several point clouds and maps are produced to illustrate the defective regions of the studied façades. At a sub-stone level, a more detailed analysis is carried out to extract different metrics which are of interest to identify decayed areas by means of machine learning techniques.

A preliminary experiment has been performed with geospatial data from a historic building and the obtained results demonstrate the potential of the proposed methodology.

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Camera Placement Optimization for Vision-based Monitoring on Construction Sites

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Abstract –

For successful vision-based monitoring, the camera placement is an important and challenging issue. However, the previous Art Gallery Problem – which is a traditional optimization problem closely similar to the camera placement problem – did not take into account characteristics of construction sites, and thus faced difficulties in placing cameras on site and collecting adequate video/image data of construction activities. To handle the drawback, this paper aims to develop a camera placement optimization framework that considers characteristics of construction sites. The framework consists of two main processes: (1) problem definition and mathematical modeling and (2) optimum camera placement. For the validation, the case study was performed. The results showed the applicability of the developed framework in finding the optimal number, locations, and viewpoints of surveillance cameras for vision-based site monitoring. In conclusion, this research can contribute to propose proper camera placement on construction sites, increase quality of collected visual data, and improve the performance of site monitoring.

Keywords –

Vision-based monitoring; Operation-level; Construction site; Camera placement; Optimization;

1 Introduction

A number of video/image data are collected on construction sites for the purpose of vision-based monitoring. Recently, Unmanned Aerial Vehicle (UAV) is extensively utilized for video/image data collection and analysis in practice [1]. However, practitioners still install surveillance cameras on construction sites for continuous operation-level monitoring. It can be explained that the UAV-based visual data has difficulties to provide the operation-level information (e.g., work time, direct work rate) while it contains more macro, project-level information (e.g., progress measurement) [2]. In contrast, cameras located at construction sites have a capability to capture video/image data involving operation and logistics of input resources such as workers, equipment, and materials [2-4].

For successful operation-level site monitoring, camera placement is a critical and challenging issue to be addressed. In practice, the camera placement is usually conducted manually based on experts' knowledge or experiences. The manual processes make the camera placement to become time-consuming and cost-ineffective. In response to this issue, many researchers have made efforts to solve Art Gallery Problem (AGP) – which is a well-studied open research area that finds the optimal locations of safety guards such that they satisfy the maximum visual coverage in an art gallery. AGP theorems and algorithms are also widely adapted and applied to optimize the camera placement in the visual sensor network domain [5-11]. In the construction domain, Albahri and Hammad [12] attempted to find the optimal camera placement in indoor buildings using Building Information Modeling (BIM).

Even though the previous works showed promising results in finding optimal camera configurations, they focused on the camera placement in controlled, arranged environments for limited purposes. Thus, it is still challenging to determine proper number, locations, and viewpoints of cameras due to various unique conditions of construction sites. To handle such limitation, this paper aims to develop a camera placement optimization framework that considers characteristics of construction sites.

2 Literature Review

In this chapter, the authors review previous works on vision-based monitoring systems on construction sites and previous approaches for solving camera placement problems including Art Gallery Problem.

2.1 Vision-based Monitoring at the Operation-level on Construction Sites

Vision-based monitoring at the operation-level is generally carried out on construction sites for the purpose of safety and productivity management. In the past, project managers directly visited construction sites for gathering operation-level information. However, the manual methods made the monitoring tasks to become expensive and time-consuming [13].

To address the problem, many studies have been performed to develop automated vision-based monitoring systems, which automatically extract safety and productivity information from video/image data. Chi and Caldas [14], for example, presented an image-based safety assessment method for earthmoving operations. In addition to the safety assessment, Kim et al. [15] applied fuzzy inference for supporting immediate risk awareness of workers. Vision-based analysis techniques were also utilized to detect workers' unsafe behavior detection. Han and Lee [16] presented a method that detects unsafe behavior from stereo images. Park et al. [17] developed a vision-based method that recognizes non-hardhat-wearing states of construction workers. Automated vision-based productivity analysis also raised attention. Many researchers focused on developing an activity recognition method for earthmoving equipment; for instance, the method proposed by Kim et al. [18] analyzed interactive operations (e.g., proximity, individual actions) between heavy equipment for recognizing earthmoving activities. Golparvar-Fard et al. [19] used spatio-temporal features and support vector machines to classify actions of earthmoving excavators and dump trucks. Gong and Caldas [20] developed a video-based analysis model for evaluating concrete pouring operations of tower cranes. Bugler et al. [21] also presented a fusion approach of photogrammetry and video analysis techniques for assessing earthmoving productivity.

2.2 Art Gallery Problem for Camera Placement

Art Gallery Problem (AGP) is the well-documented optimization problem of finding minimum number of safety guards and their locations required to cover the interior of an art gallery [8]. Because camera placement optimization has similar natures with AGP [5], AGP-based approaches have been performed to optimize camera networks in various domains.

In the camera surveillance domain, researchers primarily aim to maximize coverage of stationary cameras for indoor building. The cameras were installed to observe pedestrian and unexpected events (e.g., crime, traffic accidents) for security/traffic monitoring purposes [8-9,22-23]. Other researchers also considered Pan-Tilt-Zoom and omni-directional cameras for coverage modeling and maximization [6-7,24]. In recent years, the camera placement problems are extended to multi-objective optimization for maximizing camera coverage and minimizing installation costs simultaneously [5-6,11]. In the construction domain, a few studies have examined the camera placement problem in building environments. The work in [24] visualized and calculated the coverage of multiple cameras in public building spaces. The coverage modeling method presented in [25] used Building Information Modeling (BIM) for a simulation-based optimization and was further developed in [12].

The previous research showed promising results in camera placement optimization for indoor spaces and urban areas. However, it is still challenging to determine proper number, locations, and viewpoints of cameras to be installed on construction sites. To overcome such limitation, this paper develops a camera placement optimization framework considering characteristics of construction sites.

3 Research Framework

The research framework is composed of two main processes. First, we perform problem definition and mathematical modeling. Second, the optimum camera placement is found through site modeling, coverage simulation, and genetic algorithm.

3.1 Problem Definition and Mathematical Modeling

The goal of this research is to optimize number, locations, and viewpoints of cameras that maximizes effective coverage given site-specific constraints (e.g., installable locations). The camera coverage (without occlusions) can be represented with its effective distance and view angle as shown in Figure 1. For the spatial modeling of construction sites, a 2D grid-based matrix was used. The grid size was set as 0.5m x 0.5m based on the expert suggestions during the interview.

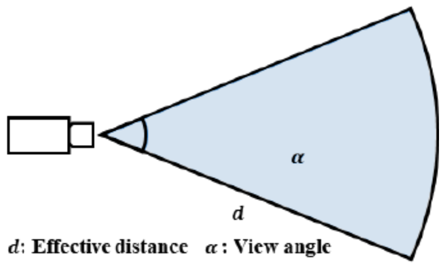

Figure 1. Camera coverage modeling

Next, the mathematical model was developed in order to manage the defined problem as follows.

Objective Functions

$$max\ \sum_{\theta}\sum_{i}\sum_{j} x_{i_1 j_1 \theta_1} e_{i_1 j_1 \theta_1 i_2 j_2} w_{i_2 j_2} \tag{1}$$

Constraints

$$P\sum_{\theta}\sum_{i}\sum_{j} x_{ij\theta} \leq Budgets \tag{2}$$

$$\sum_{\theta} x_{ij\theta} \leq l_{ij}\ for\ \forall i,j \tag{3}$$

$$1 \leq i \leq n, 1 \leq j \leq m, 0 \leq \theta \leq 360 \tag{4}$$

where

$$x_{ij\theta} = \begin{cases} 1, & if\ a\ camera, with\ viewpoint\ \theta, is\ at\ (i,j) \\ 0, & otherwise \end{cases} \tag{5}$$

$$e_{i_1 j_1 \theta_1 i_2 j_2} = \begin{cases} 1, & if\ a\ camera\ (i_1, j_1, \theta_1)\ covers\ cell\ (i_2, j_2) \\ 0, & otherwise \end{cases} \tag{6}$$

$$w_{ij} = spatial\ importance\ weight\ of\ cell\ (i,j) \tag{7}$$

$$l_{ij} = \begin{cases} 1, & if\ a\ cell\ (i,j)\ is\ installable \\ 0, & otherwise \end{cases} \tag{8}$$

The objective function plays a role in maximizing the total weighted effective coverages for vision-based site monitoring. By multiplying the spatial importance weight, possibilities in finding camera configurations that cover targeted monitoring areas can increase (e.g., work zones, travel paths, and material storages). The first constraint (Equation (2)) indicates that the total costs (i.e., number of cameras multiplied by unit prices) should be less than allocated budgets. When considering a camera dimension (around 0.5m x 0.5m) and a grid size, it is necessary to include Equation (3) to ensure that only one camera is located at each cell; however, this constraint can be released if a grid size is set sufficiently larger than a camera dimension (e.g., grid size: 3m x 3m; camera dimension: 0.5m x 0.5m). Equation (3) also explains that cameras should be placed at installable locations. The last constraints are considered for lower and upper bounds of locations and orientations.

3.2 Optimum Camera Placement

The proposed problem-solving method consists of three main modules: site modeling, coverage simulation, and genetic algorithm (GA). First, the site modeling is performed to encode spatial information of the actual construction site. Next, the performance of initial camera placement is evaluated to reproduce better coverage with simulation. GA generates new candidates for camera placement based on the evaluation. Until the terminal condition (i.e., the number of iterations is larger than the pre-determined threshold) is satisfied, the simulation-based coverage evaluation and GA-based reproduction processes are iterated.

3.2.1 Site Modeling

The site modeling creates the site-layout and spatial importance weight maps. First, the site-layout map is generated based on actual site drawings or top-view images. The next step is to create the spatial importance weight map. The spatial weights are assigned as 1, 2, and 3 for normal areas (i.e., background), travel paths and material storages, and work zones respectively. Based on the site modeling, the initialization is carried out. Among the camera-installable locations (e.g., facility boundaries) of the site-layout map, the initial number, locations, and viewpoints of cameras are randomly selected.

3.2.2 Coverage Simulation

The coverage simulation module computes the monitoring performance, total weighted effective coverage, of camera placement through coverage modeling and visibility analysis. The coverage modeling calculates camera coverage without occlusions based on the given camera type (i.e., effective distance and view angle). Next, the visibility analysis is conducted to deal with occlusion effects. Rotation angles to camera locations are primarily calculated for all cells within the coverage. It is then capable of capturing cells in the same line-of-sight when they have same rotation angles. Among the captured cells, cells located farther than any occluded cells are determined as invisible points.

3.2.3 Genetic Algorithm

GA is composed of two main steps: performance evaluation and population reproduction. First, the performance evaluation processes the calculation of objective function values: the total weighted effective coverage and total costs. By using the spatial importance weight map and the measured effective coverage, the first objective function can be determined. It is also possible to compute the total costs by multiplying the number of cameras and its unit price. Based on the acquired results, the population reproduction step is carried out as follows: selection, crossover, and mutation [5]. The selection chooses a subset of chromosomes with higher objective function values from population at the prior iteration, which may result in adoption to the best solution. Afterwards, 95% of the selected chromosomes is proceeded to the crossover and mutation; the other 5% individuals remain to secure the best solutions at the last iterations. Among the 95%, 80% and 20% were further selected for the crossover and mutation respectively. The probability-based uniform selection, the scattered method, and the adaptive feasible method were applied for each process of selection, crossover, and mutation respectively. Moreover, the authors mapped the real-world decision variables (i.e., numbers, locations, and orientations of cameras) into the chromosomes as follows. Each chromosome is composed of 2D locations and orientations. Chromosomes are also generated for all cameras to be installed, which means the number of chromosomes is same as the number of cameras.

4 Case Study

To validate the proposed framework's applicability, the authors performed a case study considering practical conditions of an actual construction site. Since the selected site already had three surveillance cameras for the purpose of vision-based monitoring, it was available to compare the performance of existing cameras and the suggestions based on the proposed method. The method was implemented using MATLAB 2017a on a laptop computer [Intel i7-5500 CPU @ 2.40 GHz, 8.00GB RAM, Windows 10, 64bit].

The case study was applied to the actual site-layout where two buildings were under construction. The site scale was 70m x 30m. There were total three cameras installed. The project manager aimed to mainly monitor work zones, travel paths, and material storages with the maximum budgets of $2,000. They purchased the surveillance cameras with the unit price of $500.

The effective coverage of both existing and suggested camera networks (with three cameras) are visualized with the red lines in Figure 2. The total weighted effective coverage rate (WVCR), calculated with Equation (10), was increased from 45.7% to 87.1% with the suggested camera placement.

$$WECR = \frac{\sum_\theta \sum_i \sum_j x_{i_1 j_1 \theta_1} e_{i_1 j_1 \theta_1 i_2 j_2} w_{i_2 j_2}}{\sum_i \sum_j w_{ij}} \qquad (9)$$

5 Conclusions

This research proposed a camera placement optimization framework for vision-based monitoring on construction sites. To validate the applicability of the proposed framework, the case study was carried out considering actual conditions of construction sites. The performance of existing camera networks and suggested solutions was compared. The results showed the suggested design outperformed the existing camera placement in terms of the total weighted effective coverage rates. With the proper camera placement, it is expected to collect adequate quality of video/image data and support vision-based monitoring tasks successfully.

Several research challenges remain to be improved. For instance, the proposed framework can be applied to diverse construction projects involving various unique site conditions. It is then available to identify and incorporate more various elements in the camera placement framework. Although it is a challenging issue to find proper 2D locations of surveillance cameras in practice, optimization with 3D modeling can be addressed for further studies.

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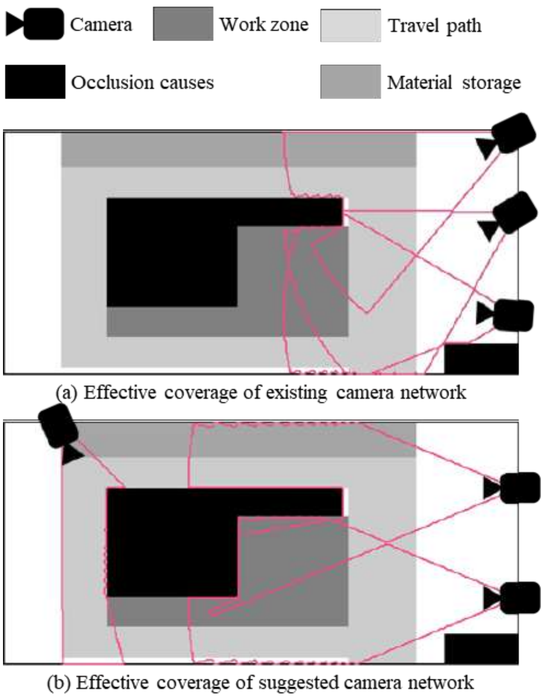

Figure 2. The coverage areas of camera networks

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A Deep Residual Network with Transfer Learning for Pixel-level Road Crack Detection

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Abstract –

Image-based crack detection methods have been extensively studied due to their cost-effectiveness in terms of data acquisition and processing. However, automated crack detection still remain a challenging task due to complexity of image background and different patterns of cracks. To address these issues, this paper proposes a deep residual network with transfer learning for pixel-level crack detection on road surface images. The network was trained on 71 images of CrackForest dataset and tested on 47 images of it. Experimental results suggest that the deep residual network is superior to the existing algorithms with recall value and precision value of 84.90% and 93.57%, respectively.

Keywords – Crack Detection; Residual Network; Deep learning; Transfer Leaning

1 Introduction

Cracks on a road pavement that are not timely repaired increase maintenance and repair costs due to the acceleration of surface deterioration. To establish a proactive maintenance plan, road inspection data should be obtained frequently. In general, a government agency responsible for road monitoring either manually inspects the status of road networks or by using special road monitoring vehicles equipped with laser scanners, infra-red cameras, or high definition video cameras. However, it is still challenging to timely monitor a significant portion of road networks.

Image processing and machine learning algorithms have been widely studied to detect cracks on road pavement. Radopoulou and Brilakis [1] proposed the pavement management system that automatically detects patches in video frames. The authors used the video acquired by the car's parking camera in patch detection. Ouma and Hahn [2] proposed a pothole detection method on asphalt road pavements using the fuzzy c-means algorithm. The consumer-grade smartphone devices were used as road data collectors for the low-cost automated system. Oliveira and Correia [3] proposed a system for the automatic detection and characterization of cracks on road pavement images captured by a digital camera. These papers shows that the road crack detection methods based on image processing and machine learning algorithms allow frequent updates of road conditions at low cost.

CNN (Convolutional Neural Networks) have been used for road crack detection since CNN demonstrated an excellent performance in ImageNet Large Scale Visual Recognition Competition (ILSVRC) 2012 [4]. Gopalakrishnan et al. [5] used the VGG16 model, a kind of CNN, to identify the presence of cracks in images. Compared with the performance by traditional machine learning methods such as SVM (Support Vector Machine), RF (Random Forest), and LR (Logistic Regression), the CNN model proposed in [5] showed the highest accuracy for crack detection in highway images. Zhang et al. [6] proposed a CNN model with six layers for detecting cracks on road images. They conducted a comparative research with existing algorithms, such as SVM and boosting method, to confirm the superior crack detection performance of the proposed CNN. Wang et al. [7] applied a CNN to detect the existence of pavement crack using two different scales of grid (32×32 and 64×64).

Although the CNNs studied so far have performed well in terms of identifying the presence of cracks in a certain image region, they had a limitation in terms of detecting cracks at pixel-level. Sufficient pixel-level accuracy that can quantify the width, shape, and length of the crack enables detailed analysis of the road surface distress.

In this paper, we propose a deep residual network with transfer learning for pixel-level crack detection. The deep residual network classifies all pixels in road images into cracks and background. To achieve high performance with a relatively small number of training images, this study uses transfer learning, which is a learning method of fine-tuning the weights of a pre-

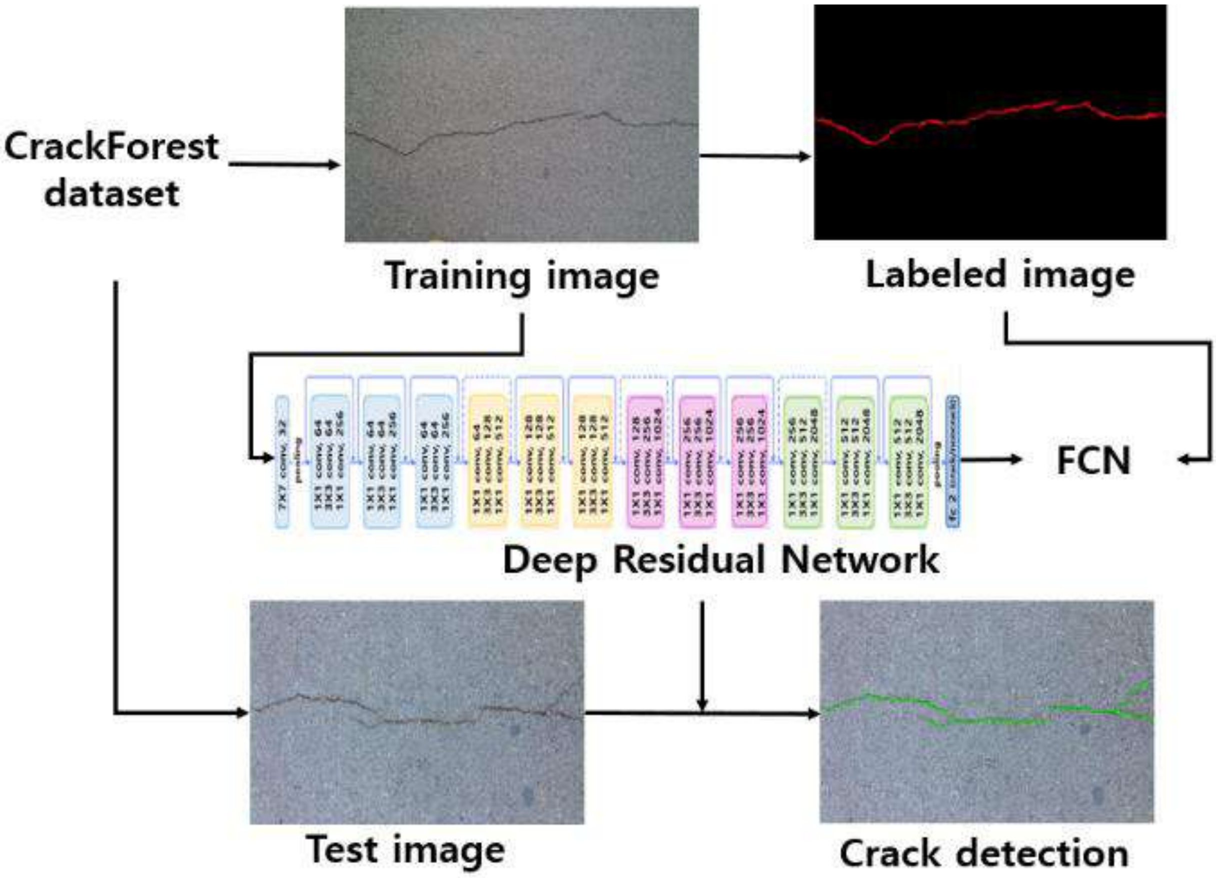

Figure 1. The deep residual network for road crack detection

trained CNN [8]. Experiments are conducted to demonstrate the performance of the proposed network.

2 Deep neural network with transfer learning for crack detection

CNN has been shown to be very effective in processing image data to perform computer vision tasks, such as semantic segmentation, image classification, object detection, and regression. A typical CNN consists of three kinds of layers: a convolution layer, a sub-sampling layer, and a fully-connected layer. The convolution layer applies convolution filters to the input image to produce output images. This layer has parameters such as number of channels, kernel size, number of filters, and stride size. The sub-sampling layer obtains feature maps with a lower dimension using average pooling or max pooling in the receptive field. In a CNN, convolutional layers and sub-sampling layers are typically repeated several times, and a fully-connected layer is placed at the end. The softmax function value of the fully-connected layer is the prediction value of the CNN.

The existing CNNs have the vanishing gradient problem that prevents the front layers of the model from learning in cases where many layers exist. The residual network [9] tried to solve this problem with a novel learning method that trains the network with the residuals–the difference between input and output of each computational block. The residual network with 152 layers shows better performance in large-scale object recognition problems than the VGG network [10] with 16 layers.

Figure 1 represents the proposed network. The network inputs are 480 × 320 × 3 images. The first layer is a 7 × 7 convolution layer with 64 depths and the second layer is a 3 × 3 max-pooling layer to perform down-sampling. The blocks, which consist of a 1 × 1 convolution layer, a 3 × 3 convolution layer, and a 1 × 1 convolution layer, are stacked behind the two layers (7 × 7 convolution layer and 3 × 3 max-pooling layer). An image passed through the 152 layers is reduced to a feature of 15 × 10 size. After that, the method of fully convolution network (FCN) [11] is applied to detect cracks using features extracted by the deep residual network. FCN enables pixel-level prediction by restoring features to original image size using the skip connection, which utilizes the intermediate layers' results and the final features of the residual network. The results of the intermediate layers compensate for losses in the up-sampling process performed by the bilinear interpolation.

A CNN typically require a large amount of labeled images to achieve high prediction accuracy. However, it is difficult to collect hundreds of thousands or even millions of road images and to label them manually. To address this problem, transfer learning was proposed to fine-tune pre-trained weights with big data, such as ImageNet. Unlike existing learning methods that randomly initialize the weights of CNN, transfer learning uses the weights of a pre-trained CNN as initial weights before the training process. Transfer learning has been shown to be useful in solving image classification problems of various domains, such as medical image

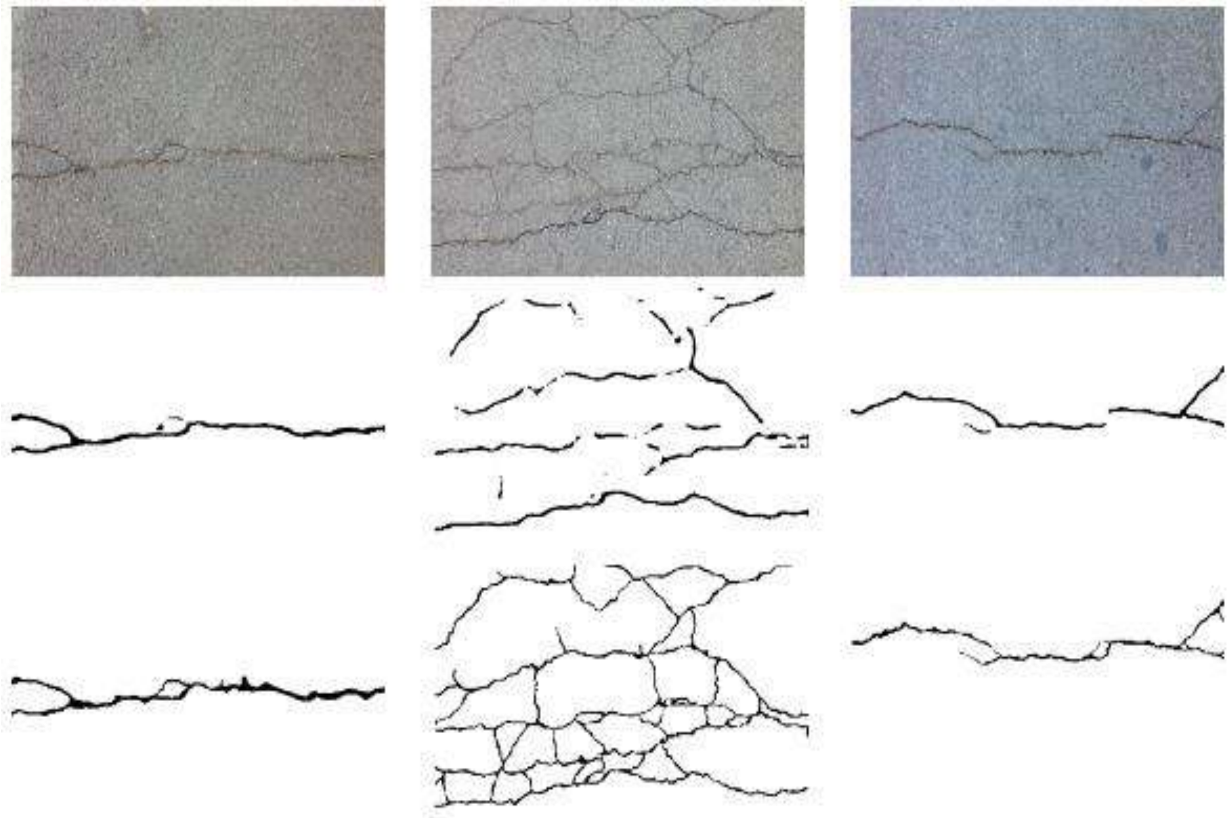

Figure 2. Results of residual network on CrackForest dataset (from top to bottom: original image, network prediction, ground truth)

processing [12]. In this context, we propose a deep residual network with transfer learning. Figure 1 illustrates the training and testing process of the proposed network. In this paper, the residual network with 152 layers, pre-trained by ImageNet dataset were used to detect cracks in images.

3 Experimental study

In this section, the performance of the deep residual network is analyzed. The training and test process of network was implemented in Python code. All experiments were performed on desktops with GTX 1080 Ti GPU and an Intel Core i7-7700 processor. The network was trained with a dataset used for the CrackForest [13], which is the existing crack detection method. The dataset consists of 118 images of the road surface in Beijing city acquired by iPhone5 with focus of 4mm, aperture of f/2.4, and exposure time of 1/134s. The images contain various types of noise, such as oil stains, road-specific textures, and shadows. The resolution of images is $480 \times 320 \times 3$. Each image has a pixel-level ground truth labeled manually. All pixels except for the crack pixels are classified as background.

For direct comparison with the CrackForest algorithm [13], the experimental environment was set in the same manner. The precision, recall, and f1-measure, by examining the correspondence between the predicted pixel and ground truth, were calculated to evaluate the proposed network. We followed the assumption of the CrackForest algorithm that the predicted pixels which are within 5 pixels from the ground truth pixel are considered to be true positive pixels. 71 images of the dataset were used as training data, and the remaining 47 images were used as test data. The results are shown in Fig. 2, and the performance comparison between the proposed network and CrackForest algorithms are summarized in Table 1. Experimental results show that crack detection using the deep residual network is superior to the existing CrackForest algorithms with k-nearest neighbors algorithm (KNN) and support vector machine (SVM).

4 Conclusion

This paper proposes a deep residual network with transfer learning for pixel-level crack detection. The proposed deep residual network demonstrates better accuracy than traditional image processing and machine learning algorithms in pixel-level crack detection. The proposed network is able to quantify the geometry of cracks on various roads by performing pixel-based crack detection with high accuracy. If the network can be utilized in a variety of road image dataset with future studies, it is expected to help the asset managers establish proactive road maintenance strategies.

Table 1. Result evaluation on CrackForest dataset

Method	Precision	Recall	F1
CrackForest (KNN)	80.77%	78.15%	79.44%
CrackForest (SVM)	82.28%	**89.44%**	85.71%
CrackForest (One-Class SVM)	81.25%	86.45%	83.77%
Deep residual Network	**93.57%**	84.90%	**89.03%**

Acknowledgement

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Patch-based crack detection in black box road images using deep learning

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Abstract -

This paper proposes a method for patch-based crack detection of black box road images, for efficient road pavement monitoring. The proposed method is based on deep learning and consists of two modules: road extraction and crack detection. The road extraction module uses the segmentation process of a Fully Convolutional Network (FCN) called FCN-8s to leave only the road area in the image. The crack detection module performs patch-based crack detection on the extracted road area using a convolutional neural network. To the best of the authors' knowledge, the proposed method is the first attempt to detect road cracks of black box images, which are not orthogonal but skewed actual road images.

Keywords – Crack detection; Deep learning; Patch-based analysis; Road surface monitoring

1 Introduction

Proactive road maintenance is an important process for repairing road defects like cracks. For proper maintenance, monitoring of road surface conditions should be performed frequently for large areas. However, it is difficult to efficiently inspect pavement conditions with conventional monitoring methods utilizing inspectors or special vehicles. Recently, mobile devices such as mobile phones and automobile black boxes have become popular. As the performance of the camera mounted on the mobile device increases, it is possible to observe the surface condition of the road by the device attached to the windshield. If a method to utilize this video data for road condition monitoring is developed, significant improvement is expected in the traditional road monitoring method.

Various computer vision algorithms and machine learning based models have been developed for automatic road crack detection. A widely used vision-based crack detection method was to detect the morphological features of cracks by detecting the intensity change of pixels [3,5,7]. Some studies were based on machine learning approaches, which derived features of crack images through a large number of images, and then classified the images into crack and non-crack, or analyzed the types of cracks [4,5,9]. Recently, crack detection methodologies using deep learning have been emerging. Deep learning trains the weights that make up the neural network model based on a large amount of images, and conducts crack detection even with complex backgrounds. The crack detection study using deep learning is divided into patch-based and pixel-based method [1,2,10]. In this study, deep learning based method for detecting cracks in the unit of patch is pursued in black box images.

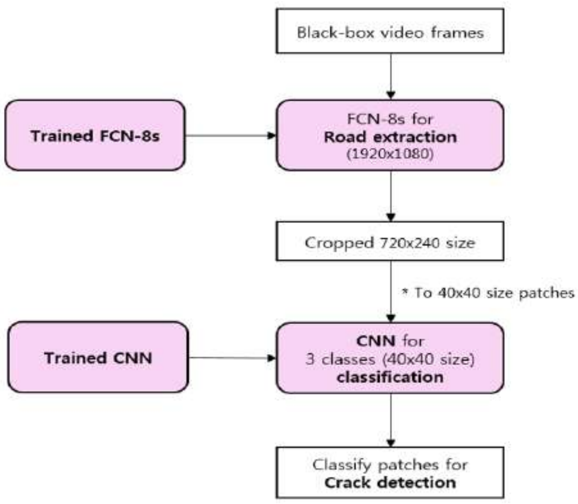

Figure 1. The patch-based crack detection of black box images.

2 System description

Figure 1 shows the patch-based crack detection method proposed in this study, and the method consists of two modules. The first module performs road extraction using a Fully Convolutional Network (FCN) architecture [6], and the second module performs crack detection in the extracted road area using the CNN model suggested in this paper. Cropping is performed between the first module and the second module, in order to limit the area to which the CNN is applied in the extracted road image.

Areas other than roads within a black box road image are not needed when performing crack detection. For the extraction of the road area only, the first module utilizes the segmentation process of FCN-8s [6] which consists of the 13 upstream convolutional layers of VGG16 [8] and an upsampling process. The second module divides the extracted road surface into several small images and then classifies each image into three classes: crack, lane, and others. In this study, a CNN architecture was designed to detect cracks in image patches with a 40 × 40 pixel resolution.

The proposed CNN model consists of five convolutional layers, three pooling layers, and two fully connected layers. The kernel sizes of the convolutional layers are determined considering the small size of the input image. The kernel sizes of the first convolutional layer (C1) and the second convolutional layer (C2) are7 x 7 and 5 x 5, respectively. The kernel size of the remaining convolutional layers (C3, C4, and C5) is 3 x 3. The pooling layers (P1, P2, and P3) are used for maxpooling to reduce the size of the feature map by half. The first fully connected layer (FC1) has 128 channels and the last fully connected layer (FC2) contains three channels for the classification into the three classes. Figure 2 shows more information about the CNN model for crack detection.

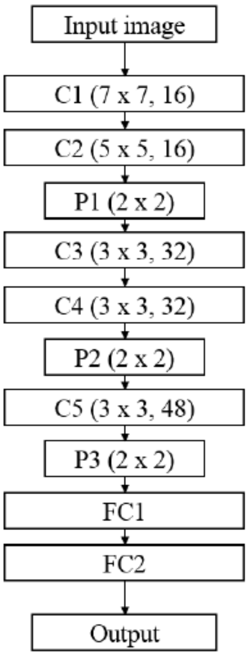

Figure 2. The CNN architecture for crack detection

3 Experiments and Results

The road extraction model was trained with 352 images of 1920 × 1080 pixel resolution, while the CNN model for crack detection was trained with 30,000 images of 40 × 40 pixel resolution. For testing, a total of 50 black box images were used. The black box images were cropped to 720 x 240 pixel size after the road extraction process. In the cropped image, patches that contain non-road areas were excluded from the analysis for crack detection. Consequently, 7259 patches of 40 x 40 pixel size were classified into the three categories. The results of the road extraction were a precision of 98.78% and a recall of 96.13%. In equations (1) and (2), True Positive is the number of patches classified as crack among the real crack patches. False Positive is the number of patches classified as crack among the patches truly belonging to either lane or others. False Negative is the number of patches classified as lane or others when the patches are in fact cracks.

$$\text{Precision} = \frac{\text{True Positive}}{\text{True Positive} + \text{False Positive}} \quad (1)$$

$$\text{Recall} = \frac{\text{True Positive}}{\text{True Positive} + \text{False Negative}} \quad (2)$$

The classification accuracy of the three classes was 91.13%, and the precision and the recall were 88.14% and 72.01%, respectively. The factors that reduce the performance of crack detection are as follows. A patch containing a lane or shadow was, in some cases, misclassified as crack; this is a factor of affecting the precision. On the other hand, patches with blurry cracks or with both cracks and lanes caused the recall to drop.

The results of the road surface extraction and crack detection are given in Figure 3. The middle images in Figure 3 is the result of road extraction and the background pixels are marked with white. The patches classified as crack are indicated with yellow borders in the images on the right side in Figure 3.

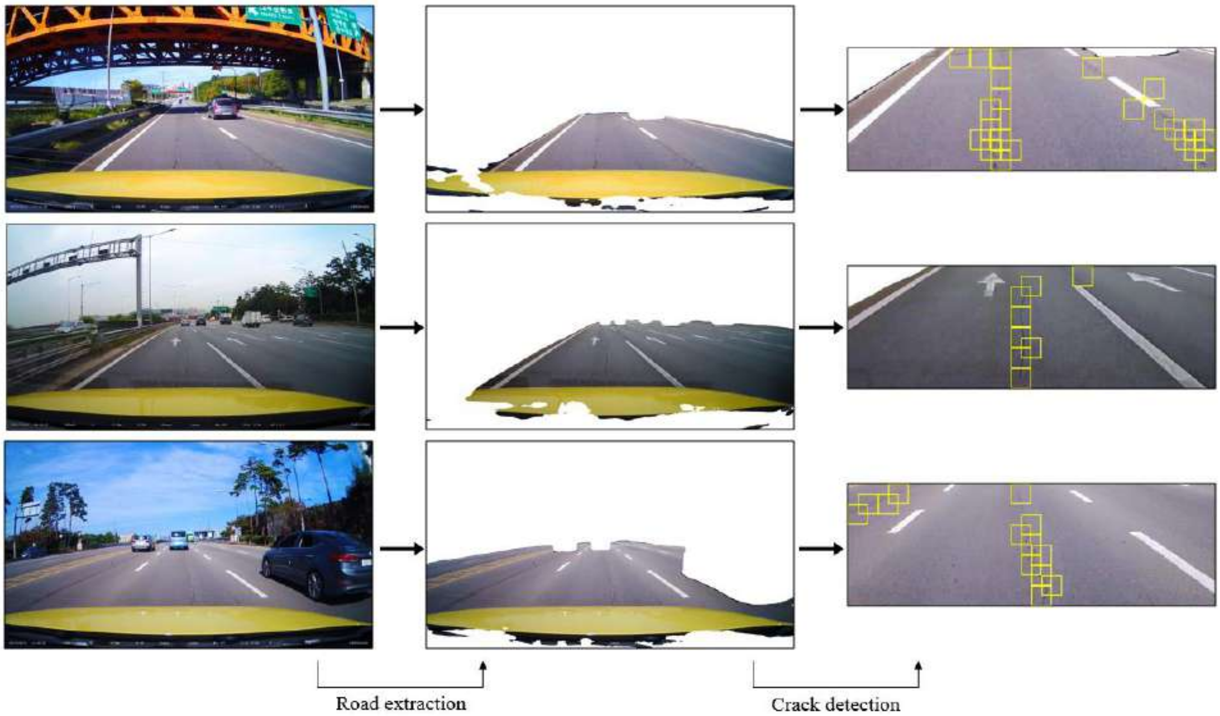

Figure 3. Three example images of road extraction and crack detection; original images (left), road extraction images (middle), and crack detection images (right).

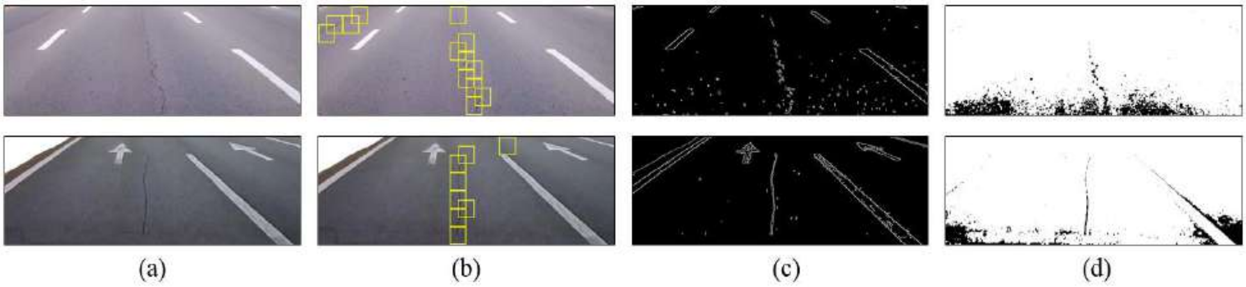

Figure 4. Comparison with other operators for crack detection; (a) original images, (b) proposed method, (c) Canny edge detector, (d) simple thresholding.

Figure 4 shows the comparison of the results of applying the proposed method and other methods to the black box images. In Figure 4(b), the yellow patches were classified as crack by the proposed CNN model. It can be seen that the patches with cracks were well distinguished from the lane and the undamaged road area. Figure 4(c) shows the results of crack detection using Canny edge detector. Because of the large difference in pixel intensity values between the cracks and the surrounding roads, cracks can be detected by the edge detector, but noisy parts of the road surface or lanes can be detected as cracks, as shown in Figure 4(c). Figure 4(d) shows the results of crack detection by simple thresholding. Because cracks are darker than road surfaces, they can be detected when images are binarized with an appropriate threshold. However, since the intensity of the road surface is not constant, areas with dark intensities other than cracks can be mistaken for crack. To detect cracks with an edge detector or thresholding, preprocessing of the input data or post-processing of the output image may be required. However, in the proposed method, no other work is required before and after the crack detection in the extracted road area.

4 Conclusion

This study suggested the use of black box images for effective road maintenance. The black box image has the merit of being easy to acquire; however, the image has a limitation that it is skewed and objects such as other vehicles or buildings are included in it. In this study, we applied the deep learning to extract the road surface from a black box image and detect the crack patches on the extracted road surface. The performance of the road extraction was more than 96% for both precision and recall; it was performed well as a preparatory work for detecting cracks in an image. In the crack detection, the accuracy, precision, and recall were 91.13%, 88.14%, and 72.01%, respecetively. For more detailed analyses, the patches can be categorized into more than three classes or more training data can be used. Using the data of many vehicles equipped with mobile devices as proposed in this study, efficient pavement management can be achieved.

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A Mathematical Job Allocation Model to Maximize Career Development Opportunities for Construction Workers

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Abstract

The job allocation models used in construction projects have been designed mainly to meet the objectives of the employers such as maximizing productivity and tended to pay inadequate attention to meet the needs and objectives of construction workers. Meeting the objectives of workers, however, is a basic component of corporate social responsibility and vital to improve job satisfaction among construction workers. Among various items on wish-list of workers, availability of career development opportunities in projects stands out as a key factor affected considerably by job allocation decisions. This paper presents an innovative mathematical model for optimization of task allocation in construction projects to maximize the availability of career development opportunities to individual construction workers, paving the way for their career development. A Euclidean distance function in n-space is specified as objective function of career development which measures and compares the distance between ideal skill levels of employees to initial skill levels and developed ones after job allocation. The proposed model is applied to an illustrative case project involving the allocation of tasks to workers with different skill levels in a construction contractor company. Results show a successful task allocation which has contributed to workers' occupational development and made them closer to their ideal skill level.

Keywords

Construction Industry; Career Development; Mathematical Model of Job Allocation; Corporate Social Responsibility

1 Introduction

The construction industry is one of the extensive global employment sectors which provides career opportunities for a noticeable percentage of the labour market and contributes to a substantial share of the world's gross domestic product (GDP) [1]. As a result, construction industry is acknowledged widely as a fundamental driver of national productivity in most developed and developing countries; and therefore improving the productivity of construction industry through workforce planning has been a major focus of research over the past several decades [2, 3]. Numerous novel conceptual and mathematical workforce planning techniques have been developed to improve the productivity of workers through optimizing the hiring and firing decisions [4], multiskilling strategy [5], training of existing workers [6], optimization of crew composition [7], and optimizing the job allocation [8]. However, while meeting the productivity objectives is crucial, placing the focus solely on productivity and other financial objectives of the employers, has led to a significant level of ignorance with regards to effects that job allocation decisions may have on main players in construction projects, i.e. the workers [1]. One of the direct effects of job allocation decisions on workers is related to amount of career development opportunities made available to them through allocated jobs [9].

Accordingly, job allocation planning provides an opportunity to maximize the availability of career development opportunities for the workers. However, to the best of our knowledge, there is currently a lack of a systematic method to account for career development opportunities in optimizing the task allocation in construction projects. The existing literature on career development opportunities in task allocation to workers is mainly limited to (1) qualitative models of career interests, choice, and development [10-12], and (2) theoretical propositions such as psychological theory of work adjustment [13], and social learning theory of Career Decision Making (CDM) [14]. In the present paper, an innovative mathematical model for optimization of task allocation to maximize career development opportunities available to construction workers is proposed. The proposed model is applied to and solved for an illustrative case project involving the allocation of tasks to workers with different skill levels in a construction contractor company.

2 Mathematical Model Formulation

The model proposed in this study aims at solving the problem of job allocation among available personnel with the objective of maximizing the career development opportunities available to workers. It is assumed that employees begin their career from entry level and promotions to higher levels are based on achieving the experience requirements for different skills required for the level. In addition, it is assumed that the amount and breakdown of the work to be performed, number of available labour forces along with their skills and proficiencies, and their historical learning rates are known or have been previously measured. The objective is to distribute the given workload among individual workers in a way that a majority of workers take a step forward in meeting the skill experience requirements for promotion to the next career level.

2.1 Terminology and Notation

We denote I as the set of primary skills of workers. For instance, if the skillsets required in a building operation include reinforcement iron-working, carpentry, and concrete pouring, these three primary skills are elements of the set I.

The skill level of the worker is denoted by set E. Five stages of skill development is presumed based on the modelling of human expertise suggested by Dreyfus [15]. Description of the abilities and requirements of each skill level are explained in 'Table 1'. Skill level acquisition is mainly assumed by years' experience. First skill level i.e. $\mathrm{e}=1$ indicates a novice worker (0–3 years of experience), $\mathrm{e}=2$ represents a beginner worker (3-7 years of experience), $\mathrm{e}=3$ denotes a competent one (7-15 years of experience), $\mathrm{e}=4$ indicates a worker with proficient skill level (15-22 years of experience), and $\mathrm{e}=5$ indicates an expert worker (22-30 years of experience).

The type of the activity is denoted by set J; e.g. values of $j=1,2,3$ may be assigned when working on columns, beams, and slabs, respectively. In the classification adopted by this study, each activity is comprised of several tasks which are denoted by set M. It is worth mentioning that task $m \epsilon M$ corresponds to one or more required skill(s) $i \epsilon I$.

2.2 Decision Variables and Objective Function

The objective targeted in this study is to maximize the personnel's career development opportunities. The decision variables are the amount of work allocated to each worker in each skill (y_k^i). Based on literature, we assume that promotion of each individual worker to the next career level is achieved through improving his experience in required skills to the minimum level of experience required by the next level position [12]. The enhancement in skill level of individual k in skill i due to performing the allocated job (y_k^i) is formulated by the equation below:

$$S_{ik} = \dot{S_{\imath k}} + \alpha_{ik} \times y_k^i \tag{1}$$

Where $\dot{S_{\imath k}}$ is the initial level of experience of individual k in skill i, y_k^i is amount of work related to skill i which is allocated to individual k, α_{ik} is a coefficient obtained from learning rate of individual k in skill i, and S_{ik} is the improved skill level of individual k in skill i after performing the allocated task.

We assume that each employee has a particular goal in terms of desired job and level in the organizational hierarchy, which we herein define as the ideal job for the candidate. According to Parsons [16], employee's active involvement in selecting their career instead of letting chance to operate in looking for a job, may lead to considerable increase in their job satisfaction and efficiency as well as a decrease in employers' costs. The ideal job for each candidate can be determined based on candidate's desired job or best fit based on various psychological character analyses methods. We assume that the key requirement to qualify for the ideal job is to achieve the required skill levels for the job which can be identified from Human Resource (HR) data and qualification of current/previous individual holding such positions. In this study, parameter $\ddot{S_{\imath k}}$ is defined to represent skill level associated with the ideal job for candidate k. The current skill levels of worker and those associated with the ideal job of the workers are defined by vectors presented in equations (2) and (3), respectively.

$$\dot{S_{\imath k}} = \left(\dot{S_{1k}}, \dot{S_{2k}}, \dots, \dot{S_{\imath k}}\right) \tag{2}$$

$$\ddot{S_{\imath k}} = \left(\ddot{S_{1k}}, \ddot{S_{2k}}, \dots, \ddot{S_{\imath k}}\right) \tag{3}$$

A value of zero for the level of a particular skill is possible and means no experience in that particular skill. A Euclidean distance function in n-space, E^n, is defined to quantify the distance between the current level of skills and the ideal level of skills as defined by equation (4). The distance of each individual k from its ideal job is therefore defined as:

$$D_k = \sqrt{(\ddot{S_{1k}} - S_{1k})^2 + (\ddot{S_{2k}} - S_{2k})^2 + \dots + (\ddot{S_{\imath k}} - S_{ik})^2} \tag{4}$$

Accordingly, to maximize the career development opportunities for each worker, the objective function is defined as follows:

$$\text{minimize } max_{\{k \in K\}}\ D_k \tag{5}$$

Table 1 Different skill levels and their descriptions

Skill level, E	Title of skill level	Description
1	Novice	The worker can assist other experienced workers, and transfer goods.
2	Beginner	The worker can work independently on simple tasks under supervision of a senior worker.
3	Competent	The worker can perform all simple and complicated tasks within his skill range.
4	Proficient	The worker can perform all tasks, within his skill range, quickly and with minimum deficiencies.
5	Expert	In addition to performing all tasks, within his skill range, the worker can supervise other workers.

2.3 Constraints

The constraints considered in this model are presented by equations (6) to (8). Constraint (1) sets the total amount of work allocated to personnel to be equal to the total amount of work available in the project for the entire crew in a particular trade. Judgments of fairness include four distinctive types of perceptions. Distributive justice perception adopted in this study aims at ensuring fair distribution of hiring, promotion, and workload allocation over individuals [17]. Constraints (2) and (3) are defined to account for distributive justice. Constraint (2) ensures that the maximum working hours per week for each worker does not exceed the specified limit value (U_k). Constraint (3) ensures a minimum weekly number of allocated hours of work (L_k) to each worker. In these two constraints, w is total number of weeks in lifespan of the project.

$$Constraint\ (1):\quad \textstyle\sum_{k=0}^{K} y_k^i = H_k \quad ,\forall i \in I \tag{6}$$

$$Constraint\ (2):\quad {y_k^c}/{w} \le U_k \quad ,\forall k \in K \tag{7}$$

$$Constraint\ (3):\quad {y_k^c}/{w} \ge L_k \quad ,\forall k \in K \tag{8}$$

3 Case Study; Results, and Discussion

The illustrative case study considered in this paper involves allocating the tasks in a construction operation to a crew of ten personnel (P_1 to P_{10}). The activity involves three different tasks characterized by six different skill types, presented by S_1 to S_6, with five competency skill levels considered for each skill type. The initial and ideal level at each skill are known for all workers and presented in 'Table 2'. Upper and lower bound of weekly workload of each individual worker are considered as 10 and 60 hours, respectively. COUENNE, an open source code for solving global optimization problems [18], was selected to solve the problems within AMPL framework. Two different scenarios are considered to evaluate the effectiveness of our model in maximizing the career development opportunity as characterized by the distance of each worker to its ideal skill set. In the first scenario our proposed model is used to allocate the tasks, while in the second scenario the tasks are allocated by applying the conventional productivity maximization job allocation approach [8]. The outcome which includes developed skill levels for all employees after job allocation, allocated hours to personnel, and final distances (the distance between developed and ideal skill levels) are presented for both scenarios below.

Table 2 Initial, ideal, and newly developed skill levels along with allocated hours at each skill type

Personnel	Skill	Initial skill level	Ideal skill level	Developed skill level		Allocated hours (y_k^i)	
				Scenario 1	Scenario 2	Scenario 1	Scenario 2
Bob Johnston (P_1)	Carpentry (S_1)	3	5	3.12	3	38	0
	Concreting (S_2)	4	5	4.06	4	31	0
	Electrician (S_3)	2	5	2	2	0	0
	Form working (S_4)	1	3	1.19	1	49	0
	Plastering (S_5)	4	5	4	4	0	0
	Reinforcement (S_6)	0	3	0.24	0.48	120	240

George Fine (P_2)	Carpentry	0	3	0	0	0	0
	Concreting	3	4	3	3	0	0
	Electrician	3	5	3.60	3	201	0
	Form working	2	4	2.06	2.48	32	240
	Plastering	1	5	1.02	1	6	0
	Reinforcement	1	3	1	1	0	0
Jerry Jones (P_3)	Carpentry	2	4	2.05	2	25	0
	Concreting	3	5	3.07	3	33	0
	Electrician	3	4	3	3	0	0
	Form working	1	4	1.10	1	52	0
	Plastering	2	4	2	2	0	0
	Reinforcement	0	3	0.26	0.48	128	240
John Rossi (P_4)	Carpentry	2	4	2.08	2.48	39	240
	Concreting	1	2	1.03	1	32	0
	Electrician	2	4	2	2	0	0
	Form working	1	4	1.15	1	50	0
	Plastering	2	4	2	2	0	0
	Reinforcement	0	3	0.12	0	118	0
Martin Davidson (P_5)	Carpentry	0	3	0.11	0	38	0
	Concreting	2	4	2.06	2.29	32	145
	Electrician	4	5	4	4.67	0	170
	Form working	4	5	4.19	4	49	0
	Plastering	3	5	3	3	0	0
	Reinforcement	2	4	2.24	2.54	121	270
Michael McCray (P_6)	Carpentry	0	1	0.08	0.15	39	76
	Concreting	3	3	3.03	3	32	0
	Electrician	3	5	3	3	0	0
	Form working	3	5	3.15	3	49	0
	Plastering	0	3	0	0.33	0	164
	Reinforcement	1	3	1.12	1	119	0
Mike Parks (P_7)	Carpentry	1	5	1.18	1	181	0
	Concreting	2	4	2.09	2	45	0
	Electrician	2	4	2.66	2	222	0
	Form working	1	3	1.09	1.64	45	320
	Plastering	0	4	1.19	0	397	0
	Reinforcement	0	2	0	0	0	0
Nick Lewis (P_8)	Carpentry	0	4	0.12	0.38	40	127
	Concreting	2	4	2.06	2.28	32	142
	Electrician	4	5	4	4.65	0	163
	Form working	4	5	4.19	4	48	0
	Plastering	3	5	3	3	0	0
	Reinforcement	2	4	2.23	2.19	119	95
Steve Gill (P_9)	Carpentry	2	4	2.08	2	40	0
	Concreting	1	3	1.03	1	32	0
	Electrician	2	5	2	2	0	0
	Form working	1	3	1.15	1	49	0
	Plastering	2	4	2	2.48	0	240
	Reinforcement	0	2	0.12	0	118	0
Tom Peterson (P_{10})	Carpentry	0	3	0	0	0	0
	Concreting	1	4	1.27	1.23	135	118
	Electrician	3	5	3.09	3.36	31	122
	Form working	2	5	2.27	2	135	0
	Plastering	3	5	3	3	0	0
	Reinforcement	1	3	1	1	0	0

Table 3 Initial and final distances for personnel

Personnel	Initial Distance	Final Distance	
		Scenario 1	Scenario 2
Bob Johnston (P_1)	5.29	5.03	5.03
George Fine (P_2)	6.16	5.96	6.02
Jerry Jones (P_3)	5.57	5.32	5.32
John Rossi (P_4)	5.57	5.39	5.41
Martin Davidson (P_5)	4.79	4.56	4.38
Michael McCray (P_6)	4.69	4.56	4.45
Mike Parks (P_7)	6.93	5.96	6.77
Nick Lewis (P_8)	5.48	5.25	4.94
Steve Gill (P_9)	5.38	5.24	5.22
Tom Peterson (P_{10})	6.24	5.96	6.02

In first scenario job allocation has been performed more uniformly and evenly leading to a wide-ranging and comprehensive skill development of all employees. As it can be seen in 'Table 2', in our model, all employees have received a certain amount of hourly job in at least three skill type and most of them have developed their skill levels for almost all of skill types. On the contrary, in second model, majority of personnel have been allocated a large amount of job in just one skill type leading to overdevelopment of one skill whereas keeping the rest undeveloped.

Results from 'Table 3' indicate all employees have become closer to their ideal skill level after job allocation. However, some subtleties reveal when comparing the final distances derived from two scenarios. Maximum final distances in first and second scenarios for all personnel are 5.96 and 6.77 , respectively, while there is a similar maximum initial distance of 6.93 for both cases. This small change from 6.77 to 6.93 in second scenario, emphasizes the argument that conventional productivity oriented approach does not consider the employee's perspective objectives e.g. career development into optimization planning. In contrast, results of our model indicate a noticeable contribution to career development of employees and their closeness to ideal skillset (%13.9 for 'P_7' and %4.8 on average). Another important advantage of our model is concentration on career improvement of critical employees with longest initial distances to make sure final distance for none of organization personnel does not exceed a threshold value. On the other hand, second model has unnecessarily reduces the distance for employees such as Martin Davidson (P_5) and Michael McCray (P_6) whilst there were people with higher priority for job allocation such as Mike Parks (P_7) and Tom Peterson (P_{10}).

4 Conclusion

In this paper, an innovative job allocation optimization model was presented to maximize the career development opportunities available to the construction workers. Maximizing the career development opportunities available to workers through a systematic workforce planning may lead to considerable increase in job satisfaction of workers and attractiveness of construction industry to skilled workers. The results of the case study presented in this paper showed that implementing our proposed model compared to the conventional productivity oriented model results in a significant improvement in the career development of workers in general and %13.9 advancement in workers' closeness to their ideal skill set in critical employees. In addition, the proposed model allocates the available jobs more uniformly leading to multi-dimensional skill development of employees whereas in the other model, most of personnel have been allocated a large amount of job in just one skill type leading to overdevelopment of one skill while keeping the rest undeveloped. For future studies, work on more complex problems consisting of various construction trades with personnel from different departments within an organization is suggested. In addition, more constraints reflecting time specific and site specific limitations and regulatory conditions can be considered into modelling.

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Combining Building Information Modeling and Ontology to Analyze Emergency Events in Buildings

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Abstract

Building information modeling (BIM) is a new technology that supports lifecycle information management for buildings. Ontology, derived from philosophy, is another technology utilized to describe real-world entities and to infer their semantic relationships. Each year disasters such as fires, earthquakes and floods affect not only buildings but all occupants inside, and hence, identification of critical building elements and devices vulnerable to a disaster is a must in order to perform countermeasures to ensure the safety of lives and property. At present, many simulation-based tools such as FDS have been successfully employed to mimic the impact of a disaster. Nevertheless, most of such approaches consider only the spatial or geometry data of a building. Other building-related attributes such as materials and equipment that certainly influence how a disaster proceeds have not been thoroughly examined. Thus, this research develops BIM plug-in programs to extract not only geometry but building materials and equipment/devices information in order to craft a disaster-specific ontology. Semantic relationships are modeled using Semantic Web Rule Language (SWRL) constructs, so as to represent the interdependencies among building elements and devices under a given disaster. The combined approach can accommodate not only spatial relationships but functional constraints pertaining to internal building elements and devices. It may help disaster mitigation officials forecast and assess the impact and progress of a disaster. A train station was utilized to demonstrate the proposed approach, with focuses on the fire and flood types of disasters. Better disaster mitigation strategies can be prepared if the proposed approach is adequately utilized.

Keywords –

Building Information Modeling; Ontology; Ontology Web Language; Semantic Web Rule Language; Disaster Mitigation

1 Introduction

Much research on critical infrastructure (CI) can be traced back to U.S. President Clinton's Executive Order 13010, which formally defines CI as the systems that whether real or virtual, the stop and destruction of these systems will have an impact on national society, economic and public health security [1]. The September 11 attacks on the World Trade Center demonstrate the urgent need for subsequent CI-related studies [2-3]. Among CI-related studies, one area of significant importance is about interdependency relationships among CI systems. For instance, according to the survey conducted by Mendonça and Wallace, the total loss of the power, telecommunication, oil and gas, and water sectors in the September 11 attacks due to indirect factors is more than that due to direct factors [4]. The term, CI interdependency, has been coined to denote such a cascade effect because one system failure will often trigger a series of failures of different CI systems. Mitigating the impact of such CI interdependency relationships thus has been regarded as one of the most important tasks during the disaster response phase.

Although it is worthwhile to collect and analyze the interactions of large-scale CI systems at the national level, in practice for a CI owner or operator it may be more useful and desirable to limit the CI scope to all components within a CI system, i.e., investigating the interdependency relationships among all subsystems or components of a given CI system. For instance, a wafer fabrication plant is often a large building with numerous specialized equipment and devices. Such a building is too valuable to be shut down. Thus, when a disaster occurs, one needs to identify vulnerable building elements and devices so as to perform appropriate countermeasures in hopes of mitigating the impact resulting from CI interdependency.

In the architecture, engineering and construction (AEC) sector, building information modeling (BIM) is a new and promising technology and can be defined as a digital representation of the physical and functional characteristics of a facility [5]. In fact, a building's BIM model contains not only detailed geometric information but materials and equipment-related data. Such data sets could be a valuable asset to disaster mitigation; nevertheless, previous research majorly investigates how to extract the geometry information of a BIM model in support of disaster simulation tools such as FDS. During the course of a fire incident, actually both the location and status of each automatic sprinkler device may need to be obtained and analyzed so as to help predict how the fire will proceed. BIM certainly can provide such assistance and requires further investigations.

Ontology comes from the philosophy field. It can be used to represent BIM and disaster-related attributes and to perform reasoning tasks. In other words, if we can build a BIM model close to the real world and transform it into an ontology model with disaster-related concepts, we could apply the ontology model to the identification of critical building elements and devices vulnerable to a given disaster. To this end, the objectives of this research include:

1. Developing a model transformation tool that can extract needed BIM data into the proposed ontology model. The design of the ontology model is based on the disaster-mitigation-related literature. Nevertheless, actual values or individuals need to be generated based on the corresponding BIM model. A computerized tool is developed to expedite such a transformation process.
2. Solving the problem regarding the lack of semantic relationships in the current BIM-based geometry data set. Current disaster simulation tools can extract only the geometry data; however, having such semantic relationships can further improve the disaster simulation process. For instance, currently if a FDS-based tool is supplied with the geometry descriptions of each room or space, since doors or windows inside such rooms or spaces are represented as openings, they are not linked into any wall. Because fire can be prevented from entering another room if a fire-proof door is installed, such information can be easily encoded into a semantic relationship and be used to help the disaster simulation process. Nevertheless, in current geometry data sets derived from BIM tools, no such semantic information exists.
3. Developing rule-based constraints to locate critical building elements and devices vulnerable to a given disaster. Once the semantic relationships can be encoded into the proposed ontology model, one can develop Semantic Web Rule Language (SWRL) constructs to formally describe different behaviors under the context of a different disaster. SWRL constructs are frequently utilized in other domains with ontology models and reasoning tools. Here the SWRL constructs pertaining to functional constraints of a critical building element and devices will be defined.

The manuscript is structured as follows: Section 2 describes important literature to highlight key features of ontology models. Section 3 presents the proposed approach with tools, while Section 4 discusses the application with a real case data set. Finally, Section 5 concludes the research and indicates future research work.

2 Related Work

In the previous research conducted by Leite and Akinci [6-7], they proposed an ontology model with four classes for handling building emergency events, i.e., Content, ContentType, BuildingSystemSupply, and Threat. ContentType is defined as the type of an asset within a building. An asset (represented as Content) in a building must be worth protecting, e.g., a painting or a critical device. These assets require the building to provide some supply (represented as BuildingSystemSupply), which may be water, electricity, gas, etc., to work properly; therefore, asset types and building systems supply form a many-to-many relationship. Additionally, one asset may be subject to one or more threats (represented as Threat). It is hypothesized that the threat posed by a building system is causing the asset to be destroyed or malfunctioned.

In their papers, two types of such damage have been identified. The first one is about spatially adjacent influence, which makes the assets close to the destruction point also damaged. For example, the water leakage event can be expanded from the lowest position of the event. If the leakage problem is not fixed, all the assets close to the event location will be affected. The second type is about connectivity, which means that any system failure resulting from a pipeline can be expanded into other places along the pipeline, so as to create more system failures, such as power failure. In fact, all the systems needing power supply within the circuit loop are stopped. Cascading effects may occur among all the devices and equipment needing such systems.

In order to solve the problem regarding CI interdependency, researchers have utilized the input-output model and obtained positive feedback [8]. However, there are two issues associated with this approach. One is about the difficulty of collection inoperability information for a facility, which is common to almost all CI-related approaches. The other is about the difficult of identifying all relationships between the target CI systems or components. The input-output approach does not provide a clue to such identification; hence, qualitative analysis such as expert evaluations is often utilized and have been criticized for years.

Because BIM contains both geometric and non-geometry information, it could be used to assist in the CI analysis. Based on Leite and Akinci's ontology model, the research team utilizes BIM tools to automatically craft an ontology model representing the spatial layout of a given building. Since it is difficult to manually convert a BIM file to an ontology model, such model transformation tools can not only reduce the conversion time but ensure the quality of the model, which has not been seen or reported in the literature.

3 Methodology

This section will first describe the entire research process. First use the Add-in function of Autodesk Revit 2015, the BIM model editing software. Using Revit API to write the convert program from BIM model to ontology model in Visual Studio 2015. Extract and compile the BIM model information required by the disaster impact architecture into the OWL file format. Then use Protégé 5.0.0 to turn on the converted ontology model. Begin to construct disaster impact rules with semantic web rule language. And use the disaster impact rules to infer the impact of disasters. Finally, we use semantic query web language to present the results through the query.

Autodesk Revit 2015 provides Add-In function. Users can use it to write C # programs with the Revit API for working in Revit. The OWL file format is derived from the RDF file format and is similar to the XML format. Therefore, the convert program is mainly written using the XML library and the Revit API. OWL file format can be divided into declaration area, category area, property area and object area. The declaration area is an OWL file attribute declaring to be used in other areas, such as swrlb, owl, swrl, and protege, and is represented by xmlns: swrlb. Since the OWL file format is not, after all, an XML file format, not all XML libraries are available. This method requires the use of a flexible XML library to successfully write. For example: Some XML libraries have header files that do not allow "<? Xml version =" 1.0 "?>", Which must be added to "encoding" or something else. The category area is a category that is written in the ontology model, for example: the category of the door, denoted by "<owl: Class rdf: ID =" Door "/>. The property area describes the Object Property and Data Property in the ontology model. The difference with the category area is that it needs to define Domain and Range. The object area is Instances that describe the ontology model. The formation of the OWL file format across four regions enables Protégé to access a nearly real-world ontology model transformed from BIM with vast information.

Revit API can be divided into the main categories of objects, names and declarations. An object's category and name are simple compared to the association. From ElementCategoryFilter, you can filter the required object names and categories to IList <Element>. However, it must describe its association with other objects. That is, it must describe what gate is at what wall in the object area of the OWL file. In the program, in addition to using the Insert function to describe what the door is located outside the wall, there is also the use of BuiltInParameter.ELEM_ROOM_NAME and BuiltInParameter.ELEM_ROOM_NUMBER describes the relationship between the object room. Finally, the format in the OWL file is combined with the object information retrieved by the Revit API.

After the process of conversion to form ontology model, you can use ontology editing software Protégé to open it. SWRL is to write rules and make inferences about ontology models. Flooding was used as a case study in this research. First, the categories of disaster impact architecture include doors, walls, rooms, appliances, flooding, sockets and switchboards. Properties then include HasDoor for the door, Height for the flooding height, and DoorFlood for the flooding height of the door. HasDoor is mainly the object-to-object property, and Height is the property of the object and the value. Through the combination of the object and the property, HasDoor describes the framework for analyzing the disaster impact.

Then, in order to set the rules, the pre-defined scenarios need to be designed. Therefore, based on the research needs to infer the impact of flooding, the key is to prove the feasibility of this method, so only in a simple way to infer the flooding, and mainly flooded by the door so highly reduced way to research.

The research will be set to the following assumptions:

1. Assume that the main corridor flooded at a height of 2000mm.
2. The doors have their height reduction coefficient. If the flooding height is 2000mm, the coefficient of the door is 0.8, then after the door, the flooding height is 1600mm.
3. Electrical appliances have their damage height and damage properties. If the damage height of the computer is 600mm and the flooding height is 800mm, then the computer's damage attribute will be YES.
4. Sockets and distribution boards have their own damage properties, and will affect the electrical properties of the stall. If the distribution board is damaged, then all the electrical stalls. If the outlet

is damaged, the appliance associated with it will stop.

5. The rule will deduce that if the flooding height of a certain area is a certain height, it will affect the flooding height of all the places, the situation of electrical damage and stalling.

The research is based on the above assumptions SWRL preparation. It should be noted that the rules of the SWRL because it can only be simple reasoning and no difference set concept. After the rules are written, inferences about the effects of flooding can be obtained, and its process as shown in Figure 1.

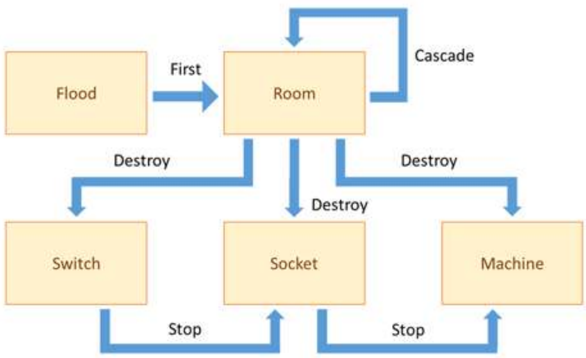

Figure 1. Reasoning Process Diagram

The disaster impact rules of SWRL can be divided into two types, one is to infer the flood level, as shown in Equation 1, and the other is to infer the electrical state, as shown in Equation 2.

Room(?r) ^ HasWall(?r, ?hw) ^
HasDoor(?hw, ?hd) ^
Room(?r2) ^ HasWall(?r2, ?hw2) ^
sameAs(?hw, ?hw2) ^ differentFrom(?r, ?r2) ^
DoorWeak(?hd, ?dw) ^
RoomHeight_1(?r2, ?rh1) ^
swrlb:multiply(?new, ?dw, ?rh1)
-> RoomHeight_2(?r, ?new)

(1)

Machine(?m) ^ MaBreakLevel(?m, ?mabl) ^
MaInRoom(?m, ?mair) ^
RoomHeight_1(?mair, ?rh1) ^
swrlb:lessThanOrEqual(?mabl, ?rh1) ->
MachineDestroy(?m, "1"^^xsd:int)

(2)

Equation 1 first use *sameAs(?hw,?hw2)* to find rooms with the same wall, and then use *HasDoor(?hw, ?hd)* to select the wall has door, and use *differentFrom(?r, ?r2)* to exclude the room itself, and next use *DoorWeak(?hd,?dw)* to get the height reduction factor, and finally get the reasoning result of flood. Equation 2 mainly uses *swrlb:lessThanOrEqual(?mabl, ?rh1)* to compare *MaBreakLevel(?m, ?mabl)* and *RoomHeight_1(?mair, ?rh1).* If *MaBreakLevel(?m, ?mabl)* is less than or equal to *RoomHeight_1(?mair, ?rh1)*, MachineDestroy(?m, "1"^^xsd:int) will be expressed as 1, that is, destroyed.

SQWRL uses MySQL-like settings to further refine the results of SWRL for completeness and alignment. it uses in the research was to reduce the flooding height by using a factor so that the flooding height only decreased as a result of the cascade effect. Therefore, the method of determining the final value is to take the maximum value of the result as its setting criteria. The rule also uses numbers to indicate the stalling and destruction of equipment. If the flooding height reaches its height of damage and stall, set its associated value attribute to 1 to indicate that the device has been destroyed or stopped. Corollary results were generated electrical stall table, electrical damage table, flooded altimeter table, socket damage table, outlet stop table and power distribution board damage table. Equation 3 uses SQWRL to select the flooding height of each room.

Room(?r) ^ RoomHeight_All(?r, ?rh) ˚
sqwrl:makeBag(?b, ?rh) ^ sqwrl:groupBy(?b, ?r)
˚ sqwrl:max(?max, ?b) -> sqwrl:select(?r, ?max)

(3)

4 Case Study

The model of Taipei MRT Nanjing Sanmin Station comes from the project and station managers. The station's main body is divided into three floors, ground floor, hall floor and platform floor.

The top floor of the MRT station is the ground floor. It usually has a device to prevent floods. The height of the pump's switch is located at a flood level of 200 years plus 110 cm. The basic height of the entrance also increased. Used to prevent flood entering MRT station.

The hall floor for the main flow through the site. The name of the space through the hall can be divided into recreation room, environmental control room, uninterruptible power system room.

The bottom of MRT station is platform floor. This floor more facilities for the ventilation shaft, exhaust and intake. It is mainly to solve the pressure caused by vehicles entering and leaving the rise and fall. And by air pressure to provide vehicle braking and deceleration features. In addition, this layer is also equipped with pumping equipment, pumping equipment for the entire body of the site. While others are similar to the through-hall, possessing the space for environmental control and power supply system and also based on the symmetry.

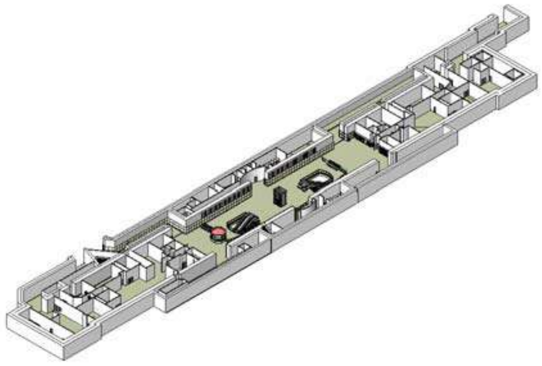

Figure 2. Hall Floor of Nanjing Sanmin Station

However, the details of the platform floor are not clear. And the ground floor only has entrance, not too many objects. Therefore, research proposals, the main reference to about the hall floor. Only in this way can we get the complete and accurate research results.

When the building information model is transformed into the ontology model via Add-in, the model itself is not a model that can be correctly analyzed.

In addition to the designer's design habits may cause differences, but also the following possibilities. First, the BIM software used in this research is Revit, which has the settings for connecting appliances and sockets. However, there is no clear classification of objects requiring electricity, resulting in the need for electricity if not for mechanical equipment, electrical equipment, etc. Objects, are required in the program clearly defined as the need to power the object is also defined in the ontology editor software. Second, most building information models have not yet added switchboards, sockets and electrical appliances. Therefore, the model used for the construction of the Nanjing Sanmin Station in this research has not been provided yet. Therefore, it is necessary to establish electrical appliances in each area so as to understand flooding mechanism is the more appropriate approach, and the ontology model to add, is a more efficient approach.

As shown in Figure 3, this is the result of SWRL reasoning. RoomHeight indicates the water height of the room affected by flooding. RoomHeight_1 indicates the results obtained by cascading the first flood effect. Similarly, RoomHeight_2 is the second time. And RoomHeight_All sets the value of all the water heights. The research is to find the maximum of all water heights because we defined the water height of room comes from the other rooms that would cause this room the highest water height after cascading effect.

However, although SWRL successfully deduced the result, it did not sort it out. So we need to use SQWRL to rank the results we need. As shown in Figure 4, the research continues by writing the SQWRL in SWRL and shows the results in the program, while Figure 5 shows the detailed results. In Figure 5, “1” indicates that the appliance has been damaged, “0” indicates that the appliance continues to operate, and Total_Machine_Stop tab, Total_RoomHeight tab, Total_Socket tab and Total_Switch tab in addition to the Total_Machine_Destroy tab.

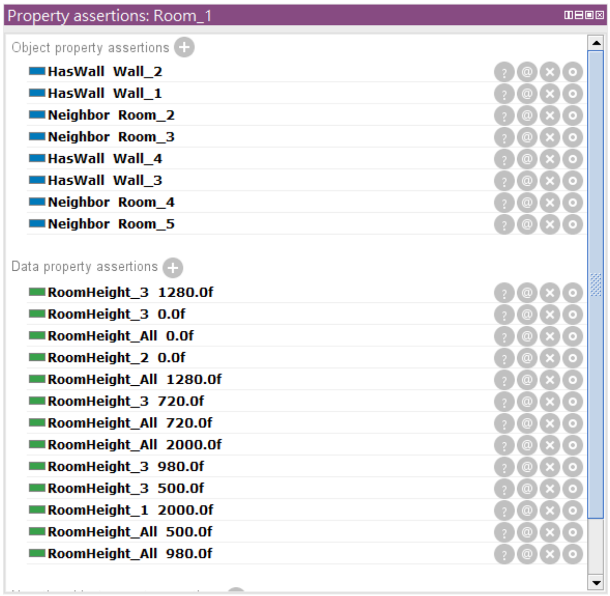

Figure 3. Room_1 Result of SWRL Reasoning

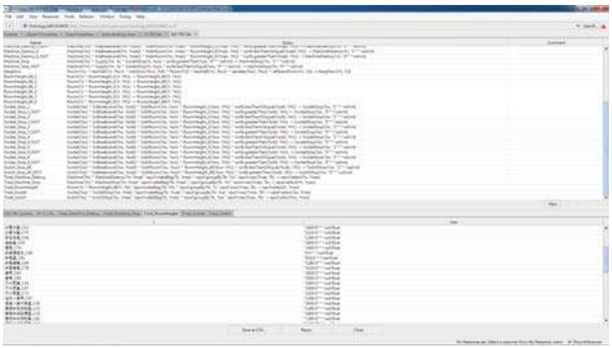

Figure 4. Result of SQWRL Query

5 Conclusions

When analysing the progress of a disaster inside a building, one needs a model representing the building's spatial layout with important building-material-related attributes. Certainly, the Revit tool developed in this research can provide such information. In addition, disaster-specific properties and their interactions with buildings can be modelled using SWRL constructs. Take flooding as an example, one may be able to retrieve watertight doors, sluice gates and pumps information from a building's BIM model. In the future, if this method can be more complete and common method of analysis, or design the user interface to allow users to make self-defined special analysis, and based on this research method, we can analyse all kinds of disasters comprehensively at the same time and use them to get the advantage of more disaster-affected data quickly. Finally, we can analyse the matrix and vector of input-generating model. In addition to contributing to disaster preparedness, expecting to send the results back to Autodesk Revit for visualization will provide a better understanding of the impact of the disaster.

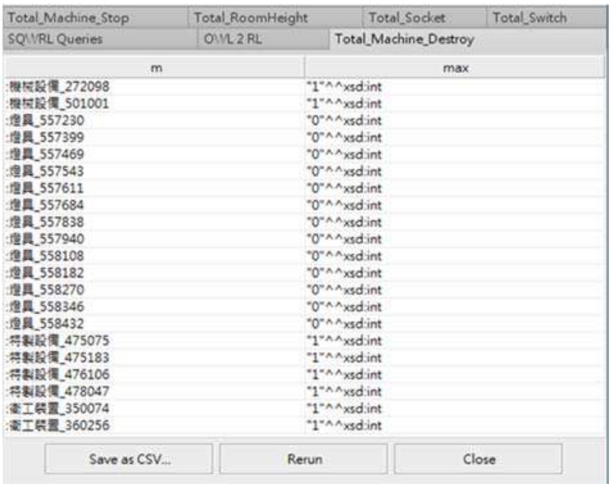

Figure 5. Detail Result of SQWRL Query

Taking the ontology model as the main reasoning can take advantage of the logical relationship between objects. If the building information model as the main body of analysis, in addition to only have to write the program is not good at logic inference analysis, the building information model of the huge information also caused the analysis time-consuming. The ontology editorial software is not only based on the advantages of logical reasoning, but also because of its SWRL and SQWRL, making it easier to write and manage. Taking the information model of the Taipei MRT Nanjing Sanmin Station as an example, the time it takes to open and change is quite time-consuming. Even when operating on a general-purpose laptop computer, it still takes about 3 minutes for the program to open the file, or change the viewing angle to wait 5 seconds. The ontology model of file capacity is better. The file size of the information model of the Taipei MRT Nanjing Sanmin Station is about 2 GB. However, the information extracted by ontology accounts for at most 1 MB, and the difference between the visualizations is not significant. Due to programmatic transformation and the extraction of valid information, it is expedited to research the reasoning. However, the version of Revit API has been greatly changed. Due to the complexity of building information model, the classification of its functions is cluttered and flawed. If this weakness can be solved, Software replacement or version has a considerable improvement, will be able to have more space for this research.

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Image-based Indoor Localization using BIM and Features of CNN

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Abstract –

This study suggests an indoor localization method to estimate the location of a user of a mobile device with imaging capability. The proposed method uses a matching approach between an actual photograph and a rendered BIM (building information modeling) image. A pre-trained VGG 16 network is used for feature extraction. Experimental results show that the best image matching performance can be obtained when using features from pooling layer 4 of VGG16. The proposed method allows for indoor localization only by image matching without additional sensing information.

Keywords –

Indoor Localization; Cross-Domain Image Matching; Convolutional Neural Network; Feature Extraction;

1 Introduction

A technique of acquiring the position and orientation information of a person in indoor environment is essential for presenting the information that the person needs at the location. The construction industry utilizes indoor localization technology for maintenance of facilities using augmented reality [4], evacuation route guidance in case of disasters [3], and understanding work situation [1,7].

Vision-based indoor localization estimates the user's location based on visual information obtained from the indoor image. Image-based indoor localization methods can utilize a pre-built image dataset that contains indoor photographs. Since the images in the dataset have the basic information (position and orientation) necessary for localization, the person's indoor position can be estimated by searching the image in the dataset, most similar to the photograph taken indoors. However, it is time-consuming and labor intensive to build datasets of indoor environments for localization.

This study utilizes the BIM (building information modelling) model of a building for its indoor localization, to construct the image dataset. BIM has become increasingly utilized as it is proving its versatile utilities in the construction industry. Since BIM contains a range of information of a building and it is easy to extract information at the location of interest, BIM is also used for localization with sensors [6-8].

This paper proposes a deep learning-based method to estimate the indoor position of a mobile device user, using an image dataset constructed from a BIM model. A deep learning network is an advanced form of traditional neural network, strengthened by the ability to learn important features without relying on human intervention. Image features extracted from a deep learning network are used to compare similarity between photograph and BIM-based images. That is, the visual characteristics of BIM is used for image-based indoor localization, without using additional sensing information.

2 Methodology

The image dataset is constructed by rendering indoor BIM views to images. The rendered images are visually similar to the actual indoor photographs, but there is a difference in style because the domains are different from each other, as shown in Figure 1. The evaluation of the similarity between images for image retrieval is mainly done by comparing their features. Conventional feature extraction methods, such as SIFT (scale-invariant feature transform), have been widely used for the same domain comparison in previous studies.

Figure 1. BIM image (left) and photograph (right) taken from the same location and orientation

This study proposes using the CNN (convolutional neural network) for feature extraction to compare indoor photographs and BIM images. CNN is a kind of deep neural network, appropriate for image processing. It consists of stacked layers and learns to extract meaningful features of images. In a convolutional layer, features in adjacent parts in image are extracted in a form of two dimensional array (feature map) and semantically related features are merged in a pooling layer [5].

Feature maps that passed through each layer of pre-trained CNNs are used as features of images for the cross-domain image retrieval. The CNN network trained for object classification with ImageNet dataset [2], a large image dataset, shows excellent performance in feature extraction even when applied to other datasets [9].

A pre-trained CNN is used to match indoor photographs with BIM images in the dataset based on the similarity between images. The evaluation of the similarity between the cross-domain images for image matching is mainly done by comparing their features with cosine distance. Figure 2 shows the proposed method.

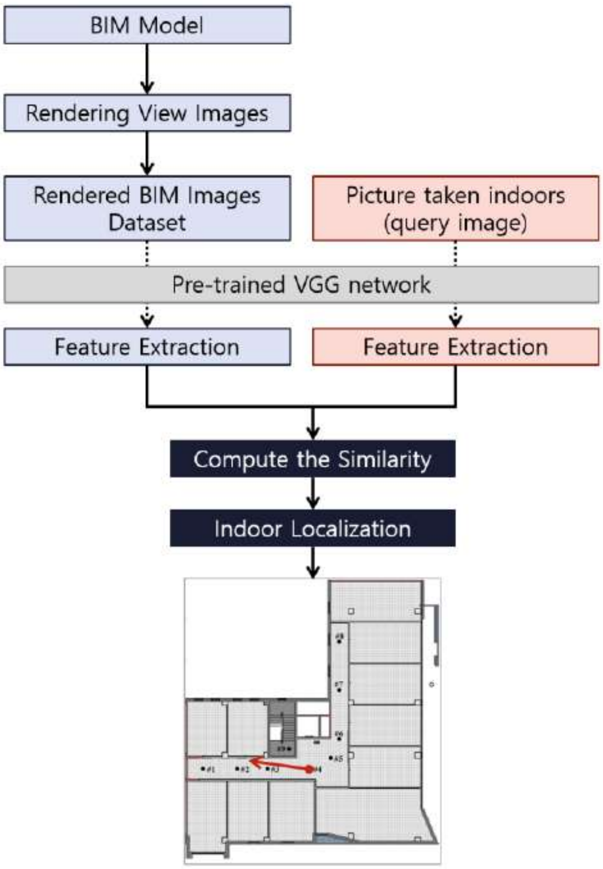

Figure 2. Image matching for indoor localization using BIM and CNN features.

3 Experiment

Experiments were carried out at the North Wing of the 1st Engineering Building of Yonsei University in Korea. As shown in Figure 3, the BIM image dataset for the experiment consists of images rendered in various directions at nine locations.

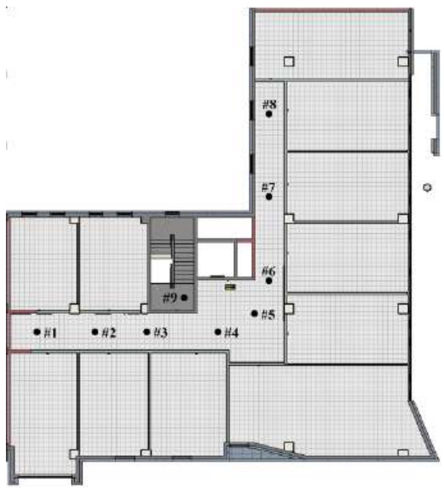

Figure 3. Floor plan of the building where the experiment was performed and the locations selected for view extraction.

Two datasets were created to evaluate the performance of the method. Level 1 dataset contained images with relatively fewer overlapping views as shown in Figure 4(a), and Level 2 dataset contained views in all directions, which resulted in more overlapping views as shown in Figure 4(b). The indoor photographs were taken in the same location and direction as the BIM images of the dataset, and the similarity with the dataset images was evaluated.

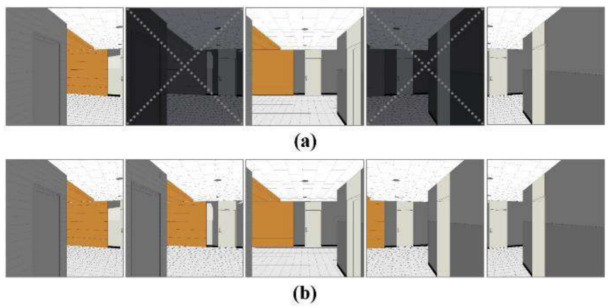

Figure 4. Examples of dataset images; a) Level 1: fewer overlapping views; b) Level 2: more overlapping views.

The VGG 16 network [10] was used as a CNN in the experiment. There are five pooling layers in the VGG

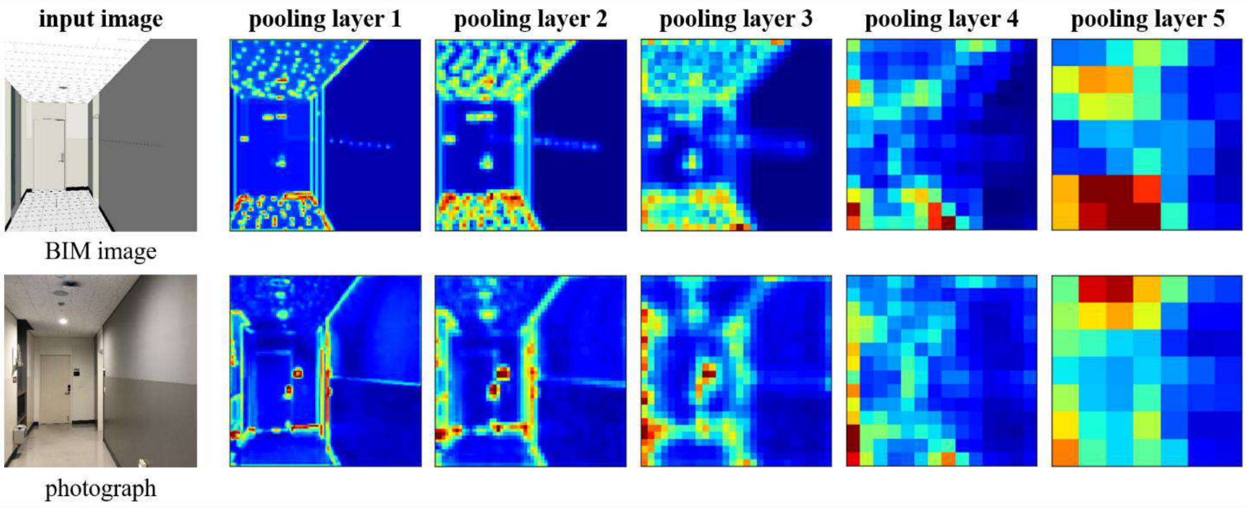

Figure 5. Visualized feature maps of BIM image and indoor photograph

network. The VGG network in the experiment was pre-trained with ImageNet dataset and the outputs of five pooling layers of the pre-trained VGG 16 network were used as features of the image. To evaluate the similarity between the cross-domain images, features from the pooling layer of the same order were employed. For example, the second layer output of the network for the actual photograph was compared with the second layer outputs of the network for the BIM images.

Table 1 shows the results of image matching based on features obtained from each pooling layer of the pre-trained VGG network for the two datasets. When using the features obtained from pooling layer 4, the image matching accuracy is over 90% in both datasets.

Table 1. Experimental Result

Dataset (number of images)	Level 1 (54)	Level 2 (86)
	Accuracy (%)	
Pooling layer 1	64.81	54.65
Pooling layer 2	64.81	52.33
Pooling layer 3	79.63	77.91
Pooling layer 4	**92.59**	**90.70**
Pooling layer 5	74.07	75.58

4 Discussion

Experimental results verified the proposed image-based indoor localization method with the high matching accuracy. The BIM image that was selected as the most similar image to the indoor photograph had the information about indoor location and orientation. In other words, when the matching was correctly done, the position at which the indoor photograph was taken could be estimated by the proposed method.

This study revealed which layer of VGG 16 network extracts the most proper features for matching the indoor photograph and BIM image. Figure 5 exhibits visualized feature maps from each pooling layer when paired BIM image and indoor photograph pass through the VGG 16 network. As the network deepens, it can be observed that features corresponding to large parts of the image are gradually extracted. Through the features obtained from pooling layer 4, which shows the best performance, it can be inferred that a global descriptor representing the structural information of the indoor is suitable for the cross-domain image matching.

As shown in Figure 5, a noticeable difference in the arrangement of colors can be identified in feature maps extracted from the front of the network. In other words, when the domains between images are different, the features that stand out in the images can be different and the difference is more apparent for features extracted from a local area. Therefore, it can be confirmed that the global descriptor is required for cross-domain image matching, and the experimental result verified that the features extracted from pooling layer 4 have the best image matching capability.

The proposed method performed well both in Level 1 and Level 2 datasets. In Level 2, there were images with high degree of view overlap between images and the number of images was about 60% larger as compared with Level 1. However, the accuracy of image matching of Level 2 was not affected much–decrease by 2% compared with Level 1. These experimental results indicate that the proposed method can be applied well in larger indoor environments.

5 Conclusions

This paper proposes an image-based indoor localization method to identify a mobile device user's location and orientation by matching the indoor photograph acquired by the user to the image rendered from the BIM model. Features for evaluating the similarity between the indoor photograph and the rendered BIM image were extracted from the pre-trained VGG 16 network. A field experiment, involving a floor of an actual building, was conducted to verify the proposed method.

This study has three major contributions. First, since the existing BIM model is used, the labor required to construct the dataset is reduced compared to the existing methods. Secondly, the feature extraction layer most suitable for the cross-domain image comparison was identified in the VGG network. Finally, since the pre-trained CNN is utilized, the proposed method can be applied in another place without modifying the network.

As a future study, it is necessary to verify the proposed method with a dataset configured in a more diverse environment. In addition, since using only a single image for localization may have limitation, it can be supplemented by using multiple images for more accurate localization. The proposed method, with the additional research, is expected to improve the traditional facility management process.

Acknowledgements

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The Accuracy Enhancement of Architectural Walls Quantity Takeoff for Schematic BIM Models

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Abstract

The emergence of Building Information Modeling (BIM) technology makes the quantity takeoff process faster and more reliable. It helps reduce the effort in cost estimation to survey the cost feedback on alternative schemes in the early stages of design. However, at these stages, the quantity could be absent or in excess because the BIM model has a low level of development (LOD). The building elements that have layered structures such as architectural walls always face such problems. This is because during the construction phase, each layer may have a different dimension. For instance, the height of the interior finish layer of the wall may be shorter than that of the core layer. On the other hand, the walls in a BIM model during the early stages usually have low LOD. Each wall layer is not created separately and some walls may overlap structural elements because the designers need a schematic BIM model that is easy to create and manipulate. This research proposes a method that will improve the accuracy of the wall quantity takeoff in the schematic BIM model by applying the concept of BIM-based clash detection. The proposed method automatically detects the overlapped areas and subtracts or adds the material quantity of each wall layer without the need for editing the BIM model. The now accurate quantities can then be used in the chosen project delivery method where a cost estimation feedback is needed during the early stages of the design process.

Keywords –

Building Information Modeling, BIM, Quantity Takeoff, 5D BIM, Quantification, Early Stages Design, Schematic BIM Model, Clash Detection

1 Introduction

Quantity takeoff is a time-consuming task in the design and construction process. Traditionally, quantity takeoff is done manually based on 2D drawings' measurements. Quantity surveyors need specialized knowledge and experience to understand the set of design drawings; which are a series of 2D projections. They have to understand the design and decide the measurement method to be used for each building element. This process is time-consuming and the results from each quantity surveyor may not be the same.

In a conventional project delivery method or Design-Bid-Build (DBB), a precise quantity takeoff for detailed cost estimation is done after the design phase for bidding. However, there are other delivery methods such as Design-Build (DB) and Integrated Project Delivery (IPD) in which design and construction teams work together as an integrated unit from the onset [1]. One of the goals of these delivery methods is to reduce the projects' cost in order to deliver the project within the owners' budget. An accurate cost estimation during the early stages of the design can help the team to make more informed design decisions [1, 2]. Therefore, precise quantity takeoff during these early stages is important.

The emergence of Building Information Modeling (BIM) technology brings with it a new method of quantity takeoff, called a BIM-based method. This method uses geometry data: such as length, area, and volume as well as the objects information: such as category, name, and level in the BIM model for quantity takeoff. The BIM-based quantity takeoff method is proven to be faster and more reliable than the traditional 2D-based method [3]. However, this is not a straightforward or automatic process [2, 4]. Some quantity can be absent from the BIM model due to the incompleteness of the model compared to the real construction [5]. This issue usually occurs in the early stages of the design; where designers make a rough BIM model in order to explore the design. Some of the data has yet to be defined and some objects may overlap each other causing inaccuracies in the quantities reflected.

Architectural elements that are layered structures always have complications when measuring quantities off of them. For example, architectural walls are non-structural elements which are used to divide or enclose spaces. These walls can be built either between structural frames as an envelope of the building or as interior partitions to separate each room. Architectural walls consist of both a core structure layer which is typically masonry units or stud framing and finish layers which are typically plaster, tiles or wall panels. Each layer has a different size and quantity. For example, the plaster layer height on the interior may only go up to ceiling height whilst on the exterior, it may cover the surface of the beam above (see Figure 1). The measurement variable for the architectural wall materials is an area. In order to measure the accurate quantity of the wall, quantity surveyors have to measure the surface area of each layer separately. They cannot use the core layer area to infer the finish layer areas - as these would differ.

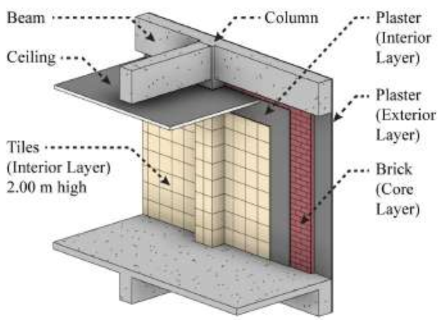

Figure 1. The example of the architectural wall that has four material layers and each layer has a different size and quantity.

In the early stages of the design, which cover the schematic design phase and design development phase, designers use a low Level of Development (LOD) [6, 7] for the wall elements in a schematic BIM model. The walls may overlap structural elements and each wall layer is not created as a separate element. This causes inaccuracies when extracting the wall and wall finishing quantities from the model.

The objective of this research is to find a new method to calculate the quantity of each wall layer in a schematic BIM model. The proposed method will improve the accuracy of the wall quantity takeoff in the early stages of the design when the BIM model is still schematic and is not as detailed. A concept of BIM-based clash detection is applied in the proposed method to enhance the BIM-based quantity takeoff. The scope focuses on architectural walls in a schematic BIM model where walls are at LOD 200 and 300 according to the Level of Development Specification 2017 by BIMForum [7]. The implementation is done by developing Dynamo [8] scripts for Autodesk Revit that can detect the overlapped area and subtract or add the material quantity for each wall layer. With this method, the chosen project delivery system such as DB or IPD will benefit from the accurate quantity takeoff for cost estimation in the early stages of the design. Furthermore, the designers or modelers can edit and adjust the BIM model easily since this method does not interfere with the original BIM model.

2 Literature Review

The strength of BIM is in its ability to share the same information among different disciplines. Hardin [1] discussed the uses of BIM in four types of project delivery methods, namely Design-Bid-Build (DBB), Construction Management at Risk (CM-at-Risk), Design-Build (DB), and Integrated Project Delivery (IPD). In the DBB method, the potential of BIM is limited because no information is shared between design teams and contractors during the design phase. Conversely, the use of BIM fits well in the CM-at-Risk, DB, and IPD methods because there are more integration and collaboration between the design and construction teams from early on. Consequently, the construction costs can be estimated during the design phase in order to verify whether or not the design is within the projects' budget.

According to Eastman et al. [2], the use of BIM for accurate quantity takeoff and cost estimation in the early stages of the project is most valuable. It is stated that "Today's use of BIM is typically limited to the late phase of design and engineering or early phases of construction. Use of BIM earlier in the design process will have greater influence on cost."

Although BIM-based quantity takeoff is reliable [2], some deviation still occurs due to practical and technical issues. With regards to the practical issues, the quality of the BIM model is a major concern [9]. Olsen and Taylor [5], interviewed general contractors and reported that up to half of the data, including architectural finishes, is absent from the BIM model because the model does not have enough detail yet. As for the technical issues, there are three causes. Firstly, some BIM software products do not have the specific modeling tools for some building elements. For example, there is no modeling tool to create formwork or rebar in ArchiCAD software [4]. Secondly, the software calculation method for some elements is incorrect [3]. And thirdly, some of the data is lost when transferring the files between BIM software products [2].

Several studies have been done on the improvement of BIM-based quantity takeoffs. Monteiro and Martins [4] explored BIM-based quantity takeoff using ArchiCAD software. This study showed that some elements could not extract the desired quantities. It was suggested to use another modeling tool in order to get the desired quantities. For example, using slab and wall tools to create stairs in order to get the volume of concrete needed. Kim et al. [10] proposed a BIM-based quantity takeoff method for building interior from a given space or room. Cho and Chun [11] proposed methods for estimating the cost of reinforced concrete structures in the design development stage by quantity takeoff and quantity prediction using data mining. Choi et al. [12] developed a quantity takeoff system that can estimate the quantity of the building frame in the early stages of the design. Rajabi et al. [13] developed a system that can estimate the quantity of mechanical, electrical, and plumbing in the early stages of the design. Lee et al. [14] studied a method to analyze the construction productivity. This study developed formulas to calculate structural formwork quantity by considering the overlapped area of concrete.

Although studies exist for quantity takeoff of many building elements, there has yet to be any research concerning the quantity takeoff for architectural walls.

3 BIM-based Quantity Takeoff Software and Its Limitation

BIM-based quantity takeoff is related to the Level of Development (LOD) of BIM elements. According to the Level of Development Specification Guide [6], LOD is divided into six levels. These are LOD 100, 200, 300, 350, 400, and 500. No standard exists to select the LOD for each BIM element in the phases of a buildings' lifecycle [6]. However, the study by Grytting et al. [15] concluded that in the early stages of the design, the LOD of BIM elements ranges from LOD 100 to LOD 300. Therefore, the proposed method used in this research is made for the wall at LOD 200 and LOD 300 since there is no definition of a wall at LOD 100 in the Level of Development Specification. The wall at LOD 200 is a generic wall with no material layers and the wall at LOD 300 is a single wall element with defined layers of core structures and finishes [7].

The early stages of the design are divided into two parts; a schematic design phase and a design development phase. In the schematic design phase, the designers may choose the walls at LOD 200 and make them penetrate columns and overlap with beams and floors of the level above. This is because schematic models need to be created and edited easily. When the design is then moved on to the design development phase, the designers may change the walls to LOD 300.

There are numerous BIM software tools on the market that can perform a quantity takeoff. However, this study makes use of Autodesk Revit software as it is currently the most popular BIM software for architectural works [5, 16, 17] and can perform a quantity takeoff efficiently.

Autodesk Revit has a schedule feature which extracts quantities in two different ways: by quantities and by material takeoffs. Quantity takeoff schedules extract data properties from the Revit elements. Material takeoff schedules extract data properties from the sub-components or materials of the Revit elements. Both quantities and materials can be extracted from architectural walls in Revit. If the wall layers are defined, the area of each material layer can be seen in a material takeoff schedule.

The investigation using Revit software reveals that when walls overlap with structural frames, the graphic shows the walls as being trimmed. When in fact, the area of the walls has not been deducted yet. Designers will then have to manually separate walls from the structural frames. One way to do this is to use the Join Geometry tool to create a cut between the walls and the structural elements. This tool will cut away the overlapped area of the walls. The quantity result is shown in Figure 2. However, editing every wall is time-consuming and the material quantities of the finish layers are still inaccurate. The areas of the interior and exterior finish layers that cover the surface of the structural elements are absent because the walls have already been cut with the structural elements (see red line in Figure 2).

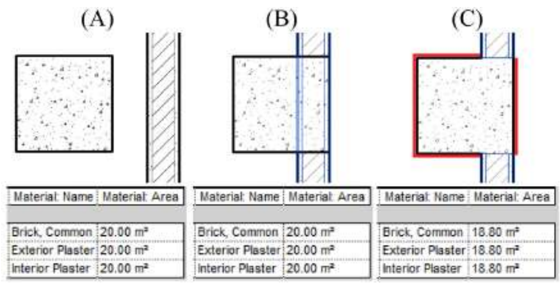

Figure 2. (A) Wall material area when the wall is outside the column. (B) Wall material area when drawing the wall through the column. (C) Wall material area decreased after using the Join Geometry tool. The red line shows the areas of the finish layers that are missing from the model.

Bečvarovská and Matějka [3] suggested that BIM models need to be made as close to the real construction as possible in order to perform an accurate quantity takeoff. Nevertheless, editing the model or creating each wall layer separately is time-consuming and impractical for the early stages of the design as the design will change many times.

4 Proposed Method

Every element in a BIM model is an object with semantic properties that represent the element in the real world. The semantic properties of each element, such as category and type can be used for multiple benefits. One benefit is that it can be used for checking the intersection between objects which is called BIM-based clash detection [2].

To improve the accuracy of the architectural walls quantity takeoff, the proposed method would apply the concept of BIM-based clash detection to assist in the BIM-based quantity takeoff. The main idea is to use the information from clash detection to subtract the exceeded quantity or add the absent quantity.

The implementation of the proposed method is done using Autodesk Revit 2018 with a Dynamo extension. Dynamo [8] is a visual programming extension in Revit that allows users to create algorithms to process data or geometry from the Revit model. Each function and variable in Dynamo is represented by nodes. Each node can be wired together to perform operations. The group of nodes can be packed into collections of nodes called packages. Packages can be published to the Dynamo website and shared with the online community.

The method for calculating the area of each layer of the architectural walls is divided into two sections: the calculation method for the core layer and the calculation method for the finish layer.

4.1 Calculation Method for the Core Layer of the Walls

The core layer of the architectural walls is the structure of the walls. The most common materials used for the core layer are masonry units such as bricks or concrete blocks and stud framing such as wood or metal studs. Generally, the core layer does not cover or intersect with other objects, thus the idea is to find the area of the wall that intersects with other objects such as columns, beams, and floors.

The workflow in Dynamo begins with the input of element categories from the Revit model. The categories are walls, structural columns, structural framing, and floors. The overall process is shown in Figure 3.

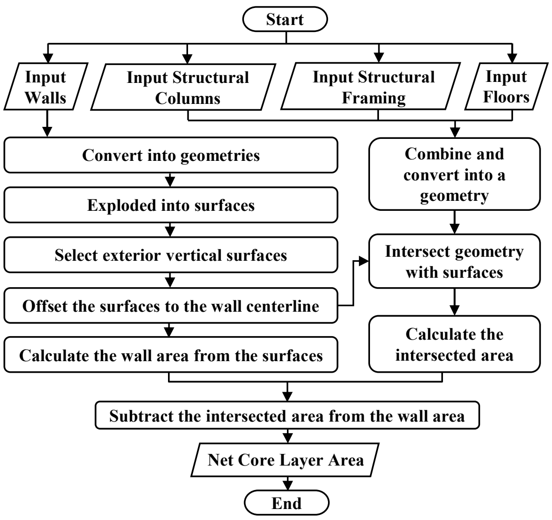

Figure 3. The flowchart diagram of the calculation method for the core layer of the walls.

The structural columns, structural framing, and floors will be combined and converted into a geometry. This geometry will be used to check the intersecting area of the walls.

The walls will then be converted into geometries and exploded into surfaces. The exterior vertical surfaces will be selected and offset to the wall centerlines. These surfaces represent the core area of the wall. They will be intersected with the structure geometry.

The intersected surface will be shown in the 3D view and the intersected area will be calculated and subtracted from the wall area. The result is the net area of the core layer (see Figure 4).

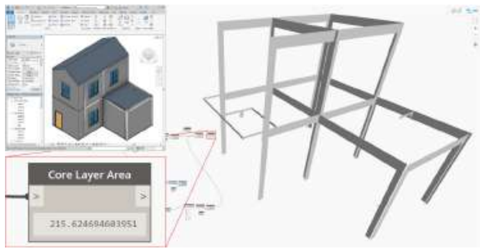

Figure 4. The surfaces of the walls that intersect with columns, beams, and floors are shown in Dynamo. The net core layer area of the wall is calculated.

4.2 Calculation Method for the Finish Layers of the Walls

Finding the area of the finish layers is more complex than the area of the core layer. This is because there are multiple scenarios for each type of finish layer depending on the materials used and the design. Usually, the materials of the finish layers are dependent on the material of the core layer.

The walls that have stud framing at their core, usually have wall panels as the finish layer. Examples of wall panels are wooden planks, gypsum board, fiber cement boards, and cladding. The area of the wall panels is usually equal to the area of the stud framing core as the panels attach to the studs. In this scenario, the same method used for calculating the core layer can be applied to this type of finish layer.

On the other hand, the walls that have the masonry at their core will usually have plaster as the finish layer. In some cases, tiles, wall paint or wallpaper will form the second finish layer on top of the plaster. The plaster, tiles, wall paint, and wallpaper usually only cover the surface of the structural elements that the walls cut through. Furthermore, on the interior, the height of the finish layers may not be as tall as the core layer. The height may only go up to the ceiling or it could have a custom height (see Figure 1). These scenarios need different methods to calculate the finish layer area.

The calculation method for the finish layers of the walls is divided into three parts: the method for the exterior finish layer, the method for the interior finish layer, and the method for the custom height interior finish layer. The concept of clash detection is still used here. Room elements in Revit will be used to check whether the surface of the wall is exterior or interior. The structural elements that intersect with the wall will be used to calculate the covered surface area of the finish layer.

4.2.1 Calculation Method for the Exterior Finish Layer of the Walls

The exterior finish layer is the wall layer that covers the outside surfaces of the building. The materials of these layers are typically plaster, tiles, cladding, or wall paint. This method is developed for the scenarios where the exterior finish layer covers the entire area of the exterior surfaces. The wall surfaces and the structural element surfaces that are exposed to the exterior are included in this method. However, it excludes the surfaces of the roof as well as the top and bottom surfaces of the floor, which typically have other materials.

The workflow in Dynamo begins with the input element categories from the Revit model. The categories are walls, structural columns, structural framing, floors, and rooms. The overall process is shown in Figure 5.

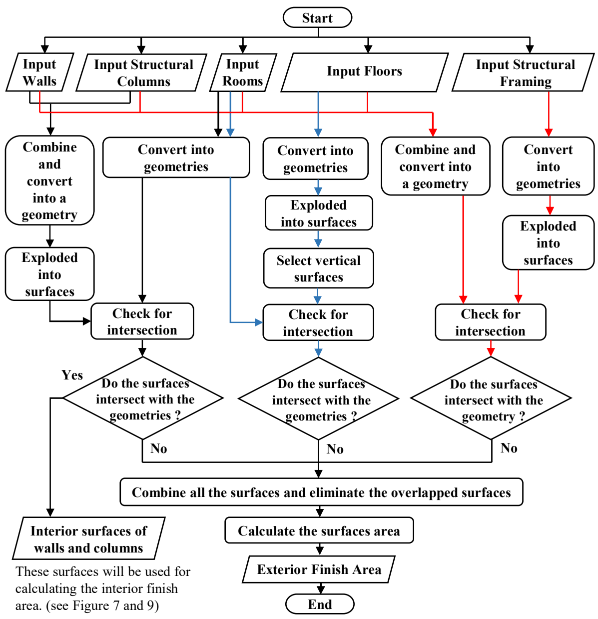

Figure 5. The flowchart diagram of the calculation method for the exterior finish layer of the walls.

In the first step, the walls and structural columns from each floor level will be combined and converted into a geometry. This geometry will be exploded into surfaces and each surface will be checked with the room geometries. The surfaces that intersect with the room will be interior surfaces which will be used for calculating the interior finish area. The surfaces that do not intersect with the room will be exterior surfaces which will be used in the final step.

The second step is to find the surface area of the structural framing (beams) that are exposed to the exterior. The walls, structural columns, floors, and rooms will be combined into a geometry. This geometry will be checked with the structural framing geometries that are exploded into surfaces. The surfaces of the structural framing that do not intersect with the geometry will be used in the final step.

The third step is to find the surface area of the floor edges that are exposed to the exterior. The floors will be converted into geometry and exploded into surfaces. The vertical surfaces will be selected. The rooms will be used to check and eliminate the interior vertical surfaces of the floors such as the interior hall and stairways. The remaining surfaces will be used in the final step.

The final step is to combine all the surfaces from the first, second, and third steps. The result is the surfaces of the wall, structural columns, structural framing, and floor edges that are exposed to the exterior. Thereafter the overlapped surfaces will be deleted. The remaining surfaces will be used to calculate the area of the exterior finish layer of the walls (see Figure 6).

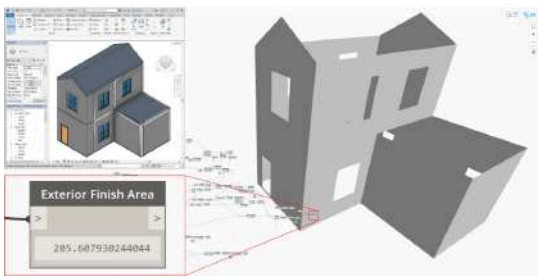

Figure 6. The surfaces of the exterior finish layer and the calculated area are shown in Dynamo.

4.2.2 Calculation Method for the Interior Finish Layer of the Walls

The interior finish layer is the wall layer that covers the inside surfaces of the building. This layer usually covers the surface of the walls and columns in the rooms. The height of this layer usually attaches to the top of the ceiling or the underside of the above levels' beams or floors if there is no ceiling in these rooms.

The interior surfaces of the walls and structural columns from the first step of the calculation method for exterior finish layer of the walls will be used. The overall process is shown in Figure 7.

In order to set the height of the interior finish layer, the Limit Offset property of each room must be set to the ceiling height or the desired height.

The rooms will be converted into geometries. These geometries will be used to subtract the height from the interior surfaces of the walls. The outcome surfaces will be used to calculate the area of the interior finish layer of the walls (see Figure 8).

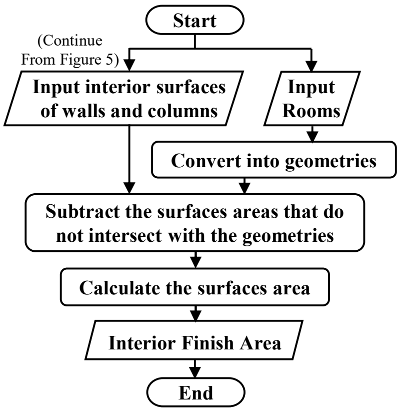

Figure 7. The flowchart diagram of the calculation method for the interior finish layer of the walls.

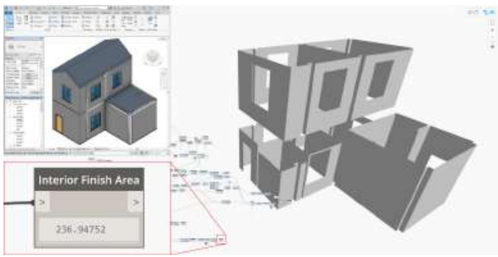

Figure 8. The surfaces of the interior finish layer and the calculated area are shown in Dynamo.

4.2.3 Calculation Method for the Custom Height Interior Finish Layer of the Walls

The interior finish layer may have a second layer. For instance, restrooms or kitchens may have a tile layer on top of the plaster layer. Sometimes the height of this layer will not go up to the ceiling height or up to the underside of the above levels' beam or floor.

The method is similar to the calculation method for the interior finish layer of the walls, but instead it will only calculate the areas for the selected rooms. The overall process is shown in Figure 9.

The desired rooms will be selected by inputting the rooms' name. The selected rooms' boundaries will be converted into surfaces. The surfaces will be extruded into 3D geometries. The height of the geometries will be controlled by the Number Slider node. These geometries will be used to subtract the height from the interior surfaces of the selected rooms. The outcome surfaces will be used to calculate the area of the custom height interior finish layer of the walls (see Figure 10).

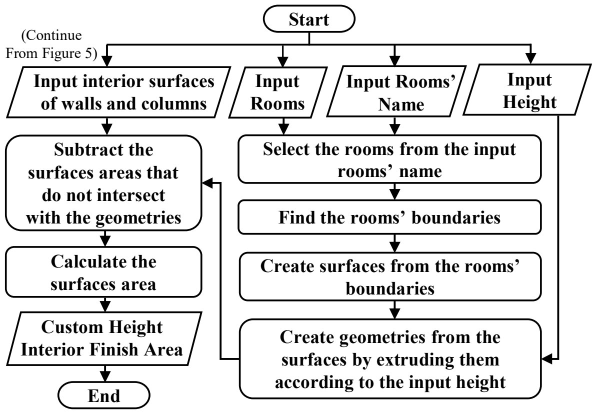

Figure 9. The flowchart diagram of the calculation method for custom height interior finish layer of the walls.

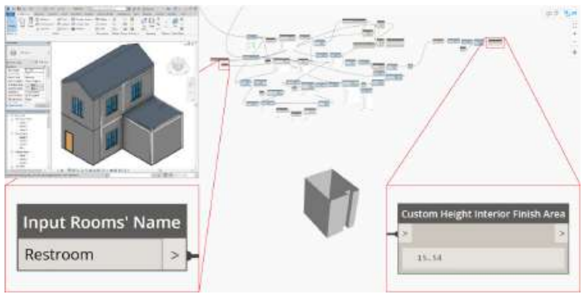

Figure 10. The interior surfaces of the restroom and the calculated area are shown in Dynamo.

5 Implementation and Validation

The implementation is done using two buildings as case studies. Two versions of BIM models were made in Autodesk Revit 2018. One is the schematic model for testing and the other is the detailed model for validating.

The two buildings are different in shape and number of floors, but wall materials, structure type, and level heights are at the same settings. The buildings have reinforced concrete columns, beams, and floors as its structure. The walls are brick masonry with plaster that covers the exterior and interior surfaces. The brick layer is 70mm thick and the plaster layer is 15mm thick. The restrooms have the tile layer on top of the plaster layer which is 10mm thick. The height of the tile layer in the restrooms is at 2.1m. The ceiling height of the restrooms is at 2.3m. The ceiling height of the other rooms is at 2.6m.

In order to compare the quantity of each wall layer, the wall at LOD 300 is used for the schematic BIM model. The walls are single elements with three layers; the core layer, the exterior finish layer, and the interior finish layer. The total wall thickness is 100mm. The walls are created by drawing through structural columns and overlapping with beams and floors. The developed Dynamo scripts are used to find the area of the core layer, exterior finish layer, interior finish layer, and a custom height interior finish layer in the restrooms (see Figure 11). The wall material takeoff from Revit will be compared with the result from the Dynamo scripts.

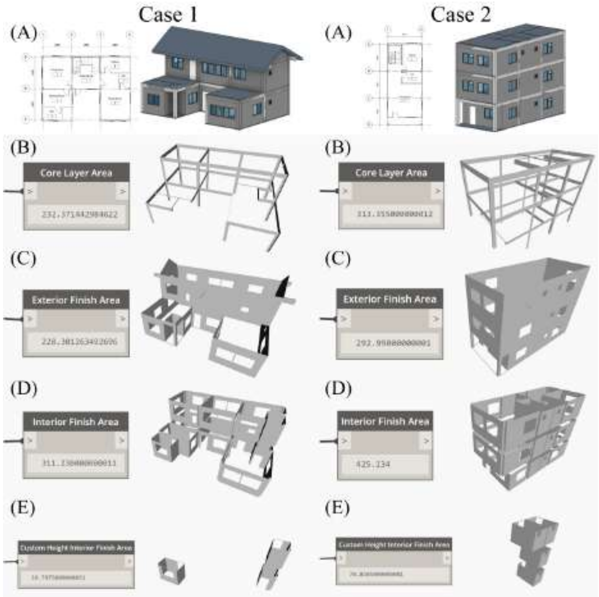

Figure 11. (A) The schematic BIM models of the two buildings. (B) The area of the core layer in Dynamo. (C) The area of the exterior finish layer in Dynamo. (D) The area of the interior layer in Dynamo. (E) The area of the restrooms' interior layer in Dynamo.

In the detailed BIM models, each wall layer is created separately. The height and the thickness of each layer are defined (see Figure 12). The material takeoff is done in Revit and the result will be compared to the result from the schematic BIM models.

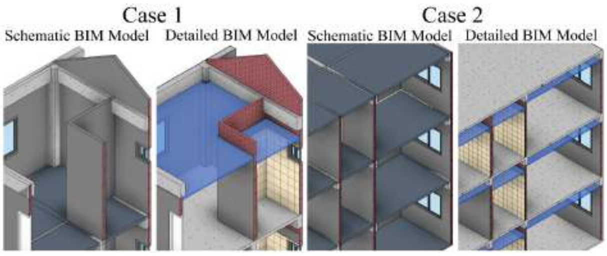

Figure 12. The comparison between schematic BIM models and detailed BIM models.

Table 1 and Table 2 show the comparison of the material area from the detailed BIM models, the schematic BIM models as well as the Dynamo scripts. The case number is written in the parentheses after the name of the wall layers. The results from the detailed BIM models form the baseline of this comparison. The results from the Dynamo scripts when compared to the baseline have about a ±1% deviation, which is acceptable. The deviation is caused by the thickness of the material layers in the detailed BIM models. On the other hand, the results from the schematic BIM models have a significant deviation.

Table 1. Comparison result between detailed BIM model and schematic BIM model

Wall Layers	Detailed BIM Model	Schematic BIM model	% Deviation
Core (1)	234.60 m^2	299.31 m^2	-27.58%
Core (2)	315.95 m^2	391.08 m^2	-23.78%
Ext. (1)	226.08 m^2	299.31 m^2	-32.39%
Ext. (2)	291.00 m^2	391.08 m^2	-34.39%
Int. (1)	314.65 m^2	299.31 m^2	4.88%
Int. (2)	426.83 m^2	391.08 m^2	8.38%
Tile (1)	39.55 m^2	N/A	N/A
Tile (2)	70.50 m^2	N/A	N/A

Table 2. Comparison result between detailed BIM model and Dynamo scripts

Wall Layers	Detailed BIM Model	Dynamo Scripts	% Deviation
Core (1)	234.60 m^2	232.37 m^2	0.95%
Core (2)	315.95 m^2	313.36 m^2	0.82%
Ext. (1)	226.08 m^2	228.30 m^2	-0.98%
Ext. (2)	291.00 m^2	292.99 m^2	-0.68%
Int. (1)	314.65 m^2	311.23 m^2	1.09%
Int. (2)	426.83 m^2	425.13 m^2	0.40%
Tile (1)	39.55 m^2	39.80 m^2	-0.63%
Tile (2)	70.50 m^2	70.85 m^2	-0.50%

6 Conclusion

The proposed method for calculating the area of each layer of the architectural walls is executed in Dynamo - a visual programming extension in Revit. Each Dynamo script is designed to calculate the surface area in a specific scenario. For example, if designers want to find the area of the exterior paint, they will use the script that calculates the exterior finish layer. If designers want to find the area of the interior plaster, they will use the script that calculates the interior finish layer. If designers want to find the area of the interior wall panels that only attach to the stud framing layer, they will use the script that calculates the core layer.

The results from the Dynamo scripts are accurate when compared to the results from the detailed BIM model. With this method, the designers who work in the early stages of the design can know the accurate quantity of the architectural walls and finish layers without having to make a detailed BIM model. The model can easily be edited while the designers get instant feedback. The accurate quantity of the walls and finishes can be used to estimate the building cost in the early stages of the design process for the project delivery methods which have higher collaboration between design and construction teams, namely DB and IPD.

However, these Dynamo scripts still have their limitations. The scripts cannot find the area of the surface if there are multiple materials used. For example, if the tile layer has two types of tiles, the scripts cannot separate the areas of each type. In this case, a detailed BIM model is needed for the accurate quantity takeoff.

In future research, the implementation will need more case studies for validation and the Dynamo scripts will need to be improved. There are three possible features to improve on in the future Dynamo scripts. Firstly, the Limit Offset property in each room should be adjusted automatically. As of now the user still has to edit the Limit Offset property to match the ceiling height manually, - which is error-prone. Secondly, the adjustable height of the custom interior finish layer should be limited to the ceiling height or floor-to-floor height. Lastly, in the case that there are many wall types in the building, the user should be able to select the wall type that will be used in the calculation.

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Analysis of Construction Accidents Based on Semantic Search and Natural Language Processing

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Abstract –

Retrieving proper accident cases and extracting risk factors from them are crucial for construction safety management. However, the process was often challenging due to unstructured properties of text data in accident reports, which caused limited, inefficient, and non-consistent information retrieval and knowledge gathering. To overcome the problems, this research aimed at developing a semantic search system to retrieve proper accident cases based on user's deliberate intentions and to extract safety risk factors automatically using Natural Language Processing. The performance of the system prototype was evaluated by construction practitioners with promising results for more usable construction accident database development (i.e., thesaurus) and efficient accident analysis using the thesaurus.

Keywords –

Construction Accident, Safety Management, Semantic Search, Natural Language Processing

1 Introduction

The construction industry is known to be one of the most dangerous industries. According to the Korea Occupational Safety & Health Agency (KOSHA), 29.3% of occupational accident occurrences (26,570 records) were from construction sites in 2016. Moreover, the number of victims by the construction accidents has been steadily increasing for the last three years [1].

The Korean Society of Civil Engineers (KSCE) published a research report of which contents insisted that construction accidents showed similar patterns in occurrence. The patterns consist of (1) what caused the accident, (2) where it occurred, (3) when it was, and (4) how the results came out. These attributes are referred to construction accident risk factors one by one: (1) hazard object, (2) hazard position, (3) work process, and (4) accident result [2].

Since the construction accidents occur in similar patterns, many studies determined that it is possible to prevent construction accidents by identifying and eliminating the risk factors by analyzing similar cases [3,4,5,6,7]. For this reason, retrieving proper cases and extracting risk factors are crucial to preventing construction accidents.

To support academic and industrial efforts on accident analysis, two public institutions operate and manage construction accident databases. One is KOSHA, a database run by itself, and another is Construction Safety Management Information System (COSMIS), run by Korea Infrastructure Safety Corporation (KISTEC). The integrated data of the two databases cover more than 4,000 records of historical construction accidents.

However, the construction accident cases are written in the form of text document which is difficult to be managed and analyzed [8]. The situation generates some troubles in searching and analyzing accidents. The search algorithm implemented on the current database follows binary search "same or different", hence it could only retrieve results exactly matching the given query word by word precisely. This might limit useful information of previous cases, especially due to many synonyms and natural languages used in the construction domain, which would be used as basis for conducting construction accident analysis [9,10]. Besides, accident analysis process would be inefficient and the results could have non-consistency due to laborious task such as perusing numerous accident reports and labeling risk factors manually [11,12,13].

Taken altogether, analyzing construction accident cases based on current databases is difficult due to the unstructured properties of text documents. To overcome these problems, the research aimed at developing a semantic search system supporting two major functions: to retrieve proper cases based on user's deliberate intentions and to analyze accident cases by extracting risk factors automatically.

Accessing KOSHA and COSMIS, the research collected 4,263 reports of construction accidents which had occurred from September 1 1990 to October 18 2017. Natural Language Processing (NLP) was used to manipulate the text data of the reports and conduct the research. Meanwhile, the research adapted pre-existing risk categories identified by the Construction Risk Factor Profile [2] in order to define the labels of construction accident risk factor as mentioned in the first paragraph.

2 Research Methodology

2.1 Web Crawling

Construction accident reports were collected from KOSHA and COSMIS websites by the web crawling method which is a web-based process that accesses websites and collects target data [14]. Websites are usually constructed with Hypertext Markup Language (HTML), a standard language of websites used to specify detail features of entries such as position, font, color, and size. Once the web crawler is set to extract certain information, it finds the tags (e.g., <position>, <font>, <color>, <size>, etc.) and takes the information from each tag.

The process consists of two steps: (1) list page parsing and (2) target page parsing [15]. In the first step of list page parsing, the web crawler (i.e., web crawling algorithm) extracts Uniform Resource Locator (URL) links of target pages from the list page that covers the user's query. Afterwards, during target page parsing, the web crawler extracts actual data from the target pages. The procedure is provided in Figure 1.

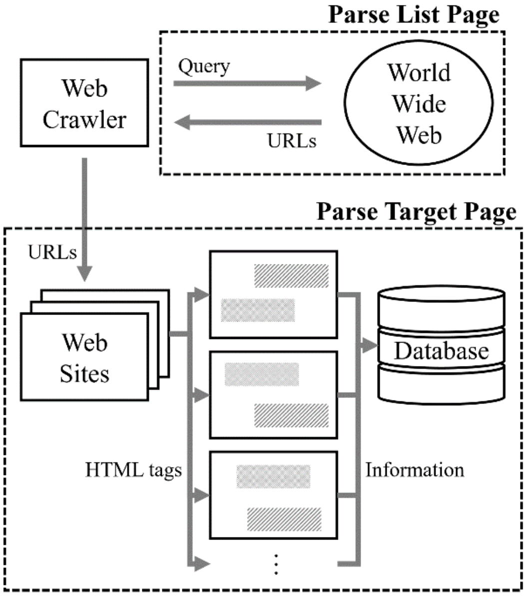

Figure 1 Web Crawling Procedure

2.2 Preprocessing

Text data preprocessing was conducted in order to convert raw data into an understandable format for the computer by splitting text strings into several valid words [15]. In this research, the preprocessing was composed of four steps. First was data cleaning; all punctuation marks were eliminated since those non-verbal items were worthless to understanding the text data. Second was tokenizing; every sentence from accident reports was split into a single word (i.e., token) based on space marks. Third was normalizing; each token was converted into its canonical form. Fourth and the last was stopword removal. Stopwords (i.e., less informative tokens) including grammatical components and person's name were removed to improve data quality. For instance, a sentence "During installation process, John lost his balance and fell down." would be converted into "installation process lose balance fall down" after preprocessing as explained in Figure 2.

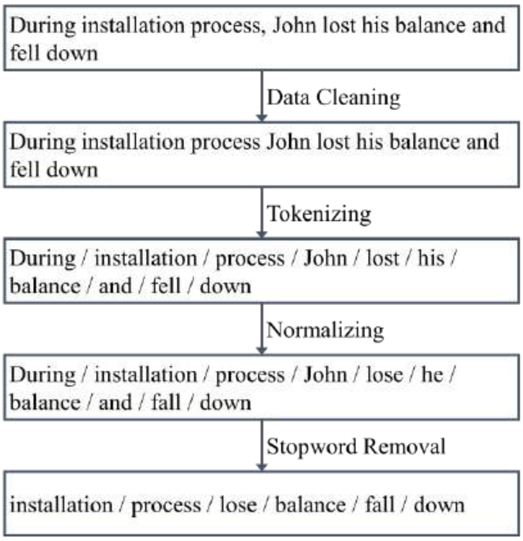

Figure 2 Procedure of Text Preprocessing

2.3 Query Expansion

For the purpose of including the user's deliberate intention to queries, the newly developed search system is able to expand the given queries using the thesaurus [16]. According to ISO 25964-1 standard, a thesaurus is a kind of advanced dictionary containing additional information such as the synonym, hypernym, and hyponym of each term [17]. Generally, plenty of advanced search engines already have been adopting query expansion using a thesaurus to overcome uncongenial result problems [18,19]. The research established a construction accident thesaurus using several construction dictionaries and a list of similar terms derived from the Word2Vec algorithm.

Specifically, twelve construction dictionaries with the total of 15,564 terminologies were adopted to the system. The construction dictionaries represented term relationships in the construction industry (e.g., synonym, hypernym, hyponym.), hence query expansion using dictionaries could be regarded as considering the relationship of meanings between terms.

Word2Vec is an algorithm which creates a corresponding vector for each term based on distribution similarity of surrounding terms [20]. For instance, in the two sentences "A worker got hurt on head" and "A worker got injured on hand", the term "hurt" and "injured" will be mapped close to each other since the surrounding terms are very similar. Consequently, it could be deducted that the Word2Vec algorithm clustered terms using the similarity of term usages which existed in the accident reports.

2.4 Frequent-based Search

The last steps to the search algorithm include assessing relevance of documents and returning the search results. To get a quantitative achievement in relevance assessment of documents, the research adopted a frequency based ranking method called BM25 which considers two frequency indicators – Term Frequency (TF) and Inverse Document Frequency (IDF). TF is the number of occurrences of a term in a document, which implicates the importance of a term. That is, the larger the TF is, the more important the term is. However, if a term exists in every document, then the term cannot be used as a distinctive feature for judging the importance among documents. For this reason, IDF, an inverse number of documents which contain a certain term, was designed to normalize the scale effect of TF [15,21]. Since higher BM25 score means the document is more relevant to the query, the accident reports are sorted in descending order.

After identifying user-wanted accident reports based on the BM25 score, predetermined four kinds of risk factors were extracted by conducting Named Entity Recognition (NER). NER is a text classification method which labels each term with informative categories such as person's name, place, object, action, and so on [22]. Among existing NER algorithms, the research employed Conditional Random Field (CRF) to determine each term's label on the basis of conditional probability of the surrounding terms, hence had been showing the highest performance at text labelling [23]. The conditional probability of each class y for a target token is calculated as Equation (1), where Y represents a set of labels (i.e., set of risk factors) X represents a sequence of observations which equals to the surrounding terms. On the right side of the Equation (1), t_j and s_k represents feature functions of which output is 0 or 1, λ_j and μ_k are weighting values for each feature function, and Z(X) is a constant normalizing the maximum probability as 1. Consequently, the target token was labelled by the class with the largest probability as provided in Equation (2), where y^* indicates the label of the target. The correct dataset was constructed by 51 rules which labelled terms related to risk factors from each sentence base on the relationship between sentence elements [24].

$$P_{\Lambda}(Y|X) = \frac{1}{Z(X)} \exp\left(\sum_j \lambda_j t_j + \sum_k \mu_k s_k\right) \tag{1}$$

$$y^* = \underset{Y}{argmax}\, P_{\Lambda}(Y|X) \tag{2}$$

3 System Prototype

A system prototype was developed to test the proposed methodology and evaluate the results. Figure 3 provided the result page of the system prototype with the query "타워 크레인 추락" which means "Tower

Crane Fall" in English. The system prototype was developed by localhost, which means only local computers have authority to access. This is to block unwanted users, since the research is in experimental stage.

When a user gave a query "tower crane fall" as an input, the system preprocess the query with data cleaning, tokenizing, normalizing, and stopword removal. The query would be divided into two tokens "tower crane" and "fall", then expanded based on the thesaurus to various queries: "tower crane", "crane", "lifting equipment", "lift", "T/C", "coping", "jib", "winch", "falling", "drop", "collision", "fall beneath", etc. The expanded queries were visualized in the top of the prototype as the red box in Figure 3. One of the most powerful text visualization tool, Word Cloud, was applied to show the queries, of which the font size indicates importance and leverage [25,26].

After searching and ranking appropriate documents with the queries based on the BM25 score, the system retrieved the most proper accident reports right below the Word Cloud. The accident name and short description of each case are provided in rows as marked with the dark blue box in Figure 3. For detailed information, users can access the original report simply by clicking the case.

Eventually, the CRF model extracted risk factors from the text data of retrieved reports. The risk factors (i.e., hazard object, hazard position, work process, and accident result) were provided on the right side of accident descriptions, marked in orange, light blue, green, and purple boxes each. For instance, the first case was "Haeundae I-park tower crane collapsed" of which content was that "Jib of tower crane collapsed due to sudden gust". The risk factors of this case were identified as "jib" for the hazard object and "collapse" for the accident result. As some of accident reports did not specify every risk factor explicitly, several blanks existed in the result.

Figure 3. Layout of System Prototype

4 Validation

4.1 Validation of Query Expansion

The retrieval results based on query expansion were validated in qualitative approach using Normalizing Discounted Cumulative Gain (NDCG), a commonly used approach to evaluate information retrieval results. NDCG examined whether relative documents were ranked high in the retrieval result by comparing documents from the result and correct set at every rank position p [27]. The NDCG is defined as Equation (3), where rel_i is the relevance of the result at position i and $|REL|$ represents the number of relevant documents up to position p [28].

$$NDCG_p = \frac{\sum_{i=1}^{p} 2^{rel_i} - 1 / \log_2(1+i)}{\sum_{i=1}^{|REL|} 2^{rel_i} - 1 / \log_2(1+i)} \quad (3)$$

To secure testing set, one query and 10 documents were given to each of 4 questionnaire groups composed of 4 construction practitioners with less than 5-year work experience. Then, each group ranked the documents based on the relativity of documents with the given query with 5-point scale: '5' represents the very high level relevance and '1' represents the very low level. NDCG score was calculated using the ranked results for four queries. Finally, the research compared the retrieval results with the testing set which questionnaires ranked and quantified the difference based on NDCG. The scores of each query were 0.98, 0.98, 0.94, 0.98, where 1.00 represents a consensus and otherwise 0.

4.2 Validation of Risk Factor Extraction

In the first step, the relevance of correct set generated from rule-based approach was verified. Same questionnaires with the former step were involved to label every risk factor from 101 documents. Then, the results of rule-based labeling were compared to the results of human-based. As a result, the rule-based approach showed an average accuracy of 93.75% establishing its relevance as training set for the CRF model. Specifically, labeling of hazard object scored 96% (82 from 85), hazard position 87% (46 from 53), work process 95% (82 from 86), and accident result 97% (98 from 101) which are provided in Table 1. The population of each risk factor would be different since not every accident report contained all of the risk factors. Since the relevance scores were considerably high, the CRF model, trained by the rule-based labeled data, must be trained attentively.

Table 1 Verification of Rule-based Labeling

Risk Factor	Relevance of Rule-based Labeling	
Hazard Object	82 / 85	96 %
Hazard Position	46 / 53	87 %
Work Process	82 / 86	95 %
Accident Result	98 / 101	97 %

Next, the labeling results of the CRF model were validated using the remaining 10% of data based on precision and recall of each risk factor. As provided in Table 2, most of the precision and recall scores came out to be sufficient to insist the feasibility of the system. Even though the recall rate of the hazard position was evaluated quite low, the overall results showed promising applicability of the proposed system. The precision and recall rates would become higher as the accident reports are accumulated constantly.

Table 2 Validation of CRF Model

Risk Factor	Precision	Recall
Hazard Object	0.95	0.68
Hazard Position	0.93	0.52
Work Process	0.86	0.74
Accident Result	0.99	0.90

5 Conclusions

Analyzing construction accident cases is crucial for safety management, since construction accidents occur in similar patterns which could be represented by hazard objects, hazard positions, work processes, and accident results. However, the current databases collecting accident reports have limitations to retrieve and analyze accident cases due to unstructured properties of text reports. This research thus developed a prototype of semantic search systems that retrieve similar cases based on the user's deliberate intentions and analyze accident cases by extracting risk factors automatically by applying text-mining techniques.

The developed system would have several contributions to both of industrial and academic sectors. For the industry level, the system would help provide accident references for safety managers to explain the causes of accidents and precautions to prevent them by applying the developed thesaurus and NER. For the academic level, the research identified relationships between keywords that exist on construction accident reports by using the Word2Vec algorithm and eventually explained the feasibility of NLP-based text analyses for better construction safety management.

6 ACKNOWLEDGMENT

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Development of the Education of Open Infra BIM Based Construction Automation

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Abstract –

This paper presents the results of the practical learning experience when combine three different school level students to learn open infrastructure building information modelling (infra BIM) and automation during OuluZone workshop week. Students started to build Speedway track in OuluZone test centre with one-week resources with the help of experts from industry and teachers. In addition, for students, ten different tricks were designed to present the tasks of the responsible person on the construction site. The idea of tricks was to teach students how these experts are using open infra BIM construction automation in their work. Infrakit, which is open infra BIM cloud service, was used to connect automation systems together. Based on the one-week workshop experience including questionnaire study answers and the results of pre-test and exam for students, it can be concluded that this type of practical learning is an effective way to teach open infra BIM based automation to students.

Keywords –

Automation, Education, Infrastructure building information modelling (infra BIM)

1 Introduction

The construction industry has started to found the advantages of use building information modelling (BIM) as a tool for managing the process of design, construction, and across the supply chain. The top five advantages of using BIM has found to include scheduling, communication, visualization, coordination, and clash detection [1]. The other reasons for the grow of BIM are application of technologies and innovations, which integrates the construction process not only buildings but also in infrastructures, such as transportation (roads, bridges), energy (power generation plants), utility (networks/pipelines), recreational (parks, stadiums) and environmental (managing flood and coastal defences). [2] In fact, BuildingSMART Finland has a forum which is responsible for the development of the infrastructure BIM (infra BIM). [3] However, there are still some obstacles to adopt BIM within architecture, engineering, construction, owner, and operator (AECOO) industry, such as technical barriers, legal and liability issues. Besides those, there is also is a need for training, education, and regulations [4]. BIM teaching in educational institutions will be grown due to the recommendation of European Union [5]. There are courses offered by private companies for professionals who want to update their knowledge in the field of infra BIM, or graduate as BIM coordinator, however these courses are relatively expensive. Therefore, universities and polytechnics are starting to provide BIM courses for construction and architecture students. [6]

Education in Universities and Universities of Applied Science schools is often lecture-based, instructor-centered pedagogical models. Courses can be included lectures and exercises with detailed spots. Practical knowhow about infra BIM and automation students is gained mainly from summer jobs, since the lack of money is prevented this type of practical learning from schools. However, the authors' opinion is that practical learning is vital to understand the theory as well as to learn new technologies and how to collaboration with expertise in the field. These skills can help students to find their future jobs. The idea that student can use learned information from teacher to real world challenges and problems have found to be excellent, but a challenging way to be as deep learning of the subject, and found a promising option for BIM education [7, 8]. BIM should be teaching as a process improvement methodology rather than only a technology. Giving students real word problems and active learning experiences will encourage to self-directed learning and critical thinking [9].

There is relatively rare any collaboration between school levels. Some articles are about the connection of courses between universities or different topics, such as BIM and sustainability [10, 11]. The objective in OuluZone+ project (started in March 2017 and ended in December 2017), which is presented in this article, was to connect the special open BIM and automation expertise of three different educational level institutions and to utilise their resources, and to be a practical learning experience for students, as well as for teachers, too. The goal was to plan, implement and evaluate the OuluZone workshop week in OuluZone test centre. Before the one-week workshop in OuluZone test centre, the students were trained in the lectures to understand the basics open infra BIM and automation knowhow from to implement the workshop. The goal during the OuluZone workshop week was that students use their know how from lectures and build the Speedway-track with one-week resources with the help of expertise from school and from industry. Findings and lessons learned from the practical learning experience are presented in this article.

2 Finnish Educational Framework System

In Finland after finishing the mandatory basic education at age of 15, the student can select different educational paths. Infra BIM related courses offered at all levels after basic education. However, there is rarely any collaboration between the school levels.

The goal of the OuluZone+ project is to develop research, development, and education environment for open infrastructure BIM is between the institutions of The University of Oulu, the Oulu University of Applied Sciences (OAMK), and Oulu Vocational College (OSAO). These institutions are presenting the three different level that is collaborating in the OuluZone+ project.

Before the workshop week in the OuluZone test centre, students learn practical knowledge in selected courses, presented below, in each institution. Teachers are using both cognitive and behavior approach to teach BIM to students [10]. This means that the theory of BIM is learned by lectures but also from experts from industry.

For a Masters Degree students of Technology there is a five-credit course called "Information modelling and automation building construction and maintenance", at the Department of Structures and the Construction Technology Research Unit at the University of Oulu. During the course, the students are trained to learn the Novapoint boulevard program, RTK-GNSS positioning techniques, Novatron's 3D machine control system using a mini excavator, and the use of the Infrakit in the real-time control of the site. Annually, the course has an average of 10-15 graduate civil engineer students.

For engineering students at the Oulu University of Applied Sciences (OAMK) there is a five-credits course entitled "Infra BIM modeling and building a construction project". At the start of the annual course, OAMK has about 80 engineering students and 40 master students. For masters students there is a course called "Computer modeling at infrastructures". The teaching of measurement techniques has unfortunately decreased in recent years due to teacher resources, and it has been integrated more into other courses. AutoCAD Civil3D is used to teach boulevard design.

The Oulu Vocational College (OSAO) provides teaching for construction machinery and lorry drivers as well as logistics instructors. The basic education for young people is three years, with a one-year course of about 20 students; thus a total number was 60. In addition, adult education includes some 40 students. OSAO has four different machines (three excavators and one wheel loader) on the campus of Haukipudas with Scanlaser Oy's and Novatron Oy´s 3D machine control system installed in educational use. In addition, the University of Oulu maintains a Sunward mini excavator machine, where Novatron Oy's 3D machine control system, at OSAO's premises at Haukipudas. Several test simulators as in Figure 1, which estimate performance and gives feedback to the user. The test simulator is integrated into Leica's 3D machine control system so that the simulation corresponds to a truly genuine environment. The scope of the 3D Driving tutorial for construction experiments is 15 competence points.

Figure 1. Test simulator (Tenstar) integrated to Leica's 3D machine control system to practice the use of excavator.

3 Development of the Education Workshop for Open BIM Based Construction

3.1 Tools for Implement Ouluzone Workshop Week

The OuluZone test centre is a place located around 30 minutes away from the city centre of Oulu built by the City of Oulu. In OuluZone test centre, one can do activities such as motor sports, research, and education.

The OuluZone workshop week, the construction site was decided to be the Speedway track, and the beginning of its cutting operation. The geometry of Speedway-track was first done in traditional 2D drawings. The total length of the track is 437m in with a straight line of 65m. The 3D model of the Speedway track (Figure 2) was made in Mitta in open file formats such as DXF and LandXML. It was calculated that the weight to be cut was 7848 m^3, filling 7727 m^3 and surplus mass 100 m^3.

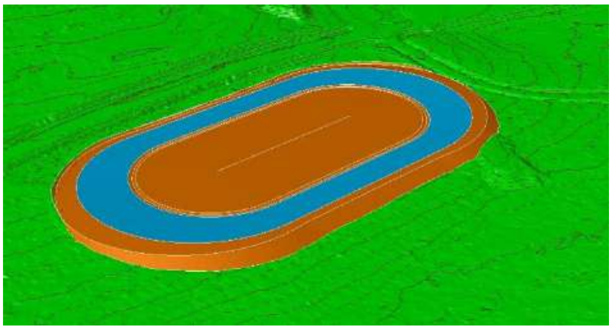

Figure 2. Speedway-track in 3D DFX format (Mitta Oy).

For practical implementation in OuluZone test centre, it was decided that OSAO brought necessary machineries and dumper trucks to start the Speedway-track building. The University of Oulu organized other necessary infra building information modelling (infra BIM) and automation technologies and systems. To support the development of education, technology companies and key infra actors were challenged to bring their technology.

Based on authors previously projects [12] and experiences Infrakit have been found to reliable. That was the reason why Infrakit (www.infrakit.fi) was used as an open infra BIM tool for real-time monitoring of Speedway-track progress and for quality checking. In addition, Infrakit can be integrated into many machine control systems such as Trimble, Topgeo, Leica Geosystems, and other software. In Figure 3. shows how different automation systems of Novatron are connected real time to Infrakit and used to share data between a designer, project owner, site foreman, machinery and surveyor. The students and teachers had an Infrakit-training day before the OuluZone workshop week. The goal of Infrakit-training was to present to the audience, how the Speedway project is set up in Infrakit. In addition, meaning coordinate systems, designed files in correct formats and other necessary information needed in the beginning of the construction site was also presented.

Figure 3. Automation system and operation models (Novatron Oy).

All the measurement devices, such as RTK-GNSS-tablet, and mobile devices, meaning the android guidance system in trucks, tablets for construction leaders, and laptops that were used on the Speedway construction site are integrated into the collaboration cloud via Infrakit internet system. The other necessary equipment needed in Speedway-track construction site were RTK-GNSS-base station, three to four pieces' reference points around the Speedway track, machines with 3D-guidance systems both Scanlaser and Novatron, Leica-robot tachometer, Trimble R10–RTK-GNSS-system with Infrakit, a video camera connection, and Drone-monitoring. In addition, there were two excavators, wheel loader, and two trucks from OSAO.

3.2 OuluZone Workshop Week Preparation for Students

The OuluZone workshop week was 30 October to 2 November 2017. During this period, all the students and teachers had a common information event about the workshop days in OuluZone test centre in the University of Oulu, two working days Speedway-track contract site in OuluZone test centre, and a finally enclosing day in OAMK.

There was pre-test at the beginning of the week and end exam at enclosing day, both were based on Common Infra BIM Requirements (YIV2015) [13]. The result of the pre-test and exam was analyzed. In addition, during the enclosing day the students and teacher was answered in questionnaire study regarding: 1) what was successful, 2) how OuluZone workshop week can be developed, and finally 3) to give the school grade from 1 to 5.

The amount of students was 6, 41, and 13 from the University of Oulu, OAMK and OSAO, respectively. The students from OSOA were decided to be responsible for working machines. They started two weeks earlier of the preparation of the workshop week. The students learned the basics about positioning, charting, coordination systems, and GPS measuring. These profession skill demands are part of their degree and were estimated during the workshop week.

Students from University of Oulu and OAMK were divided into 10 groups' occasional order. To students, 10 different tricks were planned:

1. Construction' head manager
2. Site foreman
3. Designer
4. BIM coordinator
5. Excavators, trucks, and wheel loader drivers
6. Surveyor
7. Construction consultant
8. Construction security officer
9. Speedway Project owner
10. Drone-monitoring

The purpose of each trick was present the tasks of the responsible person on site, and how they are using open infra BIM in their own work. The responsible person on the trick was professionals from industry (Mitta Oy, Leica GeoSystems Oy, Destia Oy, Novatron Oy, and Infrakit Oy), or were a teacher from the University of Oulu, OAMK, or OSAO. The connection of ten tricks to open infra BIM is shown in Figure 4.

Figure 4. Ten tricks for students during the OuluZone workshop days in OuluZone test centre.

During the OuluZone workshop days, the student group visit each trick about 25 minutes. During this time, the students heard about the work of the responsible person and had a possibility to ask. Each student was to give a paper and pen to do his or her notes for example to write a report to the teacher. Transfer time one trick into other was about 10 minutes.

3.3 Objectives to OuluZone Workshop Working Days

The objective of the first workday in OuluZone test centre was to practice and to understand how the open infra BIM is used on Speedway track site. The following things are expected of students to learn:

- How is the map of the Speedway track site, machine control system and realization measuring recorded?
- How can all the experts on the Speedway track site communicate each other in real time and do changes if needed?
- How is the schedule of the Speedway track, and the calculation of masses done based on the model?
- How the information from Scanlaser's or Novatron's Guiding 3D systems in excavators can be used for the controlling?
- How is the quality check of the excavator done by measuring the cutting surfaces continuously?
- What is the reason to measure separate "point of reference" of RTK-GNSS systems?
- What is the reason to use Drone-plane to follow and control the progress of the construction site?

The objective of the second workday in OuluZone test centre was the automation change and problem scenarios. The aim was for the student to understand why the information model needs to be monitored and why it must react whenever possible changes occur. The following possible problem scenarios were planned and what must be done:

- The excavator is excavated (intentionally) 10 cm too deep. The actual point is stored, whereby the error should be detected by the Infrakit system (supervisor) and reacted to it or interrupted the excavation
- Adding a drum scraper model to the excavator machine control system. The background map shows it. The driver and the manager should observe it and ask for this model from the site manager who request a template from a road designer.
- Some layer thickness is incorrectly a type cross section; the automation operator should note and request a repair from the designer, or be repaired by the automation operator.
- The excavator driver x reports the observed rock surface and asks the job director for blasting operations.
- A person appears on site without any safety equipment. The supervisor suspends the work situation, removes the person and orders the contractor for the sanction.
- Failure of the vehicle and the working machine, condition check, etc.

4 Results and Discussion

At the beginning of the OuluZone workshop week, the students were given a simple pre-test based on Common Infra BIM Requirements (YIV2015). The pre-test contained 10 question and there were four answer options in each question. The pre-test was given to Monday and the answers were collected next day. The correct answers were told after the students' answers was given. Of 32 results, the average degree was 6.34 with the standard deviation 3.08 (Figure 5). The result indicates that students were learned something about the infra BIM during the lectures.

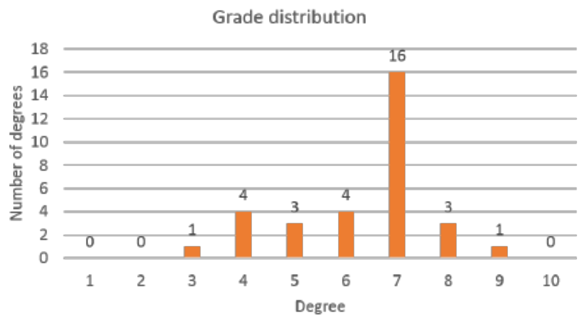

Figure 5. The 32 result of pre-test the average degree was 6.34 by the standard deviation 3.08.

During two OuluZone workshop days, the team of five to six students was visiting ten different tricks. The first day was training and the second day focused on the solving problems. Students were heard more how the experts were using Infrakit in their job function. Construction head manager (trick 1) explained how he is using Infrakit to budgeting, scheduling, and quality control. His responsibility is also the orientation of the workers on the construction site. The site foreman (trick 2) explained to students what responsibilities it is needed to keep high quality on the site based on YIV2015. Designer (trick 3) collected and checked the Speedway-model and delivered those files in Infrakit. He also controls and updates the machine 3D-guidance systems. One task for students was to calculate the quantity of masses if a blasting job was needed. BIM-coordinator (trick 4) explained to students why separate RTK-GNSS systems was needed and why "the point of references" was done. He also showed how the calibration of the guidance system was done. The excavator driver (trick 5) showed the student how the Scanlaser guidance system was used when cutting process is going on. The driver also showed how the quality check was done by measuring the cutting surfaces continuously. The job of the surveyor (trick 6) was to measure and maintain reference points and safe the collected data to Infrakit. The construction consultant (trick 7) also used power point slides to explain more detail their work, and what must be considered scheduling and budgeting. Examples of real problems how heavy rain can stop the construction site was explained. The construction security officer (trick 8) showed in the first day relevant video about safety issues in the construction site. The next day, the student's task was to point out errors and give solutions to solve the problem. The Speedway Project owner (trick 9) followed the project via Infrakit. He also used drone monitoring (trick 10), especially the schedule and mass control. Figure 6 presents students visiting tricks 5 and 6 to learn more about how to measure "the point of reference” and the 3D machine control systems of Scanlaser and Novatron in excavators.

Figure 6. Trimble R10-RTK-GNSS-system (trick 6) and Bobcat excavator with both 3D-guidance systems of Scanlaser and Novatron (trick 5).

The students were possibility to ask questions and do some tasks during their visits in tricks. The communication between experts was done via chat service in Infrakit, but also mobile phone, and face-to-face meeting. The students followed the Speedway site progress and saw the progress of the site, and how it was recorded into Infrakit in real-time (Figure 7).

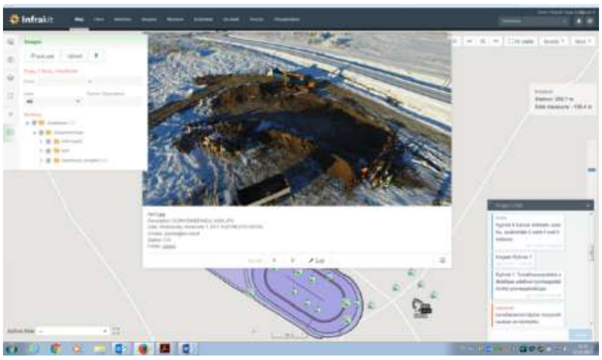

Figure 7. Speedway project in Infrakit. Pictures from Drone-plane (trick 10) are recorded and thus the site can be monitor in real-time for example in mobile application.

During the workshop days, the teachers and the experts were evaluated the student groups based on their activity and spontaneous. The level of groups was variable. Some groups were relatively silent and as opposite, there were relatively good groups. Students were not informed of the evaluation, which could explain the difference between groups. There was no competition.

The last day of workshop week was the event for discussion and feedback. Similar type of exam than the pre-test was for students. The students were not informed of the exam, so they could not be prepared themselves for it. Based on 49 results returned it can be said that the degrees were higher than pre-test degrees (Figure 8). This time, the average degree was 7.67 with the standard deviation 2.63.

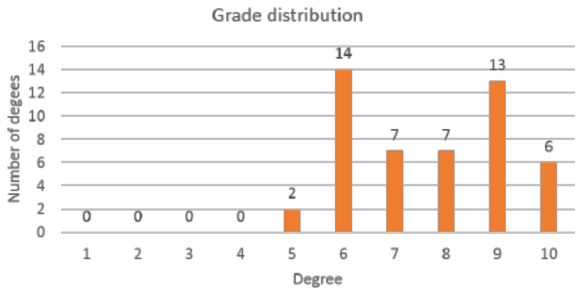

Figure 8. The 49 result of exam of final day. The average degree was 7.67 by the standard deviation 2.63.

Feedback from students, teachers and experts was collected during the enclosing with day questionnaire study. In addition, a questionnaire in e-mail was used, since most of the experts did not have time to participate in enclosing day. Based on the answers of the questionnaire studies, the successful thing during the workshop was the collaboration between the students of University of Oulu and OAMK. The students worked and motivated each other. The students think that the experts brought much more information on different situations on working life, skills versatility, advice, and new perspectives. In addition, the reason why in the construction site is needed so many expertise was clarified.

There were also things what should be developed for the next OuluZone workshop week. Since the OuluZone workshop week was organized the first time, it was rather difficult to estimate how much time is enough on each trick. Some of the tricks can be merged together and some other can give more time. Infrakit was acting a major role during the workshop, however some students think that the information obtained was repeating itself. Maybe next time it would be a good idea to give some small tasks like budgeting or calculation. However, it must be sure that students are learned those before workshop and tested their skills during the workshop.

Based on the 49 questionnaire study answer, it can be stated that overall the whole experience was successful. Overall the grade from the first workshop was 3.42/5 the standard deviation 3.56. For the reason for good experience from this first OuluZone workshop week, it has been decided to continue to organize OuluZone workshop week in year the 2018, too. Based on the feedback, the workshop week is changes so that there will be three working days instead of two. During the first two days, students will be trained to take the charge of the Speedway-track construction site under the supervisor. The idea is for motive students to learn open infra BIM and automation to take subject seriously.

5 Conclusion

In this article, it is reported the results from the OuluZone workshop week. Students from three different levels i.e. University of Oulu, Oulu University of Applied Sciences (OAMK), and Oulu Vocational College (OSAO) were guided through open infra BIM based Speedway construction automation with the help of the experts from industry and teachers.

During the OuluZone workshop days, students learned by doing what are the tasks of the responsible person on the construction site, and how they are using open infra BIM and automation. In addition, the problem solving on the construction site was found to be an interesting way to learn in collaboration of other students and experts of industry and teachers. Based on the gained feedback, this type of practical workshop was an excellent way to bring novel knowhow from industry to improve education in courses.

Therefore, it can be concluded based on the results of pre-test and final exam as well as questioner study that practical learning is an effective way to teach open infra BIM based construction automation for students. The collaboration between three school levels will be continued in next improved OuluZone workshop week in the year 2018.

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A Methodology for the Development of Interoperable BIM-based Cyber-Physical Systems

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Abstract –

Building Information Modeling (BIM)-based processes are increasingly being adopted worldwide. With it, possibilities to exploit digitization had been appearing for the AEC sector. In that context, the present work aims to investigate how, and in which form, a Cyber-Physical System (CPS), one of many different but complementary technologies associated with the future of manufacturing, could be employed in the Construction industry. Recognizing that the core of CPS should be the dynamics of construction processes, the initial focus is in how to develop Process Data Models (virtual) that could communicate with Product Data Models (BIM models), and receive/send data in almost real-time from/for the existent hardware (sensors and actuators) in the physical production processes. This article present some preliminary work based on the standardized methodology of IDM/MVD, which are part of the buildingSMART solution for interoperability along with Industry Foundation Class (IFC) data schema. The proposed methodology considers an IDM modelled in Business Process Modeling and Notation (BPMN) language in such detail as to expose the workflow of production. The contribution in this context is in mapping production processes in BPMN notation into Petri Nets (PN) semantics. Petri Nets are an adequate model to construction processes, with precise semantics and largely used in the simulation of discrete events. With PN models it would be possible to develop the BIM-based control strategy, and test and implement it in real controllers. An illustrative example is provided in the context of automating cut and bend of rebar.

Keywords –

Cyber-physical systems; IDM-MVD; Construction Simulation; BIM

1 Introduction

Building Information Modeling (BIM)-based processes are increasingly being adopted worldwide. It could be viewed as the digitization phenomena that allows further adoption of technologies related to the automation and employment of robots in the Construction industry [1].

However, BIM models, with probably rare exceptions, are in reality Product Data Models [2]. For the effective introduction of automation technologies, it would be necessary to have, explicitly, Process Data Models [3]. Automated Construction [4], in its core, should be about control systems for production processes. Advanced applications of automation and robotics in construction already emphasized this notion [5].

In that context, the present work aims to investigate how, and in which form, a Cyber-Physical Systems (CPS) could be employed in Construction. A CPS could be viewed as a control system, which integrates the cyber world of computational models of products, process, organization behind production, supply-chain, and so on, with the physical world of sensors monitoring material, equipment, manual labor, machines and robots, and its actuators. It is a complex field of research that is in its infancy.

Towards a viable development of such a CPS, it would be economical to adopt open standards and current industry practices. Industry Foundation Class (IFC), both a data schema and a file format to exchange building information of its entire lifecycle, is becoming a *de facto* open standard for the interoperability in the aforementioned processes.

The focus is in how one could develop, in the interoperable scenario proposed by buildingSMART, a process (virtual) model that could communicate with Product Data Model (BIM models) and the hardware/software in the production processes.

This article present some preliminary work based on the standardized methodology of IDM/MVD, which are part of the buildingSMART standards, and are used to specify a subset of IFC entities. First, an IDM should be modelled in Business Process Modeling and Notation (BPMN) language, in such detail as to expose the workflow of the production process. Then a map between BPMN and Petri Nets, an adequate model to construction process with precise semantics and used in simulation of discrete events [6], is applied providing the basis for implementing a CPS.

An example is provided in the context of automating cut and bend of rebar.

2 Cyber-Physical Systems in Construction

Cyber-Physical Systems (CPS) is probably one of the most important technology associated with the current Industry 4.0 paradigm for manufacturing, because it is the integration of many of them. Implementations of such systems are already happening in the manufacture industry, mostly in automotive and aerospace.

One way to see it, is that it enables the integration between the virtual world (digital models and simulations) with the physical world (by means of sensors – Internet of Things/Industrial Internet – and actuators – Automation equipment and robots). The necessity of integration between different systems, or islands of automation, is not new.

Depending on the way cyber-physical system is defined or approached, one could find many or few research articles in the literature. If bidirectional data transfer between computational platforms with virtual models of construction and the construction field is sufficient to have an effective CPS, there is plenty of works dealing with monitoring the work done on site with different sensors [7]. However, to consider that it is necessary to have an actuator receiving commands to control some equipment on-site, it is hard to find one approach that integrate automated equipment with BIM models. Considering the evolution of the employment of robots on the field [8], it would be interesting to study the impact of CPS system in this context.

In [9], two scenarios are proposed that could employ CPS in Construction, based on the view that a CPS is a bidirectional data transfer: steel placement and light fixture monitoring and control.

In this article, it is considered that a CPS could be viewed throughout one spectrum of possibilities, which could become more functional or important as it integrates more technologies, such as sensors, automated equipment/robots, data analytics, simulation of construction process, and so on.

However, it is advocated that independently of the level of development of the CPS, the essential point for the integration is the virtual model of the different construction processes, in which it would be the bi-directional link. Henceforth, the necessity to study how to represent the knowledge of construction processes inside BIM platforms.

3 Construction Simulation with Petri Nets

It is important to note that BIM models are Data Product Models. Analyzing IFC Schema, although it is possible to instantiate processes, there are not standard construction processes already present in the schema, as are the building components used to design and construct a building.

Some author emphasize the difference and necessity of product and process model [2]. Mostly, the referred authors calls that approach Virtual Design and Construction (VDC), although the process model adopted many times are not a computational model.

To have the ability to simulate, analyze, and optimize production processes are the main drive for the importance of the process digital model. And as the simulation will be the core of a CPS, the kind of digital model should have characteristic appropriated for control systems.

Petri Nets were considered adequate to model and simulate construction processes, which presents a high degree of concurrency and synchronization.

A Petri Net is a tuple, given by [10]:

$$N = (P, T, \mathrm{E}) \quad \textbf{(1)}$$

where: P is a finite set of places; T is finite set of transitions; and E is the incident relation, representing the set of directed arcs connecting places to transitions and vice-versa, given by:

$$\mathrm{E} \subseteq (P \times T) \cup (T \times P) \quad \textbf{(2)}$$

There is also a token, a mark inside places, to represent the dynamics of the net. One transitions only occurs if there are token in every place connected to it. And if a place is connected to two transitions, and both could fire, a decision should be made.

3.1 Types of Petri Nets

There are many different formalisms to define Petri Nets with added capabilities: *Colored Petri Nets* [11], *Hierarchical Petri Net* [12], *Controllable Petri Nets* [13], and on. It is not the objective of this work, in this initial research, to define which one is more adequate to the cyber-physical system in hand, at that time. It will be considered in the following discussion a regular Petri Net.

Construction Processes would be experimented with **untimed models** with Petri Nets, as there exists an order in the events that occurs for the production of building components. Where there will be necessity to develop the control of the manufacturing process, it will be the **Control Theoretic Approach**, where there is a “model of the plant dynamics and a specification for the desired closed-loop behavior”. “There is a clear distinction between the plant and the controller and the information flow between the plant and controller is modeled explicitly” [10].

The main problem would be to create such Petri Net based on construction information, inside the current practices present in BIM implementations

4 Interoperability with IFC: IDM/MVD Methodology

Industry Foundation Classes (IFC) are both a schema for the entities of the products of the AEC industry and a file format to exchange those data product models. It comprises the entire lifecycle of a building.

The main concern with working with IFC is its complexity and size. buildingSMART is the international organization behind the efforts to promote open-BIM. As a building traditionally is represented by a set of BIM models, one for each discipline, those models are used in exchanges between different professionals to promote cooperation and concurrent work.

In each exchange, only part of a given model is needed. buildingSMART have being promoting the methodology of creating different Model View Definitions (MVD), that are a pre-defined subset of the IFC Schema, with agreed representation for the allowed entities.

However, there are few MVDs available, and this is part of the misconception that IFC do not work out-of-the-box in practice. Software vendors are certified as IFC exporters based on Coordinating View exchange (one MVD), which is not appropriate, for instance, for energy analysis.

Part of the cause for the existence of few MVDs is difficulty of the process of creating one and making it official at buildingSMART [14]. The methodology consist in first creating an Information Delivery Manual (IDM), basically a diagram in BPMN (Business Process Modeling Notation) notation, which all professionals could understand, and based on that, translate each piece of information, based on MVD Concepts.

Considering this scenario, where the different professionals involved in Construction are more comfortable in developing models using a language such as BPMN than Petri Nets, in this article it is proposed that a map between both models should be a solution for that.

As IDM is a high-level representation of a construction process, it should be exploited in the open-BIM scenario to produce process models.

5 Proposed Approach for CPS in Construction

The end of the spectrum of possibilities (most advanced) of CPS in Construction, should consist in a scenario with automated or semi-automated fabrication, with employment of machines or robots – as is currently more common in off-site production.

However, the proposed approach of this article contemplates a modular solution, around BIM models:

- A module for the simulation of construction processes in the form of a Petri Net (built upon the respective IDM diagrams) – which is considered here to be core of the CPS;
- A module for monitoring the construction processes, using whichever sensor (RFID, Ultrawide-band, laser scanners, Images, and so on). It feeds the CPS (or the platform using BIM models) with (possibly, real-time) data;
- A module for (Big) Data Analytics, based on the dynamics of the construction process and the BIM Models;
- A module for automatic decision-making routines, given to construct management personnel, or, direct control commands to machines in on- and off-site.

In that way, it aims to provide an enhancement of the employment, and existence of BIM implementations. Its most distinct characteristic is to associate the **process data model** with a CPS system, which connects and integrate with other technologies used by the enterprise.

In its simpler incarnation, it would be a way to monitor, with the capabilities of each sensor employed, what really happens on-site (off-site), so that it could be used as data to act more quickly to solve problems, and to study ways of optimization of the processes.

5.1 CPS: From IDM to Petri Nets

The idea is not new; neither was it developed by the present authors. However, upon finding previous work [15] on the subject, BPMN mapping in Petri Nets, it was considered a matter of investigation of its adequacy, in a scenario where some construction processes are currently being modelled in BPMN, and it is a language more closer to the background of the team of professionals involved in Construction industry.

IDMs are currently created using BPMN language [16]. The main problem with BPMN is that it inherits and combine constructs from different graph-oriented process definition languages with other features, drawn from a range of sources [15], and could produce semantic errors. Mapping it in Petri Nets allows the verification of its consistency. However, the main interest of Petri Nets for the proposed approach is that it is largely used to model and control manufacturing processes.

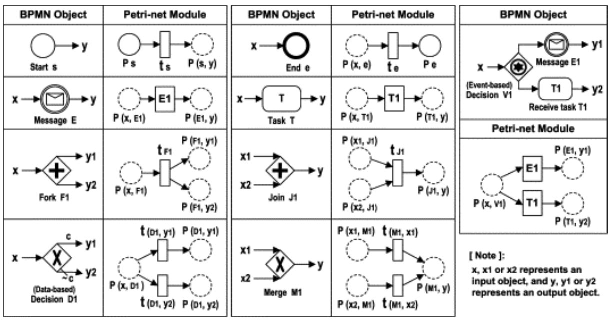

Figure 1. List of symbols considered and mapped into Petri Net constructs [15].

In [15], the authors provided a mapping between BPMN notation and Petri Net, which is adopted in this work as is (Figure 1). A subset of symbols from BPMN notation were considered, and it is compatible with symbols used for the IDM / MVD specification [16].

5.2 Example: Process for Automated Cut and Bend of Reinforcing Bars

5.2.1 IDM / MVD for Automated Cut and Bend of Reinforcing Bars

As the authors of the present article are working in the development of a IDM / MVD for the automated cut and bend of reinforcing bars as a BIM process [17][18], it was decided to use this scenario to illustrate the mapping between IDM (BPMN) to Petri Nets (Figure 2).

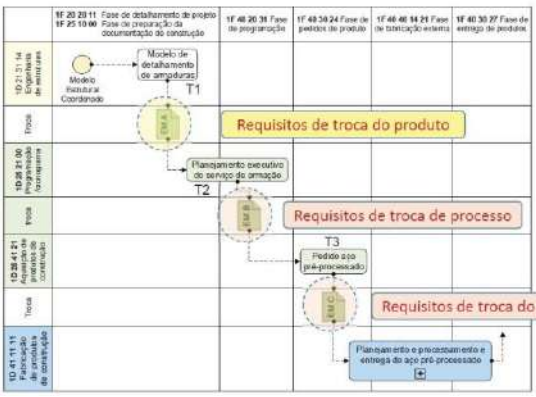

Figure 2. Example of an IDM in BPMN language for the Automatic Cut and Bent of rebars.

The IDM is the business process in BPMN notation. It contemplates 5 phases (Design Detailing and Preparation of Construction Documents; Programming; Product Orders; External Fabrication; and Product Delivery) and 4 disciplines (Structural Engineering; Schedule Programming; Acquisition of Construction Product; and Fabrication of Construction Product), following codes from NBR 15.965 (a Brazilian standard, based on Omniclass). In addition, it represents three exchange requirements: T1 (product), T2 (process), and T3 (order).

The level of detail achieved (and it is that way throughout this development in Construction industry) in modelling IDM for MVD specification is not enough for it be immediately mapped (and be relevant) in a Petri Nets, as it do not exposes detail of the fabrication process.

5.2.2 Sub-process: Fabrication of Reinforcing Bars

In the industrial process of cut and bend of reinforcing bars (rebars), there is a team dealing with orders received (containing delivery date and reference drawings for rebars processing). This team does a preliminary analysis of the order (reference drawings missing, errors in data filling in the forms), and contacts the client if necessary. If everything is correct, the next stage is to send forward the orders and the reference drawings (Rebar Detailing Project) to the scheduling team, which will transcript design data to production (geometry and quantities of each bend format). That information is entered in the production management software of the service (cut and bend) provider.

In the sequence, the Production Planning and Control starts. In general, large cut & bend providers have many equipment working simultaneously. Each equipment works with a specific diameter of steel bars, and have restrictions of bend shape that it could process (for example, maximum length of the bar to be bend).

Also, a pool of orders is stablished to achieve a given volume of production, to keep the line operating continuously, and to make some optimization in reducing possible lengths of lost from the raw material [19].

5.2.3 BMPN diagram of the fabrication process

For this example, it will be considered just one machine operating, starting from the point where the previous dynamic description ends. There are different types of machines that produces reinforcing bars [20], and here it will be considered types A or B machines (Figure 3).

Figure 3. Schnell's A type machine.

Therefore, it was developed a prototype of a sub-process for the task that appears in blue in Figure 2, with the right amount of detail, to provide a BPMN notation (Figure 4). The model considers orders arriving in regular intervals. Given the availability of appropriate reinforcing bars (same diameter and material as ordered), the processing of rebars remains active due to place rebars_batch.

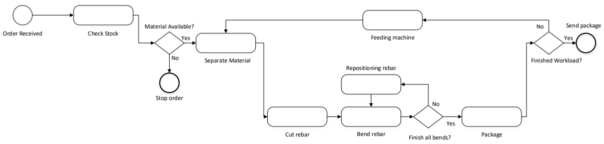

Figure 4. Sub-process for the fabrication of reinforcing rebars.

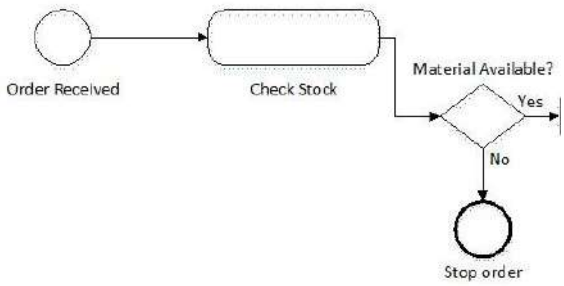

Figure 5. Initial part of the BPMN for Automated Cut and Bend of Rebars.

In the sequence (Figure 5), an order received (*Order Received*) is the start of the modelled process. The task *Check Stock* check if the material to attend the arrived order is available in the stock. Then, a gateway divides the flow: is there is material, then order follows along the path; if not, that is the end of the process (*Stop order*).

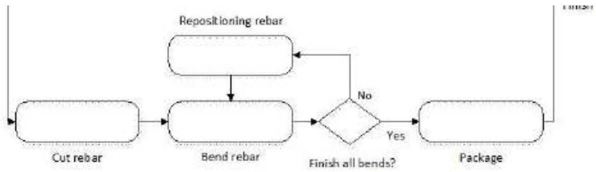

Figure 6. The part of the process were the rebars are cut and bend, following specification in BIM model.

After the gateway, there is a task (which is not represented in Figure 6) called *Separate Material*, in which the raw bars from the specified material are separated and brought closer to the machine. Then happens the tasks *Cut rebar* and *Bend rebar*. As could be more than one bend for each rebar, there is another gateway to check if all bends for that rebar were done (*Finish all bends*). If not, there is a task named Repositioning rebar, as an operator sometimes exist to conduct the positioning and gives command to the machine make another bend. When all bends were done, the flows goes to the *Package* Task.

Figure 7. Final loop to produce all rebars of a given order.

From *Package* task, there is a final gateway (Figure 7) that checks if all rebars of the given order were produced. If yes, then the flows and the process ends at *Send Package* (end node). If not, it goes to the task *Feeding machine* and then again to *Separate Material*, and the process of cut and bend of the rebar starts again in another rebar, which were previously separated.

5.2.4 Mapped Petri Net

Applying to this model the map presented in Figure 1, the Petri Net represented in Figure 8 is obtained.

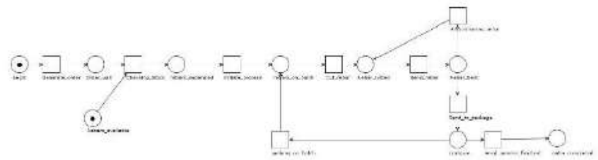

Figure 8. Petri net derived from BPMN subprocess.

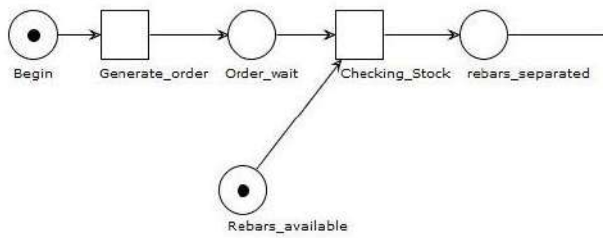

Figure 9. Initial part of the Petri Net mapped from BPMN diagram.

The token are added from simulate the dynamics of the net: one token to start the process (*Begin*), as an order arriving, and one at place *Rebars_available* (Figure 9).

The transition *Generate_order* is active and fires. Token moves to *Order_wait* place. The transition Checking_Stock become active, as there are tokens in both predecessor places (*Order_wait* and *Rebars_available*), and the token moves to *rebars_separated*. Note that the net will not work again, even with the arrival of another order, because rebars_available must also receive another token. The connection of this process with other dependent was not modelled.

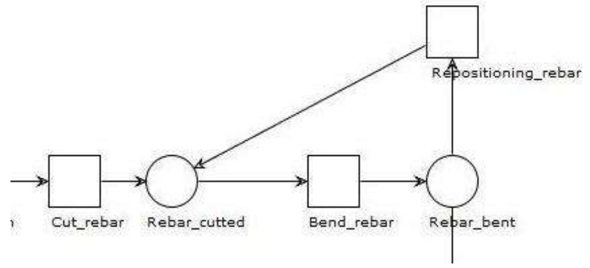

Figure 10. The cut and bend activities represented in the Petri Net.

Figure 10 do not show that after the place *rebars_separated* there are a transition *intiate_process*. After it, there is a place (that also not appears in the above figure) called *rebars_on_batch*. The token in this last place, activate the transition *Cut_rebar*, flows to *Rebar_cutted*, and then fires *Bend_rebar*, ending in the place *Rebar_bent*.

In the place *Rebar_bent* there is the possibility for two transitions to occur: *Repositioning_rebar*, if there are more bend to be made in the rebar, or *Send_to_package*, if this rebar is finished. If it is not finished, the transition *Repositioning_rebar* is activated and the token goes back to *Rebar_cutted*.

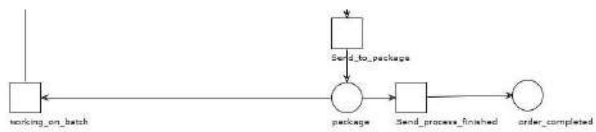

Figure 11. End of the process.

Figure 11 starts with the fire of transition *Send_to_package*, when all bend are made at the rebar. The token at *package* activates both *Send_process_finished* (if all rebars on the order were fabricated) and *working_on_batch* (if there still rebars to be fabricated). If the last transition is fired, it returns to place *rebars_on_batch*, and initiate again the cut and bend dynamics. If all work on that order is done, it fires Send_process_finished and goes to *order_completed*, with the simulation ended.

6 Results

In order to, somehow, validate the mapping (beyond test its dynamics in a software), one Petri Net was elaborated beforehand, and its dynamics tested with WoPeD (Workflow Petri Net Designer). The modelled Petri Net is represented in Figure 12.

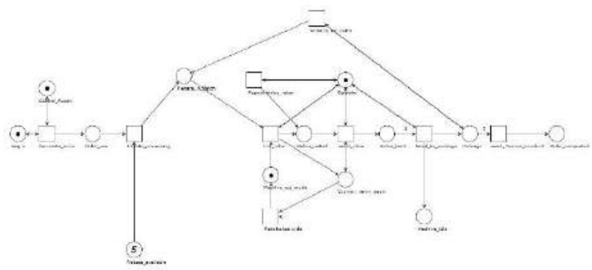

Figure 12. A previously modelled Petri Net for the same purposes.

Figure 13 represents the initial part of the process, with orders arriving; this part of the model was taken from the simulation presented at [21].

Figure 14 shows the cut and bend process of each reinforcing bar. First, the machine is in cut mode, and the operator is available. Then, the machine changes to bend_mode, and the operator makes the repositioning of rebars for further bends, until the number of bends are completed. The machine goes to idle state, and then back to cut mode.

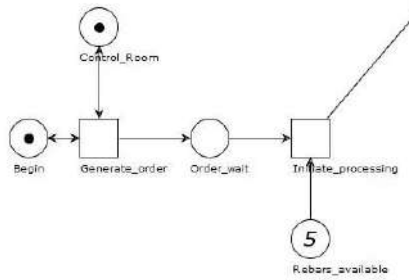

Figure 13. Petri net model for automatic rebar cut and bend (this part of the net is inspired by [21]).

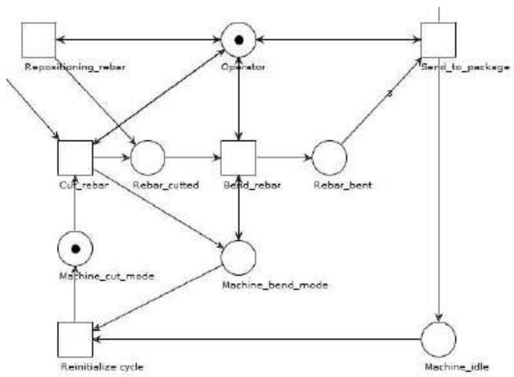

Figure 14. Processing of reinforcing bars.

At the same time, the first piece of the order, remains in the package, and maintain the rebar supply available to process new rebars in the same batch (Figure 15). The transition send_finish_process has precedence and stops further processing. The loop initiate again with a new order.

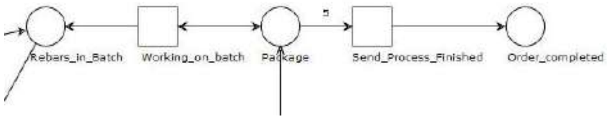

Figure 15. Final part of the model.

It is interestingly that where modelling the same process in BPMN, many details, such as the existence of an operator, and the difference in the type of machine (using one for bend and other for cut), are abstracted generating a simpler and functional network.

7 Conclusion and Future Works

This paper proposed the use of IDM/MVD workflow to start the development of a process model in Petri Net formalism. The objective in creating such model is that it could integrate information from BIM models and sensors and actuators signals for the plant process, obtaining a kind of cyber-physical system. This area is very promising, but the results are still preliminary.

The experiment of developing a simulation of construction processes as the core of a cyber-physical system was presented.

The focus of the article was in testing the relevance in using available IDMs, elaborated for BIM processes purposes, to produce one representation, Petri Nets, that allows to test its dynamics, and even its control strategy.

Initial results, were positive, as the mapping between IDM (in BPMN notation) produced Petri Nets more simple and functional when compared with a previous Petri Net elaborated from zero.

Another result is that the level of detail present in current IDMs ([14] was also analysed) is not sufficient for the proposed approach. But it is not difficult to proceed in the same notation to model sub-task or sub-activities to expose details of the fabrication processes.

Finally, a workable dynamic model in Petri Net probably needs more characteristics than BPMN could model. It should be considered a starting point to further develop to include controlled process, or a controller explicitly.

Interestingly, to produce from zero a Petri Net for this fabrication process, the resultant net was more complex, because many more details were inserted in its elaboration (and it was an iterative process) to achieve the right dynamics in the Petri Nets. When modelling with BPMN, it was easier to achieve a diagram that was translated in a simpler Petri Net, with about the same dynamics.

In the end, there was not necessary to deal with orders that necessitate different number of bends, or work packages with different number of rebars. In the mapped solution, this aspects was abstracted of the net, although it has the same dynamics.

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Information Modeling of an Underground Laboratory for the R&D of mining automation and tunnel construction robotics

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Abstract –

We discuss the idea of developing Information Modeling (IM) for an existing underground facility so that it can be efficiently utilized as a laboratory for testing automated machinery in tunnel construction and mining.

The currently existing underground laboratories are located in old mines or underground storage facilities of which there exists usually only rough 3D CAD drawings, often done with geological modeling software. We discuss the relevant information content to create a useful IM for the purpose of the R&D of tunnel construction and mining equipment. We also present the current status of the IM, created in Lab 3 at 990 m depth in Callio Lab, the new underground laboratory in Pyhäsalmi mine in Finland.

Keywords –

Information modeling, IM, BIM, Underground facility, Underground laboratory, automation, robotics, mining, tunneling.

1 Introduction

Several underground facilities of old mines, nuclear waste storage facilities or extensions of road tunnels have been utilized as a laboratory for the research or development of activities, which specifically require underground conditions. Such activities include for example basic research of physics [1], geophysics [2] mining and tunneling equipment automation as well as education of mining engineering (for example in [2] and [3]) or even experimental food production [4]. Some of the major manufacturers, such as Sandvik or Atlas Copco, have excavated their own underground facilities for the testing of tunneling equipment and robotics [5].

When converted to laboratory use, an underground space is essentially turned into a building, where people work and spend substantial amounts of time in environments, which should be characterized similarly to office buildings or normal laboratory facilities. However, there are no standards for the conversion of an underground facility into a work place. The purpose of this study is to test the idea of creating an Information Model (IM), similarly to normal Building Information Modeling (BIM). We discuss specifically the case of creating a test laboratory for the research of tunneling automation and robotics and the benefits of the approach both from the user's point of view and the infrastructure provider's (the operator of the underground laboratory) point of view. We also present the results of a proof-of-concept experiment to make an IM, using the Industry Foundation Class (IFC) [6] data format, for the creation of an office in the Lab3 facility of Callio Lab at the 990 m depth in Pyhäsalmi mine.

2 Callio Lab

The tunnel network of Pyhäsalmi mine extends down to 1430 m depth, making it the deepest metal mine in Europe. The main ores, excavated since 1962, have been copper, zinc and pyrite. However, the current forecast is that the ore reserves are going to be exhausted by the end of 2019 and the mine is due to a closure.

Because of its depth and the extraordinarily large tunnel network, created during the 66 years of underground operations, the mine has hosted a variety of research activities since 1995. The modern and extensive support infrastructures both on the main service level, at +1400 m depth, and on the surface, provide a great platform for developing the mine into a versatile underground laboratory.

In 2015, the municipality of Pyhäjärvi started the project Callio (the name Callio is derived from Finnish word *kallio* meaning *bedrock*) to co-ordinate and develop the underground laboratory activities in the mine under the brand name Callio Lab [7]. During 2015-2017, the non-mining activities included the research of mining vehicles, radiation shielding systems, particle physics detectors and an observatory for cosmic rays and even an experimental farm for growing green vegetables and potatoes in underground conditions [8][9].

In 2017, Callio Lab had four dedicated Lab facilities on the levels +75 m (Lab 1), +660 m (Lab 4), +990 m (Lab 3) and +1430 m (Lab 2) depths of the mine .(Fig 1.).

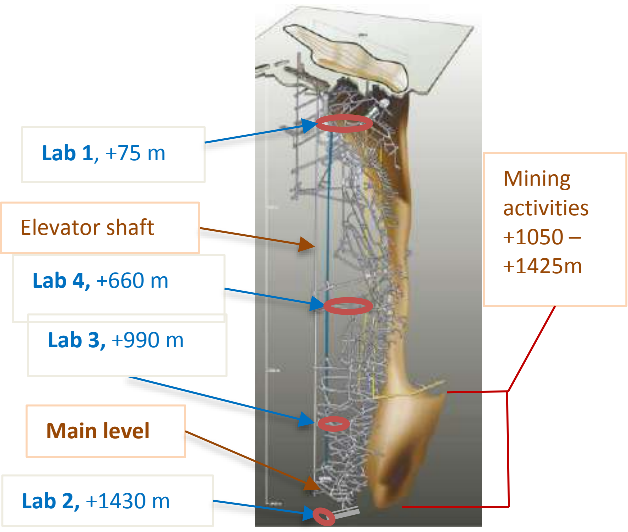

Figure 1. Cross section of the Pyhäsalmi mine. The brown column represents the ore deposits.

The main level is accessible with a mine elevator, hoisting people at 12 m/s and reaching the surface in 3 minutes. All levels are accessible with an 11 km long, truck-sized incline, which takes about 30 minutes to drive from the surface to the 1400m level. The rock conditions are uniquely stable and the rock mechanical tensions thoroughly investigated for the laboratory use, especially in the bottom part of the mine [10].

3 Testing of mining equipment, tunnel construction machinery and robotics in an UL

The creation of a possible standard IFC data model for underground laboratories requires a combination of different approaches:

- A mine model, mainly as a tool for the transportation and excavation of ore, described in the terms of geoscientific modeling, such as Geospatial Information Systems (GIS) [11][12]
- Underground tunnels, modeled as infrastructures for the transportation of people, machinery, mining and tunneling equipment (Infra IM) [13]
- Underground laboratory as a working space, with a BIM comparable to facilities in normal buildings.

For example, Fraser [14] has pointed out that the broader adoption of the IM in the mine environment is still an unchartered area of opportunity for interoperability and equipment standards for testing of both mining and tunnel construction automation. Tunnel construction and mining industry should see similar benefits as do building construction in general by adopting the use of BIM. In Europe this can be seen as an extension to open data concept of BIM, in Australia it's part of the "*Common Mine Model"* [15]. Automation and robotics can be linked via this concept as well. Mine geoscience and geophysics applications would be eventually natural additions to these studies.

Based on the discussion with the representatives of mining and tunnel industries, we propose that an IM of a tunnel construction or mining technology test facility could provide at least (but not limited to) the following types of information:

Objects

- Tunnels, which are available as test areas for mining or tunneling vehicles
- Electrical outlets, WiFi or cable connection to the internet, water supply, compressed air
- Location of rescue services with rescue chambers or other emergency services
- Offices, control rooms for operators and service areas, such as cafeteria, conference room, rest room, etc.
- Material handling spaces, for example concrete mixing
- Vehicle maintenance spaces
- Storage rooms
- Doors
- Roads and parking areas
- Elevator station or other transportation

Information tagged to the 3D model or the objects

- Mine driveway inclines
- Characteristics of the rock and surfaces
- Special areas available for blasting, drilling, installations
- Average ambient temperature
- Moisture, dust
- Other sensory information
- Specific rock mechanical considerations, such as tensions or fracture

The goal is that the comprehensive information modeling makes it easier for users to plan their test programs: How to make the automated tunnel construction or mining machinery to navigate better in tunnel networks, how to plan the testing and how to arrange the safety and facility maintenance procedures for the personnel.

Also from the underground laboratory operator's point of view, the Information model provides clear benefits:

- Better service to the customers, which helps to make the underground laboratory more competitive
- A methodology to take new tunnels into use more rapidly
- A tool for Facility Management (FM) of the underground facilities.

4 Information Modeling of Lab 3 of Callio Lab

As a proof of concept to study the viability of making an IM into an existing underground facility, we created and IFC model based on the existing 3D mine model provided by the Pyhäsalmi mine's surveying department and using existing software tools.

The Information Modeling for Callio Lab was started on the level +990 m in the Lab 3 tunnel (Fig. 2) by designating it as "office".

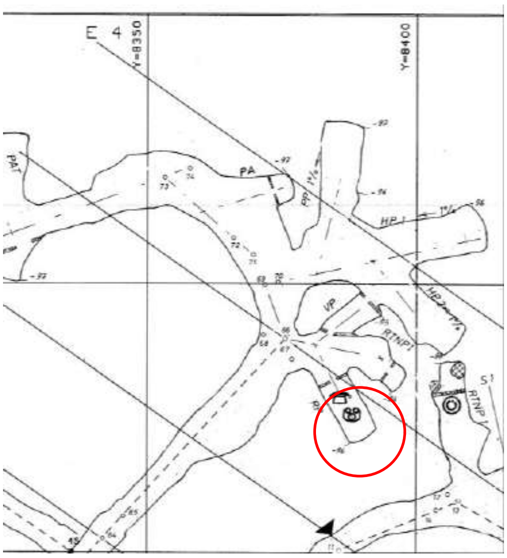

Fig 2. The location of Lab 3 in +990 level shown inside the red circle.

The IFC file for the "office" in Lab 3 was created with Autodesk Revit (Fig 3), so that it relates each object type from the building information model to the corresponding IFC entity (*e.g.* ifcWifi, ifcDoor, ifcElectricalOutlet, [16]). The IFC file can then be saved and edited as an external text file and it is possible to add simple meta-data to an IFC file.

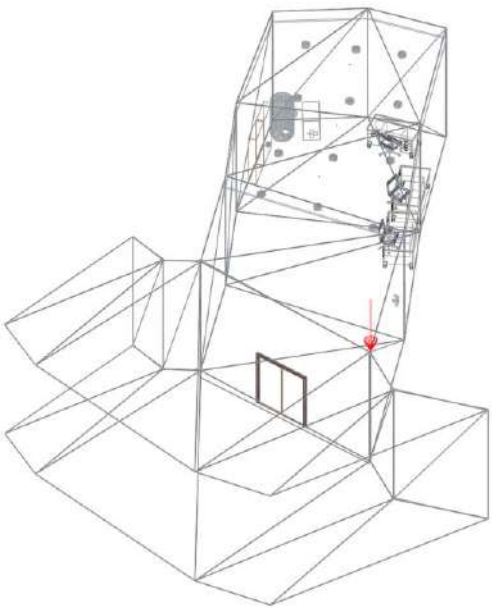

Fig 3. The Lab3 office model in co-ordination view of Revit.

However, the creation of the office based on the existing data was not straightforward. The mine's structures are modeled with Surpac geological surveying modeling software (Fig 4.) and importing the point mass information into Revit required and intermediate step of creating a tool for the conversion of data with Autodesk Dynamo.

An even bigger problem was that the resolution of the mesh in the mine model was at best of the order of 1 m, which may turn out to be insufficient for some users. The way to achieve a better resolution would then be to make laser scanning in the location (see for example Makkonen [17] and [18].

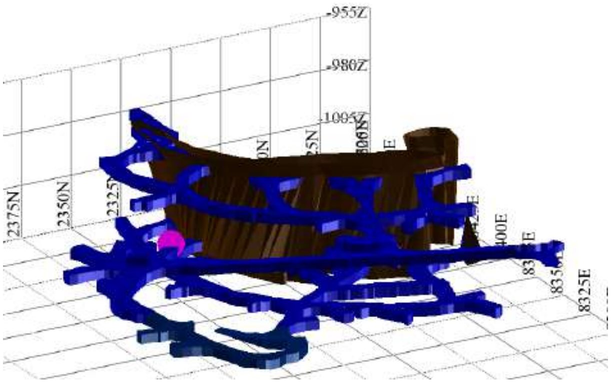

Fig. 3. The Surpac 3D plot from level +955 m to +1030 m. The location of Lab 3 is indicated with the pink ball. The black area in the background represents the ore reserves.

The work is continuing by developing the IM further. The next steps could include the creation of more objects and by tagging more information also to the adjoining service roads and tunnels. The new objects can include warning lights, valves related to plumbing location of escape pots (locations with reserve air) and available sensory information. Eventually the information shall include information about the inclination of tunnels and characteristics of wall surfaces for tunnel construction robotics.

5 Conclusions and future work

The information modeling of Callio Lab, based on the existing Surpac models of the Pyhäsalmi mine was demonstrated to be a viable possibility, although not straightforward. Based on the discussions with a tunnel construction company and a mining company we also reviewed the information, which would be useful for an IM of a testing platform of underground construction and mining automation.

The work shall continue by developing the underground laboratory IM further and implement especially the information, which is relevant for the testing of automated tunneling and mining machinery. Then we plan to collect feedback from the current users of Callio Lab and other companies in the industry. The work shall be conducted partly within the framework of the project BSUIN - Baltic Sea Underground Innovation Network, an ERDF funded Baltic Sea Region INTERREG program for developing services and technical characterization of six underground laboratories in the Baltic Sea Region in EU and Russia [19].

For the parties interested in utilizing Callio Lab's facilities, there is an open call for expressions-of-interest, accessible at Callio Lab's web page [20].

Acknowledgements

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Modelling Information Flow of Occupant Feedback in Office Buildings

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Abstract

Occupant comfort plays an important role in office buildings in terms of environmental, social, and economic aspects. Facility managers need to evaluate occupant feedback to moderate the negative consequences on office users and ultimately on the corporations that occupy office spaces. However, in the current facility management systems, occupant feedback is not effectively collected and evaluated; thus, facility managers cannot utilize this information in making critical decisions when operating, maintaining and retrofitting office facilities.

This paper presents the initial results of an ongoing research study, which focuses on integrating occupant feedback with Building Information Model (BIM) for assisting decision-makers in the facility management phase. The first step of this research study was to identify the information items that are required to represent occupant feedback for effective use in the facility management phase. To identify the required information items, interviews were performed with office users at ten office buildings and use cases were developed. To validate the use cases, interviews were performed with twelve facility managers. The aim of this paper is to present a sample of the use cases developed and describe the occupant feedback information flow observed in the office buildings. The results show that the occupant feedback data include detailed information related to: (1) location where the problem is observed, which is represented by building, and/or floor, and/or room, and/or façade, and/or table/zone/region depending on the case; (2) location of the user, that is represented by building, floor, room, table/zone/region, (3) source of the problem that is represented by type of building element and related building element, (4) source location, which specifies the location of a problem source that is different than the location where the problem is observed, and (5) time.

Keywords – Occupant Comfort; Facility Management; FM; Building Information Modeling; BIM; Use Case.

1 Introduction

Effective utilization of occupant complaints and feedback is crucial for successful operation, maintenance and retrofitting in offices. Many studies reveal the effects of occupant comfort on energy efficiency [1]; [2]; [3]; [4], employee health and well-being [5]; [6]; [7]; [8]; [9] and employee productivity [10]; [11]; [12]; [13]; [14]; [15]. Currently, to regulate indoor environment during design, operation and retrofitting in office buildings, occupant comfort standards (e.g., ASHRAE 55, EN ISO 7730) are used [16]. However, due to the variations in individuals' sensation levels, there is a poor relation between comfort conditions defined in the standards and the comfort conditions perceived by the occupants [17]. Occupant comfort and satisfaction increases when the occupant evaluations on performance parameters, such as thermal, visual, acoustic comfort, are considered by facility managers [18]; [19]. To measure functional comfort and identify possible workspace features which slows down or demotivates employees, collection of feedback from occupants is critical [20].

Collection of occupant feedback is currently performed by post occupancy evaluation (POE) tools, which are a type of building performance evaluation system. POE is defined as the "examination of the effectiveness for human users of occupied designed environment" [21]; [22]. The current POE tools, however, are lacking extensive inquiry about occupant satisfaction parameters [23]; [24], location based (spatial) occupant feedback [25] and easily understandable visualized data analysis and representation formats for facilities management (FM) [26]; [27].

Building Information Modeling (BIM) constitutes an effective platform to represent and analyze occupant feedback in facilities management. Although the need for BIM in facility management (FM) has been acknowledged by researchers and practitioners [28]; [29]; [30]; [31]; [32] BIM is still not being effectively utilized in this phase, including retrofitting activities [33]; [34]; [35]. FM is still dominated by corrective maintenance and there is under-utilization of preventive, predictive, and condition-based maintenance in facility management despite the use of advanced FM programs [36].

The study explained in this paper proposes to integrate BIM and occupant feedback to assist facility managers in making critical decisions in FM, including retrofitting activities, as well as preventive, predictive, and condition-based maintenance in office buildings. The first step of this ongoing study was to identify the information items that are required to represent occupant feedback for effective use in the FM phase. To identify the required information items, interviews were performed with office users at ten offices and use cases were developed based on those interviews. The aim of this paper is to present a sample of the use cases developed and to give an overview of the information items required to represent occupant feedback in the office buildings.

2 Literature Review

As part of the literature review occupant comfort, post occupancy evaluation (POE) and its relation to FM, existing POE tools, and FM & BIM & POE integration topics are investigated.

2.1. Occupant Comfort

There are three basic pillars of the effects of occupant comfort in office buildings. These are social, economic and environmental dimensions. The social dimension includes the well-being and health of employees. It is proved that the well-being and health of employees are directly related with the work environment comfort conditions [37]. One of the main disruptions among the employees is caused by indoor air quality. Adequate ventilation, pollutants and moisture level in the air are the key factors affecting the employee health in an office environment. Also, lighting, high level of noise and vibrations directly affects the employee's psychology. As a result, disturbing environmental conditions slows down the work rate of employees and increases the amount of mistakes due to distraction. It is observed that the absenteeism rate due to health issues is lower in offices which satisfy occupant needs; therefore, the employee productivity in such offices is comparably higher [38]; [39]; [40]. Design-related comfort aspects such as indoor air quality, noise control, thermal comfort, privacy, lighting comfort, spatial comfort and noise comfort designate the level of employee performance. It should be highlighted that physical environment of the office affects 15-20% of productivity of personnel; therefore, productivity constitutes the economical aspect of comfort condition by eventually affecting the company financial-wise [41]; [42]; [37]. The environmental effects of occupant comfort level are also investigated in the literature. It has been identified that the occupant comfort dissatisfaction leads to inefficient use of building systems and causes an increase in building's energy consumption [18]. If the environment is designed to meet the requirements of the occupants and if the occupants understand how the building operates and how the controls systems are used, then it is possible for the occupants to contribute to lower building energy use [18]; [19]; [43]; [44].

The occupant comfort condition standards are used to regulate the indoor environment during operation and renovation periods of office buildings; however. There is a poor relation between comfort conditions defined in the standards and the comfort conditions perceived by the occupants since the sensation level of every individual is different [17]. Especially the evaluations of occupant feedback on performance parameters such as thermal, visual, acoustic comfort, indoor air quality, space usage and occupant control increases the occupant satisfaction [18]; [19]. Collection of feedback from users is vital to measure functional comfort and to identify possible workspace features which slows down or demotivates employees [20].

2.2. Post Occupancy Evaluation (POE)

During the occupancy phase of the buildings, the building performance evaluations (BPE) are conducted via post occupancy evaluation (POE) tools. Post-occupancy evaluation (POE) is the process of obtaining feedback on a building's performance after it has been built and occupied. In the literature, POE tools are named as Occupant Satisfaction Measurement Tools, Indoor Environmental Surveys or Building Performance Evaluation Surveys. By collecting factors, such as energy consumption, building use, maintenance costs or user satisfaction, POE allows various and continuous improvement possibilities in buildings. Moreover, because of the advances in technology, POE transformed into a knowledge tool than a diagnostic tool in time. Generally POE tools consist of three core parts: questionnaires, bills and metrics, physical measurements (optional) [45]. The results of the questionnaire surveys enable the determination of indirect parameters and characteristics, such as individual characteristics of the occupants and their personality. The physical measurement enable the determination of direct parameters, such as air temperature, relative humidity, air velocity, globe temperature, CO_2 concentration, illuminance levels etc. Also, bills and metrics include documents related to energy consumption of the building and blueprints of the building.

2.3. Importance of POE in FM

British Institute of Facilities Management has defined

FM as "the integration of processes within an organization to maintain and develop the agreed services, which support and improve the effectiveness of its primary activities" [46]. Facility planning (space management); health, safety, security; maintenance management; and work environment comfort conditions are the main aspects of FM, in which cleaning services, support services, property services, catering services, security services, etc. are provided.

In the current FM applications, IT systems are effectively used in many service areas, such as maintenance and space management. However; work environment comfort conditions are only detected via sensors and POE is not integrated with this data. FM receives the occupant feedback not as a continuous information source, but only as the source of some work orders, which are supposed to be closed after fulfilling required maintenance. In fact, occupant feedback plays an important role for the management of work environment comfort conditions by the facility managers, and there is a need for advanced approaches for effective collection of occupant feedback data.

2.4. Existing POE Tools

There are many POE tools developed over the years focusing on different building types. Various methods and techniques were developed to extract user requirements regarding safety, health, comfort, functionality and efficiency, and aesthetic quality of buildings, and to identify defects in the system [47]. POEs are powerful tools for demonstrating whether or not building programs are delivering best value and for identifying areas for improvement. Currently, architects, built environment professionals, industry bodies and even clients prefer building evaluations through POE since they can see the benefits of evidence-based decision making in achieving their organizational goals. However the current POE tools are lacking some crucial features such as (1) extensive inquiry about occupant satisfaction parameters, (2) spatial occupant feedback, and (3) visualized representation of easily understandable data analysis results.

1. In POE measurement graphs, there is no extensive inquiry about occupant satisfaction parameters which are the indicative of occupant satisfaction. In the research studies, it is found that the satisfaction level of the occupants is measured using several parameters, but the dissatisfaction of the occupant or the reason of the complaint is not interrogated [23]; [24]. Lack of details constitutes a problem in case of a need for detection of specific problems.
2. The evaluation tools are not collecting spatial occupant feedback. The spatial information can enrich the feedback data and point out the building element related to the complaint. This information cannot be delivered to decision makers; therefore, a historical occupant feedback platform does not exist. It is known that linking the performance data to occupant location increases the system efficiency [25]. In a previous study, Hua et al. (2014; 2015) linked the occupant feedback to building spaces (i.e., rooms). However, this approach is not sufficient for open office environments and homogenous evaluations cannot be performed since usually open offices are large areas. Also, it is not possible to give feedback about the common areas other than offices.
3. There is lack of data analysis and representation of analysis results in the systems. In the current systems, the data obtained from evaluation system is not reflected in the facility management application [26]. The greatest obstacle is that the data is not processed and analyzed in a way that the decision makers need and not presented in an easily accessible, refined and visualized way [27]; [26].

2.5. FM & BIM & POE Integration

BIM is a process which uses 3D, parametric and object-based models to create, store and use coordinated and compatible data throughout the life cycle of a facility [48]. The system goes beyond a visual modeling by means of 3D numerical modeling feature. It is a multifunctional management and information exchange tool which can contain all the information for manufacturing. Also, the information embedded in BIM models can be used for the operation of the facility [49]. Thanks to the developed exchange formats such as IFC Standards, data exchange between BIM tools is possible [50]. BIM integrated FM systems utilize effective decision making during operation and retrofit phases and consequently increases the building performance and occupant satisfaction [51]. The usage of BIM in FM bridges the information gap between the authorities in design and construction phase and the owner. It helps to reduce the costs since the data is ready to use and easy to reach in the model. Also, the models can be integrated into building automation systems which helps the FM to manage the buildings more effectively. Lastly, by enabling faster analysis and correction of problems, it helps to improve building performance and therefore the occupant comfort. In recent years, it has been emphasized that a BIM-integrated FM system is needed for delivering facility performance data more effectively to decision-makers in FM or retrofitting processes [25]; [52]; [53]; [54]; [55]; [56]. The application of such a system is not reported in any of the studies, even though the required approaches are proposed frequently.

3 Method

To identify the information items that are required to represent occupant feedback, the current information flow between employees and facility managers are investigated for reporting of complaints and feedback. A set of interviews were performed and use case scenarios were developed based on these interviews. Ten office employees, who work in ten offices in different companies, participated in the interviews. All office buildings chosen for the study have automation systems for HVAC control and operated by professional FM firms, but are diverse in terms of size, type of offices (cellular/open-plan), type of activities, facades, finishing materials, energy efficiency levels and none of them have BIM models. All the office users were asked four open-ended questions;

1. What kind of complaints did you report before?
2. Whom did you report your complaint?
3. Which communication method(s) did you use to report your complaint?
4. Which information did you provide to the authorities about your complaint?

According to the information obtained during the interviews, thirteen use case scenarios that represent occupant feedback/complaint information flow were developed. For each use case scenario, a use case diagram using Unified Modeling Language (UML) was created.

To validate the use cases that were developed, use case scenarios and UML diagrams were presented to twelve facility managers. Their feedback was received via interviews and reflected in the use cases. The methodology is also shown in Figure 1.

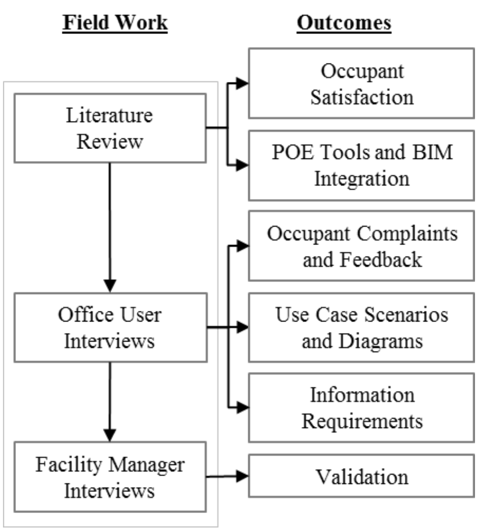

Figure 1. Methodology flowchart

4 Results

Out of thirteen use cases that were developed via interviews with office occupants and facility managers, three of them are provided as a sample in this paper. Information requirements that were identified from the use case as an outcome were presented along with each use case scenario.

Use Case Scenario 1 : Indoor Air Quality – Odor

Actors: Employee, facility manager, technical staff

Triggers: The employee realizes that there is an unpleasant odor in the office coming from the cafeteria.

Scenario: The employee realizes that there is a bad smell in the office coming from the cafeteria. He calls the facility manager and complains about it. The facility manager directs a technical staff team to the entrance floor to make an inspection about the complaint. After the inspection, the technical staff offers the construction of an automated door between the Blue Zone (offices) and the corridor that opens to the cafeteria. The facility manager accepts the offer and as a solution the door is constructed.

Outcomes: Building, Floor, Zone, and Source Location (different room for problem source, ex: cafeteria)

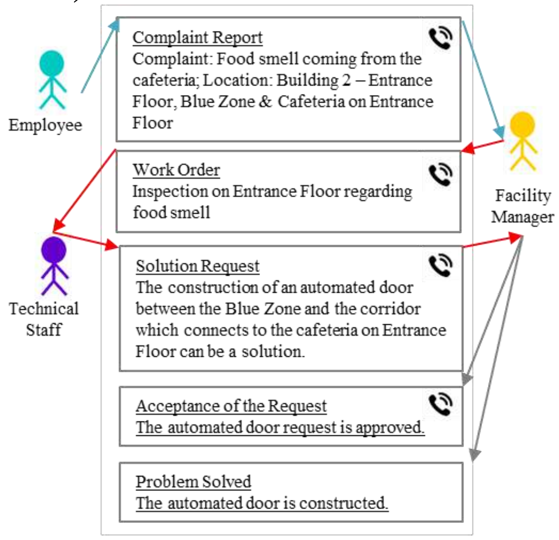

Figure 2. UML diagram of use case scenario 1

Use Case Scenario 2: Visual Comfort – Reflection

Actors: Employee, facility manager, administrative affairs manager

Triggers: The sunlight is reflecting on the computer of the employee and the employee cannot see his screen

Scenario: The sunlight is reflecting on the computer of the employee and the employee cannot see his screen.

He reports this problem to the facility manager. The facility manager comes to the office of the employee and inspects the problem on site. After identifying that the problem is observed between 11:00 and 15:00, the facility manager decides that there is a need for a window shade. The facility manager calls the administrative affairs manager, reports the problem and requests a window shade for office X. The administrative affairs manager accepts the request of window shade procurement. The facility manager purchases the window shade. By using the window shade, the employee prevented reflection on his screen between 11:00 and 15:00 while working at his computer.

Outcomes: Floor, Room, Region, Table, Facade, Time.

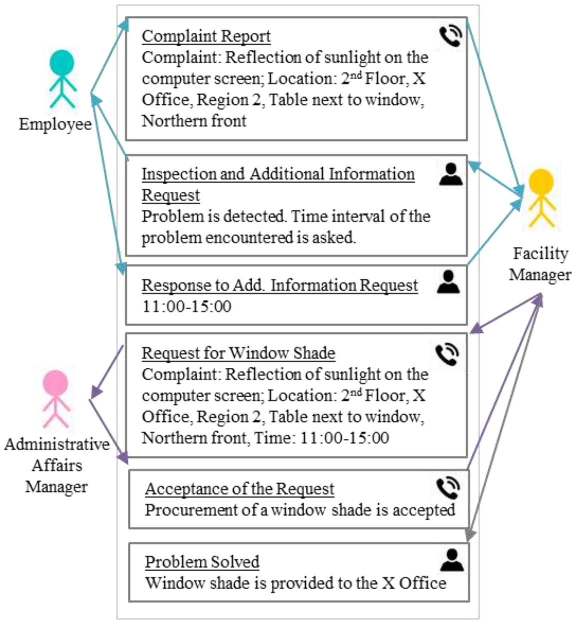

Figure 3. UML diagram of use case scenario 2

Use Case Scenario 3: Indoor Air Quality – Odor

Actors: Employee, facility manager, technical staff

Triggers: The employee thinks there is a bad smell coming from the air-conditioning (AC)

Scenario: The employee reports his complaint via a phone call about the unpleasant odor coming from air-conditioning to the facility. The facility manager directs a technical staff to do an inspection. The technical staff changes the filter in the air-conditioning unit and reports back to facility manager. The facility manager notifies the employee about the maintenance work.

Outcomes: Floor, Room, Building Element Type, Related Building Element (Building Element Location)

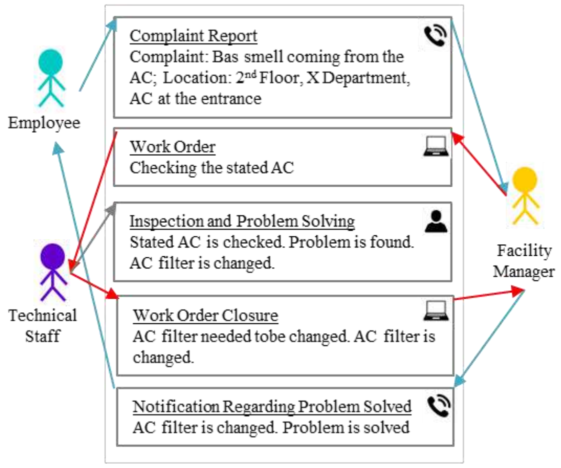

Figure 4. UML diagram of use case scenario 3

The use cases demonstrate that information requirements are different for each case. From use case scenario-1, *building*, *floor*, *zone*, and *source location* outcomes are obtained. Building, floor and zone represent the different granularity of location information of problem. The source location specifies the location of a problem source that is different than the location of the occupant. In the case of the unpleasant food smell in the office area, cafeteria represents the source location whereas the office represents the room/zone/region where the office user works.

From use case scenario-2 *floor, room, region, table, facade,* and *time* information requirements are gathered. Floor, room, region and table represent the location of the user. Since the complaint is related with a certain building frontage, the façade where the problem is observed is needed as well. Lastly, time stamp is important since the complaint is time dependent.

The information outcomes of the use case scenario-3 are *floor, room, building element type,* and *related building element (building element location).* Floor and room gives information regarding user location. Since the complaint is related to a certain building element, the type and exact location of it are needed as well.

Table 1. Information requirement outcomes of use case scenarios

Use Cases	Building	Floor	Room	Table	Region	Zone	Facade	Building Element Type	Related Building Element	Source Location	Time
1	x	x				x				x	
2		x	x	x	x		x				x
3		x	x					x	x		

Information requirements gathered from the use case scenarios are summarized and listed below:

- Location where the problem is observed (represented by building, and/or floor, and/or room, and/or façade, and/or table/zone/region depending on the case)
- Location of the user (represented by building, floor, room, table/zone/region)
- Source of the problem
  - Type of Building Element
  - Related Building Element
- Source Location
- Time

5 Conclusion

This paper presents the initial results of an ongoing research study, which focuses on integrating occupant feedback with Building Information Model (BIM) for assisting decision-makers in the facility management phase. The first step of this research study was to identify the information items that are required to represent occupant feedback for effective use in the facility management phase. The aim of this paper is to present a sample of the use cases developed to identify the required information items and describe the occupant feedback information flow observed in the office buildings.

The use cases demonstrate that information requirements are different for each case. The identified information items are: (1) location where the problem is observed, which is represented by building, and/or floor, and/or room, and/or façade, and/or table/zone/region depending on the case; (2) location of the user, that is represented by building, floor, room, table/zone/region, (3) source of the problem that is represented by type of building element and related building element, (4) source location, which specifies the location of a problem source that is different than the location where the problem is observed, and (5) time.

The next step of this study is to determine how the required information items are represented in IFC and if necessary, how IFC should be extended to represent those information items. Future work includes developing a prototype that collects occupant feedback from the user, stores in BIM and presents to the decision-makers for effective facility management.

Acknowledgement

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Automatic Reassembly of Fragments for Restoration of Heritage Site Structures

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Abstract –

A major bottleneck activity in the process of restoration of Heritage Structures is the reassembly of its fragments. Computer-aided reassembly could assist in finding the relation between them thereby reducing time, manpower and potential degradation to fragile fragments. Using geometric compatibility between the adjacent fragments as the central idea, a reassembly framework for a three-dimensional shell is proposed as a logical extension of the two-dimensional framework. Edges are extracted as polygons and relevant features are computed at each of its vertices. Sequences of the match for two fragments in the feature space are found using a modified version of Smith-Waterman Algorithm. Each match is assessed using a connectivity score. The final choice of best match is left to the user by displaying the resultant assembled fragments of prospective candidates along with the score. After pairwise matching, the global reassembly is done through a clustering-based method. This framework can handle fragments even with curved edges which can be reasonably approximated by a set of edges. We verify the methodology using a simulated dataset for both 2D pieces and a shattered 3D surface object.

Keywords –

Fragment automatic reassembly; Partial Curve matching; Feature extraction; 3D Reassembly; Heritage Restoration

1 Introduction

A large number of fragments are discovered during archaeological excavations and heritage site restoration tasks. Finding their relative positions is a very laborious yet crucial step. Manual methods are time-consuming, demands the construction of special supporting structures, labor intensive for heavy fragments and can potentially damage the fragile pieces during the process.

With advancements in technological developments to digitalize objects, computers can aid to a great extent in automating the process. [2] talks about the methods and technologies available for three-dimensional digitization of objects and monuments. [3] introduces a 3D digitizing pipeline for cultural heritage where they brief about polygonizing the point cloud to mesh to represent the geometry of the object.

This problem is similar to solving a three-dimensional jigsaw puzzle. There are a variety of approaches to solve the problem. The fragmented pieces themselves contain the clue for solving it. The clue varies from colour compatibility in the case of paintings [4], incisions on the surface for stones, marble veining directions [6], hand impressions on pottery [7] etc. Sometimes the clue also comes from knowing the end result like in the case of Skulls where similarity matching could be performed with the standard template to reassemble [8]. For highly eroded fragments, reassembly can be performed with the objective of maximising its packaging efficiency.

Unlike paintings, unearthed and abandoned fragments of buildings do not have colour or colour variations. Neither do we have a clear idea of the end result of the structure after reassembly of the fragments. The scope of the paper is to assemble pieces which have retained their geometric information without making any assumptions about the reassembled piece. We follow a framework for assembling pieces in two dimensions making use of only its geometry by contour curve matching. This has applications in assembling flat fragments like the fresco, walls. We then, logically extend the framework to assemble a three-dimensional surface object. Applications include reassembly of surfaces like domes, thin shell structures etc. This paper aims to help archaeologists reassemble interactively with user involvement only in the approval stage.

2 Related Works

The problem of reassembly has different approaches and is dealt in different ways depending on its applicability for each scenario. Every problem is essentially three dimensional. But some problems can be converted to two dimensions. Instances like flat fragments where the third dimension is uniform and does not exhibit appreciable variation belong to this category. Square type jigsaw puzzles involve utilizing boundary pixel values as the parameter to search among other pieces since there is no variation of shape along the edges [10]. Geometric reassembly dates back to 1964 where Freeman et al. encode the boundary as chains and partially matches chainlets through features for a commercially produced jigsaw puzzle [9]. As mentioned in [11], generalized reassembly is different from the jigsaw puzzles because of the uncertainty in the endpoint, unlike jigsaw puzzles where the delimiting point is fixed. The combination of geometrical and colour matching is very suitable to handle fragments of paintings.

A significant project in this domain was The Digital Forma Urbis Romae project where reassembly of marble pieces belonging to a giant map of Rome is attempted [6]. The clue, in this case, is contained in the incisions of the surface. Prediction of the pattern of the adjacent fragment based on the boundary drawings and searching for it through a number of pieces had resulted in significant improvements in its reassembly. Additional constraints come from the nature of the material - marble veining direction. Here we seek to reassemble apictoral fragments which provide us with no other clue than its edge contour. A similar problem was attempted in [12] and [13] where the fragments were converted to invariant features and compared in the feature space. Different features, the way matches are detected and their global reassembly methods are explored in various works.

In case of surface fragments like potteries, the two-dimensional simplifications do not hold. Some authors make use of the symmetry of objects by utilizing the thickness profile to reassemble pottery [5]. In this paper, we look at a generic case of reassembling 3D surface object without utilizing any information other than its edge information. Thus the proposed framework can handle missing pieces since it relies only on the strength of edge matching.

The extent of automation also varies for different works. A few works require the user to specify initial constraints like iso-planarity, adjacency while others do not involve the user at all and perform a completely automatic reassembly [12] [14]. We use very low user intervention in the following processes: (1) to finalize the pairwise and (2) reject the match when overlaps occur during global reassembly.

3 Framework

This paper aims to propose a 3D surface object reassembly framework by extending that of a 2D reassembly and verifying both the frameworks using a simulated dataset. The steps involved in the framework are described in the following sub-sections.

3.1 Extracting the Contour

The only piece of information we extract from the fragment is its contour. We attempt an apictoral reassembly. While extracting the boundary, we observed many consecutive 'almost' collinear points in the contour, which created a lot of edge jaggedness. This can be seen in Figure 1. We use Douglas-Peucker Algorithm to remove these points which do not contribute significantly to the matching process [17]. This reduces the processing complexity significantly. The choice of the threshold given as an input to the algorithm should be optimum since smaller values can be less effective and higher values can alter the shape of the fragment itself making it less suitable for the further process.

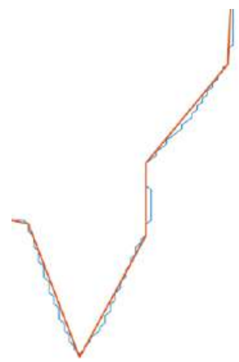


Figure 1. A fragment - Input to the Douglas Peucker algorithm (green) and output (red) with threshold = 0.01

3.2 Feature Extraction and normalization

With this reduced number of points in the contour which better capture the shape variation, we extract the following features based on [12] at every vertex:

I. Log of mean of edge lengths
II. Log of Absolute Value of signed curvature
III. Internal angle

For fragment i, let Fi_c contain the features extracted from the contour clockwise and Fi anticlockwise. The perimeter of each fragment is also stored in PM.

Distances in the feature space are highly dependent on the scale of each feature. Thus, to obtain uniformity, we use min-max normalization.

3.3 Pairwise matching

We use a modified version of Smith Waterman algorithm to match the two fragments i and j using Fi_c and Fj_a or Fi_a and Fj_c [15]. Two vertices are said to be same if their Euclidean distance in the feature space is less than Φ.

The endpoint to break the matching sequence is, cyclic matching i.e., we duplicate the sequence and append it to then end, and then match the sequence by removing repetitions [13]. The output of this is a list of matches between the fragments. The sequences greater than a minimum connectivity value C(i,j) as defined in [12] is stored in G.

$$C(i,j)= \frac{\text{Length of common boundary}}{\text{Minimum (PMi, PMj)}} \quad (1)$$

The transformation in the 2D space is estimated, checked for overlaps after transformation and displayed along with the connectivity value to the user to finalize the match.

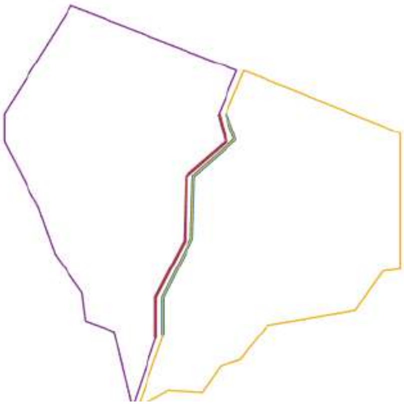


Figure 2. Fragment 2 and 3 pairwise match with Φ=0.05

3.4 Global reassembly

The order of assessment and reassembly of fragments is essential since wrong matches at initial stages potentially lead to error accumulation. Initially, connectivity score is found for all possible pairs of fragments (highest of all the matches for the pair of fragments is chosen). As proposed in [12], we use an agglomerative clustering algorithm. Pairwise matching is continuously performed for the pairs in decreasing order of their connectivity. The scores are not calculated after each iteration significantly reducing the computational requirement. After the reassembly, the fragments merge and form a single piece. Now, if any fragment is left over, the connectivity is recalculated considering the assembled fragment as a single fragment because the newly formed fragment structure might pose a good match to the leftover fragments. For our test dataset, a single iteration is adequate to assemble all of the fragments when we follow the approach of following the decreasing connectivity order. The assembled structure is shown in Figure 3.

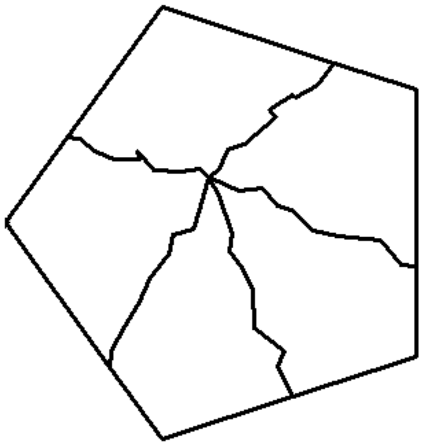


Figure 3. Assembled fragments

4 Extending towards a 3D case

The framework is easily and directly extendible to a 3D scenario. The input model now contains information in three dimensions. Techniques and technologies available to produce the digital representation of solid objects and monuments are discussed in [2]. The kind of features we compute now would differ because of the third dimension.

4.1 Creating the dataset

A unit sphere was created and shattered into 10 pieces using the 3D computer graphics application Autodesk Maya. They were randomly translated along three axes and rotated at different angles. Each individual piece is stored separately and labeled for further processing.

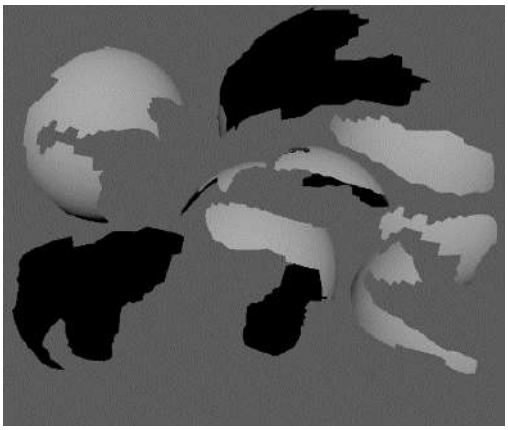
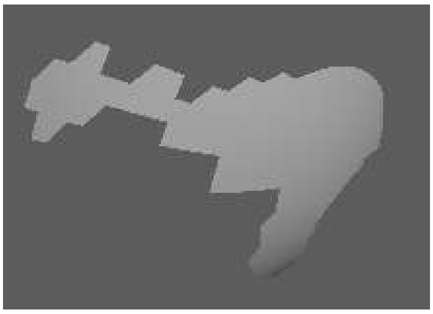


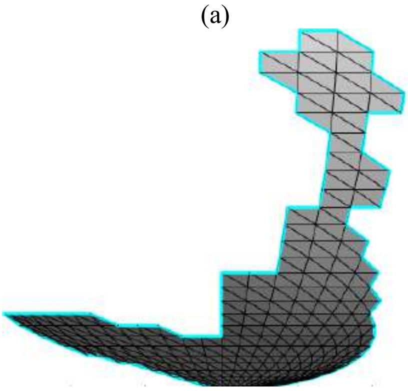
Figure 4. Input fragments

4.2 Extracting the contour

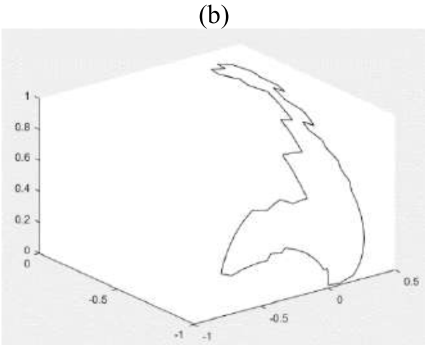
The created fragments were stored as object files (.obj) since it stores the mesh representation of the object as a set vertices with their coordinates, set of edges making up each triangle. Edges which are not common to two triangles indicate the end of the surface and are extracted to form a closed figure. Douglas Peucker algorithm is modified to be applied in three dimensions to smoothen the curve. As mentioned earlier, the threshold value decides the extent of smoothening and is necessary to maintain it constantly for all pieces. For our dataset threshold (th) was chosen as 0.005. The number of vertices constituting the contour drop drastically and hence makes the processing easier.



(a)



(b)



(c)

Figure 5. (a) Fragment when generated (b) Its mesh representation and borders highlighted (c) Extracted contour as the output of Douglas Peuckar algorithm with threshold th = 0.005

4.3 Feature Extraction

Features extracted for a 3D polygon at its vertices are different from that of a 2D polygon owing to its non-planar nature. Every curve representing a fragment has a set of points P_1, P_2 … P_n. Each point has the location in the form of 3D coordinates associated with it. We use the numerical approximation used in [18] and [19] for each of the feature defined for a smooth curve.

The features extracted here are:

1. Curvature: It measures the amount of deviation of a curve from a straight line. Mathematically, it can be obtained by calculating the reciprocal of its radius. The numerical approximation for curvature is

$$\alpha_i = 4 \cdot area_i / (a_i \cdot b_i \cdot c_i) \qquad (2)$$

where

$area_i = \sqrt{(s_i \cdot (s_i - a_i) \cdot (s_i - b_i) \cdot (s_i - c_i))}$

a_i = Distance between P_i and P_{i-1}

b_i = Distance between P_i and P_{i+1}

c_i = Distance between P_{i-1} and P_{i+1}

$s_i = 0.5 \cdot (a_i + b_i + c_i)$

2. Derivative of Curvature: This measures the rate of change of curvature with respect to arc length. This can be numerically approximated by

$$\beta_i = \frac{3 \cdot (\alpha_{i+1} - \alpha_{i-1})}{2 \cdot a_i + 2 \cdot b_i + d_i + e_i} \qquad (3)$$

where

d_i = Distance between P_{i-2} and P_{i-1}

e_i = Distance between P_{i+2} and P_{i+1}

3. Torsion: This is an indicator of the curve's non-planarity by measuring the speed at which the osculating plane rotates along the curve. A numerical approximation is given by

$$\gamma_i = 0.5 \cdot (\gamma'_i + \gamma''_i) \qquad (4)$$

where

$\gamma'_i = (6 \cdot H'_i) / (\alpha_i \cdot e_i \cdot f_i \cdot g_i)$

f_i = Distance between P_{i+2} and P_i

g_i = Distance between P_{i+2} and P_{i-1}

$H'_i = 3 \cdot V'_i / area_i$

$$V'_i = \frac{\det(P_{i+2} - P_{i-1}, P_{i+2} - P_i, P_{i+2} - P_{i+1})}{6}$$

$\gamma''_i = ((6 \cdot H''_i)) / ((\alpha_i \cdot d_i \cdot h_i \cdot j_i))$

$\gamma''_i = (6 \cdot H''_i) / (\alpha_i \cdot d_i \cdot h_i \cdot j_i)$

h_i = Distance between P_{i-2} and P_i

j_i = Distance between P_{i-2} and P_{i+1}

$H''_i = 3 \cdot V'' / area_i$

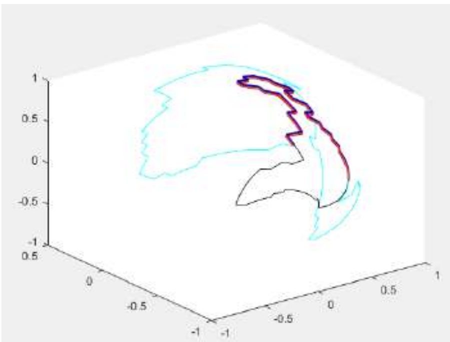
$$V''_i = \frac{\det(P_{i-2} - P_{i+1}, P_{i-2} - P_i, P_{i-2} - P_{i-1})}{6}$$

Here we take the average of γ' and γ'' to avoid introducing asymmetry in our calculations. As [16] states, only the above three metrics are enough to parameterize a Euclidean signature since they are the fundamental signature invariants. Feature extraction is done both clockwise and anticlockwise.

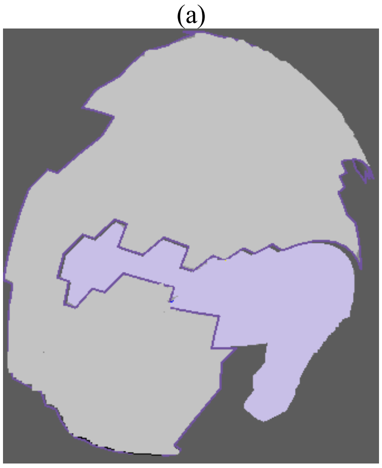
4.4 Pairwise Matching

We use the modified form of Smith Waterman algorithm like in the previous case except for the features matched. Two points A (α1,β1,γ1) and B (α2,β2,γ2) of two different fragments score a similarity score of 1 if the distance between them in the feature space is less than the threshold. For matching fragments i and j, features extracted clockwise for fragment i and counterclockwise for fragment j or vice versa is given as input to the algorithm.

A connectivity score as defined in (1) is evaluated for each pair and values below μ=0.1 are discarded. Once a good match (> 0.1) is found, the appropriate 3D transformation of one of the piece is estimated and made to merge with the second fragment and displayed (as shown in Figure 6) for the user to approve the connection. Once approved, the connectivity score and the start and end vertices of the matching part is stored separately.



(a)



(b)

Figure 6. Pairwise matching of fragment 2 and 8. (a) shows Fragment 2 (cyan) and Fragment 8 (black) with the matching portions of the fragments in blue colour and red colour respectively. (b) shows the three-dimensional merged fragments after translation

Table 1. Matrix showing the connectivity values of fragments (a) as estimated by the algorithm and (b) as calculated while creating the fragments. The rows and columns indicate fragment number. (c) shows the percentage error in connectivity value for each pair.

Observed Connectivity values for pairs of fragments									
	1	2	3	4	5	6	7	8	9
1									
2	0.127								
3	0.129	0.138							
4	0	0.163	0						
5	0	0.25	0.209	0					
6	0.313	0	0	0	0.306				
7	0.142	0	0	0.26	0	0.336			
8	0	0.556	0.298	0	0	0	0		
9	0	0	0	0.472	0.253	0	0	0	

(a)

Actual Connectivity values for pairs of fragments								
1	2	3	4	5	6	7	8	9
0.161								
0.288	0.1865							
0	0.2498	0						
0	0.2917	0.2502	0					
0.369	0	0	0	0.377				
0.26	0	0	0.311	0	0.3995			
0	0.6161	0.3435	0	0	0	0		
0	0	0	0.524	0.318	0	0	0	

(b)

Percentage Error in connectivity values for pairs of fragmnets									
	1	2	3	4	5	6	7	8	9
1									
2	20.97								
3	55.13	26.01							
4	0	34.75	0						
5	0	14.3	16.47	0					
6	15.13	0	0	0	18.88				
7	45.41	0	0	16.37	0	15.89			
8	0	9.755	13.25	0	0	0	0		
9	0	0	0	9.992	20.44	0	0	0	

(c)

The maximum error in the connectivity value was 55% (for fragment 3 with fragment 1) and the minimum was 0% (for multiple fragments as shown in Table 1c). This maximum value occurs when nearly half the original connection was undetected by the algorithm. The minimum value indicates a perfect fit.

4.5 Global reassembly

For each pair of fragments, the connectivity value calculated and approved by the user is recorded in the form of a matrix as shown below. The values less than 0.1 are reported as 0 as shown in Figure 7. The connectivity values obtained for our dataset as shown in the figure indicate that each fragment has found a strong connection with atleast one other fragment implying if no overlaps detected, just one iteration is enough to assemble back all the nine fragments.

Starting with the pair having the highest connectivity value, each pair is transformed and merged. At any point throughout the global reassembly process, the user can intervene and undo a merge if any sort of wrong overlaps is visually detected.

A major advantage is that the connectivity value need not be calculated over and over again. Since there were no overlaps, in one iteration all of the pieces were assembled back to form the assembled object as shown in Figure 7.

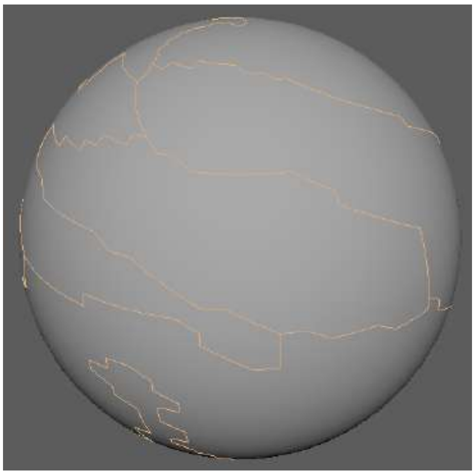


Figure 7 Assembled fragments

5. Results

From table 1c and Figure 7, it can be seen that despite having error values for pairwise connectivity, the sphere was assembled correctly because the location of matches detected were correct though only partially matched. The reasons for a partial match of the common curve could be because of the quality of the image processed and stored as vertices, choice of threshold given as input to Douglas Peucker algorithm or the sampling rate of points along the boundaries of the object.

6. Conclusion and Future work

A framework for re-assembling 3D surface object as an extension of the 2D reassembly framework was proposed and verified using simulated datasets. The merits of this framework are manifold. It is an unsupervised reassembly where the reassembled structure is not known prior to the process. The global reassembly does not compute the connectivity values after each pairwise merging reducing computational requirement. Additionally, while the user involvement was minimal, this involvement along with the cluster-based merging process prevented error accumulation. For the given dataset, the reassembly was completed in the first iteration. This way, an efficient tool for the archaeologist to speed up the reassembly is put forward.

In future work, the proposed framework will be tested on a real datasets where the fragments are not predefined by the user. This methodology can be used in addition to features extracted from fracture surfaces for validation while reassembling a solid object.

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Improved Productivity, Efficiency and Cost Savings Following Implementation of Drone Technology in the Surveying Industry

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Abstract

The goal of this study was to identify any potential benefits drone technology offers in the surveying industry as compared to traditional methods. Drone technology has advanced rapidly over the past decade, offering greater capabilities every year. These technological advances were the inspiration for this research, with an ultimate desire to identify current survey process improvements. The research was carried out in an interview format with professionals from companies offering services within this industry. It was found that replacing traditional surveying methods with drone technology results in overall cost savings for the company and increased efficiency by their field crews. These findings provide significant data for companies with surveying service offerings as operating expense reduction and efficiency increases are realized following the implementation of this new technology.

Keywords –

Drone; Unmanned Aerial Vehicle; UAV; Surveying; Construction

1. Introduction

Arguably, one of the most important factors determining the result of a construction project is site and building surveying. The surveying & mapping industry had a value of $6.672 billion in revenue in 2016. This market peaked in 2007 at $8.173 billion and fell hard following the financial crisis. With the construction industry on an upward trend again, the surveying and mapping industry has followed suit [6].

Profitability, accuracy and efficiency are critical aspects to the overall quality of the construction project, requiring that the project be complete per the construction documents and that the initial land surveys were exact. This is regularly done and tracked with surveying equipment to ensure project components are in agreement with where the project is proposed to end up. Traditional surveying not only requires that expensive instruments be used and maintained, it can also be a relatively slow process.

Current human surveying crews are required to perform numerous equipment set-ups in order to achieve total visibility of a site. Often, many obstructions come into play on active construction sites, which in turn require even more station arrangements for the crews. For each station set-up the crew is required to do, productivity drops and costs quickly escalate due to this lost time. If a crew is not physically surveying or mapping, that time spent setting up or reviewing data can be viewed as lost time. Each new set-up requires the equipment to be moved, re-leveled, and back-sights must be shot.

Enter the use of drones; what was initially a military tool, advancing to a toy for people to enjoy has now become a critical tool for the construction project process. Drones were introduced to the construction industry as a means to photograph projects through construction and at completion. They provided project teams an opportunity to access a "bird's eye" view of their construction site at a rather minimal cost. Through the advancement of technology, however, developers have found a way to utilize drones to analyze what they are seeing and provide a report to the team. The many new uses will continue to grow as drones become more common and the governing rules ideally continue to adapt and loosen.

The new, highly advanced drones available on the market today offer technology that can take the place of former surveying crews and be operated by a single individual. Partnered with a tablet and application, the drone can provide real-time surveys of the geography or structures being assessed. Not only this, operators can also program a route for the drone to take, ultimately mapping the survey process before it even begins [7].

This research investigated if drones provide both a cost and time savings for companies in comparison to traditional surveying crews. New technology theoretically should lead to increased productivity, efficiency and reduced costs to surveying companies. Potential roadblocks were also researched to determine what might currently be decisive factors pushing surveying companies away from the new technology. Some publications have been accessed to provide further sustenance to this research.

Additionally, the biggest cost savings we suspect/anticipate was in the form of reduced labor hours. Surveying companies should be able to cover more sites, meaning increased productivity. This might allow them to reduce their number of crews since they can now cover more ground with fewer people, ultimately reducing their expenses on equipment. In addition, drones typically only require a single operator, while survey crews typically are comprised of two people, although a surveyor could work alone if needed.

2. Literature Review

The construction industry has unfortunately gotten a reputation of being sluggish, plagued with inefficiencies and ultimately resistant to change – mostly because those that make up the industry are technology adverse and believe that doing things the way that they've always done them is perfectly sufficient. This is not a new trend but one that has seen decades come and go. Technology, however, has refused to accept this fact and has made data collection, organization and sharing impossibly easy; so easy that it would be self-destruction for a modern firm to not take advantage of profit margin protecting efforts that are now available.

Because our research has highlighted the many uses, advancements in time savings to the planned schedule, improved material, safety and job-site monitoring and continual ingenuity and innovation for the use of Unmanned Aerial Vehicle (UAV) technology, we have found it imperative to research and discuss some of the many ways industry has decided to implement UAV use and improve their business.

There were many examples of the bird's-eye visual and with "Job Site Monitoring: There is huge potential here. As it stands, flying a UAV over people is not allowed without a permit, but the Federal Aviation Administration (FAA) works with applicants who are willing to prove their processes are safe (and who have proper liability insurance)" [2]. This may be one of the largest issues currently facing drone implementation in surveying. The FAA has some restrictions governing who can use drones, for which purposes, when they can be used and why the use is necessary for their business. If companies are required to go through too intensive of a permitting process for each site they intend to survey, it is safe to assume many companies will remain with traditional technologies and processes already discovered and controlled. Additionally, there are other risks and costs associated with making sure that the proper liability insurance is maintained and covers all of the evolving hazards and threats that continue to develop on the surveyed site/location.

While traditional methods may be slightly more time consuming in the field and require data compilation following the survey, this might still be a better option than using drones if flight restrictions remain at the current level. It would take additional full-time staff to continually work through the permitting process for each site requiring clearance. It will be interesting to see where time takes this particular issue and if organizations will deem it valuable to invest this level of attention from their firm and the potential profit realized for the given project.

"According to a March 2016 report from Goldman Sachs, construction will be the largest use case for commercial drones in the immediate future, generating \$11.2 billion of the projected \$100 billion in global spending over the next five years" [3]. This is an exciting fact for our research. Over 10% of commercial drone spending in the next five years will be focused directly on construction. This indicates a growing demand for the services and shows a bright outlook for the technology.

Companies clearly see an advantage to using the new technology; it can only be expected to get better as technology advances continue to surface. UAV training entities and software leaders continue to evolve and present products to an industry that has resisted this type of change for so long. We believe that the numerous software products used by various stakeholders to realize simple collaboration within a project will become an issue of focus that competing software organizations will seek to find appropriate (streamlined) solutions for and that eventually an answer will inevitably emerge. We also believe that consistent FAA standards and subsequent workforce training will eventually saturate the industry to further stabilize the technology and encourage complete business adoption.

"Drone technology is moving extremely fast. It's very possible many surveyors would rather hire a service provider to collect data than invest in a tool that can be obsolete in as little as six months. They may also consider short-term leases to ensure their technology is relatively current or just rent a drone when needed" [5]. The continuous advancements in drone technologies and their uses deter many companies from potentially purchasing new drones as they would rather have subcontractors or other firms collect the data or simply wait until the drone market steadies more. There are fears that drones are merely a phase in surveying technology evolutions and some companies may not feel comfortable investing such large capital resources in technology that could possibly soon be out of date and not produce the anticipated or desired return on investment (ROI).

"They are finding a much higher return on investment due to more accurate data being accumulated by fewer people in less time with quicker results. Not working with a modern surveyor employing the best techniques is far too expensive a proposition for many companies, and they are finding the change worthwhile" [4]. Drones help in collecting accurate data relatively inexpensively. There seems to be an upward trend in organizations attempting to use drone technology because companies that have switched to the technology are able to provide accurate data that is collected by fewer people and in noticeably less time.

"The number of surveyors is actually projected to decline by two percent from 2014 to 2024 because of improved surveying technology" [5]. Thanks to advances in surveying technology, the physical number of surveyors is projected to decrease by two percent. According to the US Department of Labor, there were 44,300 surveyors in the United States in 2015. With these projections, as the industry continues to grow, the number of employees will actually drop by nearly 9,000 positions. While this is an unfortunate outlook for the job market, this projection provides a bright outlook to the industry regarding advances in technology drones can bring to the surveying industry.

3. Research Methodology

Our research included a combination of scholarly and trusted online article sources and one-on-one interviews conducted directly by our group. In most cases, we were able to speak directly with the manager of the department that operates the drones or with the individual who utilizes the drone in their daily tasks. In other instances, we emailed these same stakeholders; the same ten (10) questions were used in both scenarios. We've attempted to resolve with our research these two fundamental questions:

1. Have drones provided surveying companies with cost savings over their traditional surveying efforts?
2. Has the use of drones in surveying provided increased efficiency and productivity for their organizations?

3.1. Expert Interviews

In order to provide high quality responses to the aforementioned research questions, the group undertook a research method geared towards interviews. Approximately twenty-five (25) organizations were initially identified to interview. These companies were believed to have utilized human work crews at some time to capture surveying data and information and have since switched over to some degree to the use of drone technology. Of the twenty-five (25) companies chosen, we received feedback from seven (7) of those groups. The eighteen (18) that did not participate had varying reasons for not providing feedback. The large majority felt some of the information being requested was proprietary and preferred not to answer. The others either did not respond promptly within our research timeframe or they did not respond at all. Upon contacting the companies, the team conducted an interview with the following questions:

1. When did your company begin to incorporate drones in surveying procedures?
2. What kind of drones are you using?
3. What is the average upfront cost of the new technology per drone the physical drone and any necessary software?
4. Have you noticed a cost savings after switching to drones?
5. What was the deciding factor to switch to this surveying technology?
6. Have you noticed an increase or decrease in productivity with the new technology?
7. Approximate percentage of increase/decrease?
8. Do you have any reservations in using drones versus traditional human survey crews? Are you concerned about data quality?
9. Are there any legal or logistic hurdles that need to be overcome?
10. Are there any additional services your company has begun offering with the addition of this new technology?

The questions were not strictly seeking numerical responses, which makes visual comparison difficult through diagrams and charts. Often, the interviews were largely conversation based with in-depth dialogue regarding each question to better understand the industry. While we made efforts at extracting hard numbers from the responses, the majority of our data is dialogue from those conversations. With the responses from these interview questions, we have reviewed the data to identify trends. These trends will be used to answer the research questions, and will ultimately lead the team to providing a final decision on the thesis. In addition, the team will look into potential risks associated with drones, the evolving legal and regulatory compliance linked with their use, and the conceivable advancements this technology is sure to bring.

3.2. Research from One-on-One Interviews

Within our research we found that the organizations that we received responses from all in fact used a traditional (human/manned crew) form of surveying prior to their implementation of UAV equipment. There was one relatively early adapter who began their use in 2011. However, the other six respondents stated that they began to use drones in 2015 or 2016, four companies and two companies respectively. Likewise, most organizations made a significant upfront financial investment for the drone itself and the associated software packages; in some cases, this also included any initial training as well.

The average cost per drone varied greatly from company to company, however, it appears that companies typically spend between $40,000-$60,000 per drone including any software. Those drones that are being purchased and used also proved to be anything but standard; we found that the following drones are being used: the DJI Phantom 4 Pro, Trimble UX5, Skycatch, Firefly VTOL, Matrice 100/600 series, 3DR Solo, Sensefly eBee, Inspire 1v2, Pulse Aerospace Vapor 55, Albris and even some custom-made drones. The lack of "industry standard" when it comes to drones made comparing apples to apples difficult in regards to the cost of the upgrade. The number of drones needed, the capabilities of those drones, and the financial resources available among other factors seemed to cause a wide variation in the upfront capital expenditures by the companies interviewed. A larger sample size with more refined financial questions would further narrow in on costs associated with this technology upgrade. Nonetheless, valuable data was gathered from the seven respondents, which effectively illustrates that there is no standard practice currently in place within the surveying industry.

The amounts spent on these technologies, we have discovered, also depends on the type of surveying products that will ultimately be produced. In our research efforts, we found a nice sampling of organizations that produce small to large scale surveying projects. The

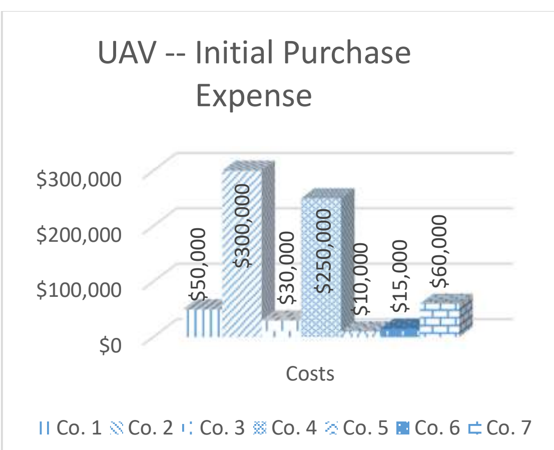

Figure 1. Graph depicting the initial costs associated with acquiring the equipment to begin surveying using drone technology.

higher the initial upfront costs, the larger the scale of surveys performed and vice versa. For instance, "Co. 2" spent approximately $300,000 for their UAV equipment and classifies their expenditure along military-grade alignment. "Co. 2" uses their drones to cover several miles, similarly to manned helicopters that were previously used for surveying projects that cover hundreds of acres. Other organizations have varying levels in scale of this and their initial expense also reflect the measure of surveying projects that they perform. Some organizations perform more of the marketing, or monitoring, type of project and the UAV's that are able to fly and hover lower to the ground are more useful for their requirements. Still others have been used to perform the more traditional construction surveying projects of parking lots, pre-construction and construction monitoring and 3D & 4D imaging – and these constitute the more average, mid-range expenditure.

One of the desired research outcomes was to determine if drones provided companies a savings in time and money. According to the interviews conducted, every company said the use of drones has reduced costs on many, if not all projects. In addition, many companies saw an increase in productivity at least by 50% through the implementation of drones; mostly these increases in productivity are exampled by their ability to take on more work with the same human workforce. One interviewee stated this productivity increase is thanks in large part to improved workflows and overall efficiency with the surveying being done from above, rather than on the ground.

Most of the companies interviewed stated that one of the primary deciding factors to incorporate drones in their company's operations was due to the anticipated cost savings. It appears that each company had done rather extensive research prior to taking this step forward in technology. Other recurring factors that pushed companies toward the technological upgrade included increased efficiency, enhanced safety for those manned work groups on the ground, improved precision and detail, while still others knew that the industry was progressing to this technology and was dedicated to take advantage of the advancements it offered.

The other desired research outcome previously identified by our group, was to ascertain potential legal or logistical issues that are present with drones that were not previously considered. The largest legal matter mentioned by companies was flying restrictions. It takes logistical planning with the Federal Aviation Administration (FAA) for airspace planning prior to the act of surveying. Although the FAA regulates airspace usage and logistics, one company interviewed by the group felt that those regulations were not enough for this new niche within the surveying industry. The person interviewed identified that there is "a growing concern that unskilled people are using the technology without grasping the complete knowledge of what needs to be done to produce quality work. As this happens, it will push back the industry and build a rift with the public against the new technology. There should be regulations and a licensing board [established]." It appears, according to these comments, that drones with surveying capabilities are too accessible to the general public that could allow anyone to buy one, advertise as a "surveyor" and perform poor quality work. This would be significantly detrimental to the industry, driving a wedge between the new technology and potential clients.

Drones do have identified risks associated with their use and organizations have decided to use the art of collaboration to minimize their exposure. Some of the alliances include partnering with entities that have specific drone insurance to help absorb some of the risks or with firms that employ individuals with aviation knowledge and experience (licensed pilots). In other examples, collaborators may also use UAV equipment that is different from what the original organization may own, which ultimately improves their capacity and the product deliverable and quality; while the other gains access to additional markets.

At this time, companies did not appear to have any reservations in utilizing UAV/drone technology. Some of these entities expressed skepticism that sat in the back of their minds surrounding the new technology, however each company seemed to have their own set of checks to ensure accuracy was of the highest quality and improved the overall industry, trade and public perception.

The final finding from the interviews showed that there are two companies that have not added additional services to their product offerings after supplementing their fleet of equipment with drone technology. While still the majority of companies interviewed have taken on different types of projects from their original surveying work. Some of the new contributions included buried pipeline mapping using thermal sensors, before & after work pile photography and wildlife conservation type projects. Others have found that inspection photos and thermal imaging are great ancillary products to be offered in tandem with their main services; however, they have focused on offering their services to new industries that have not used Light Detection and Radar (LiDAR) technology before. Most have found that having the technology is actually more of an expansion of their market instead of the actual services that they are able to offer.

And still others have decided that the drone itself is considered a "new" service offering from their original organizational structure. They have been able to offer services to "site prep" companies, which basically are tasked with moving large amounts of dirt from the site. One company is now able to monitor the dirt being removed and mark it or data point it over the period of time, as well as offer a visual image of the site. It is noted that companies tend to like the visual and bird's eye view and this fact offers a marketing tool opportunity or communicable image of what a company actually performs.

Finally, those entities that have offered an altered service mix note that they are better able to understand a number of technologies due to the drone. It's possible, not as a direct result, drone technology has inspired all within the company to be more creative and dynamic. This is because of the seemingly ever-expanding nature of the drone concept. These companies are currently pursuing sales in the Thermal, Multi and Hyperspectral, LiDAR and Normalized Difference Vegetation Index (NDVI) markets using drones.

For those who did not alter their product mix, this came as a bit of a surprise to the group as we anticipated seeing some service expansion or minimally some alteration. It does appear, however, that the addition of drones has provided both cost and time savings to all of the companies that are providing surveying services and throughout the interviews, these organizations expressed being pleased with their expenditure and identified noticeable overall improvements.

4. Conclusions

We have discovered that the organizations that we have interviewed, as well as the subsequent research we performed, made one point abundantly clear and that is that introducing drone/UAV technology to their firm has found cost savings and improved project scheduling. As discussed throughout the paper, we have highlighted the labor/crew hours that have readily been absorbed by most firms by increased projects, improved safety and job-site related efficiencies, increased collaboration and potential new product offerings.

Our group has set forth to explain the cost savings organizations have found because of their use of drone and UAV technology versus the more traditional ways to survey sites of varying forms. We planned to explore the potential differences of productivity in surveying using drones versus traditional surveying methods. The biggest cost savings we found emphasized by the interviewed companies were in fact in the form of reduced labor hours; or, it was often times quantified by increased project/job capacity.

We also discovered that because surveying companies were able to cover more sites, they were able to illustrate specifically that productivity increased substantially and warranted the implementation of new products or overall organizational growth.

Again, these forms of increased productivity were demonstrated in some ways by the reduction of crews since these specific companies were then able to capitalize on more ground with fewer people in the crew, which ultimately reduced their expenses on equipment as well as for other manual surveying procedures and continued training. In addition, drones typically only require a single operator, while survey crews typically are comprised of two or more people, although a surveyor could work alone if needed.

Again, drone and UAV technology present their own list of challenges and business structure necessities. FAA regulations, improved insurance and safety procedures, as well as the continued expense for training in an ever-evolving technology and market/industry are all examples of the new issues to be monitored and controlled by organizations. These potentially, and arguably, are substantially less taxing on a company than the traditional way of conducting surveying projects on the construction site. We believe that our research has exhibited the increased efficiencies and financial savings that have been realized by those innovative companies that invest in the drone technologies.

Resources

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Integrating Facility Management Information into Building Information Modelling using COBie: Current Status and Future Directions

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Abstract –

Building Information Modelling (BIM) has been implemented by architecture, engineering and construction (AEC) firms since it effectively manages and integrates information throughout the building life cycle bringing long term benefits compared to existing practices. BIM models serve as communication between design and construction phases. These models are used to determine geometry details, resolve constructability problems, track the types of materials, represent functional characteristics, and produce workflows among others. However, the benefits of BIM have not been fully extended to the operations and maintenance phase. Once the building is finished, the owner still needs the handover of paper documents to complete the information required to support the facility management phase. Therefore, to help owners extend information support throughout the building life cycle, this study proposes a process model to collect information required for facility management and incorporate it into BIM. A Construction Operations Building Information Exchange (COBie) approach is used to capture essential information to support facility management as it is created in design and construction. By capturing all the information, owners may be able to directly import data into maintenance management systems to support facility operations. Future directions are also discussed.

Keywords –

COBie; Facilities management; BIM; Integration

1 Introduction

Architects, contractors, consultants, and operators from many disciplines generate information in a variety of formats while designing and constructing a facility [1]. Once the facility is constructed, the information required for facility management is given to the owner for future operation, maintenance and decision-making. This information referred to as the as-built documents is compiled by the design team and is intended to show the actual location of systems and components in the building. However, the as-built documents are often poorly structured, missing, inaccessible or incomplete making it difficult for facility operators to locate necessary information and understand design objectives during their building operations tasks [1]. As-built documents should be planned to document the constructed state of a facility and reuse all the design and construction information as it is created to support facility management. To efficiently reuse all the information it is not only necessary to gather all the documents generated during design and construction, but to integrate them in a data set in order to support life-cycle operations and maintenance.

Relevant documents not incorporated in the data set and properly integrated may preclude equipment maintenance, preventive operations and other facility management goals. These goals may be achieved by considering the owner's requirements such as safe functional systems, life-cycle costs savings, extended equipment life, and reduction of unscheduled shutdowns and repairs [2]. The Computer-aided facility management (CAFM) is a widely applied approach used to support facilities management by information technology. CAFM systems track and maintain floor plans, building information, space usage, and occupancy data among others [10]. However, the value of these systems is limited since no party is assigned to update the data and information can only be distributed to facility management operators. The Computerized management maintenance system (CMMS) is a software package that upholds the information about the maintenance operations and schedules maintenance activities [3]. The CMMS improves uptime, establishes preventive maintenance, organizes work orders, help management make informed decisions, and allows data to be also useful when dealing with third parties. However, there is still some information essential for facility management that needs to be transcribed to be used for facility management since CMMS does not support related document linking. As a result, if a building wants to implement an effective management operations plan, the gathering and integration of data as it is created during design and construction is required.

The integration of information has been addressed by the integrated document management approach such as the Electronic Document Management Systems (EDMS) which is a very efficient approach to manage large numbers of documents in a systematic way [1, 4]. It has also been addressed by the model based approach defining data models such as Building Construction Core Model, Industry Foundation Classes and CADD/GIS data standards [1]. This approach is to produce documents automatically through query of an integrated representation and to communicate and exchange information across AEC disciplines.

There have been some practical changes and trials using BIM for better information transfer for facilities management. Recent developments have shown that after the completion of construction, many projects now require BIM-based documents for handover. For instance, efforts include FMie by buildingSMART [22], CAD technologies [13], building automation systems (BAS) [15]. Some countries have also mandated BIM-based documentation. In the UK, the government is pushing to implement BIM Level 3 by making mandatory that a data model can be accessed and modified in a single source (e.g. common data environment or open BIM) [21]. In the US, the requirement is a non-uniformed deliverable using a number of formats specified by the General Services Administration (GSA) [13].

However, the current procedure to integrate information lacks of a tool that helps decision makers organize knowledge on the various types of information generated during the building life-cycle to make reliable decisions and increase the life-cycle of the facility. An operational system design needs to be implemented if BIM is to integrate an effective design and support facilities management [12,21].Therefore, to help decision makers gather relevant information for facility management, this paper describes a process model to integrate information under a Construction Operations Building Information Exchange (COBie) approach. The process model describes the procedure to capture information and how to implement the COBie data set into a CMMS. In other words, the procedure traces information from its delivery by design and construction phases through its incorporation into the operations system and finally delivery to the owner. As the use of smart technologies is becoming more common in buildings, there is a need to transform FM data so that it can be integrated with smart devices. This needs changes both in the schema level of COBie and data translation effort so that the FM data can be exchanged through a network instead of just spreadsheets or IFC files. This paper discusses the process model to capture information and how to implement the COBie data sets and its future direction.

2 Data requirements for facility management operations

The Facility management and operations phase orderly controls activities required to keep a facility in an as-built condition while continuing to maintain its original productive capacity [3]. The objectives of this phase are to extend the useful life of assets, assure the optimum availability of equipment for production, ensure the safety of personnel using facilities, guarantee customer satisfaction, and provide healthy spaces [1, 2, 3]. In order to comply with the objectives, facility managers must reuse effectively a wide scope of information created during design and construction by different parties to support operations and maintenance [1]. The information required to support facility management produced during the design phase includes material types, floor characteristics, building functions, floor plans and systems. Later, during the construction phase information required includes equipment lists, connections between equipment, product data sheets, warranties, preventive maintenance schedules, and submittal register among others [1, 2]. Today, directives have been created to establish goals for reduction of energy and water consumption and to improve sustainability goals for both new and existing facilities [12,13]. These directives not only affect how facilities are designed and constructed but also how they will be operated and maintained [2, 10]. The operations and maintenance activities will be guided to minimize operating costs while increasing occupant's productivity, improving energy performance, water consumption, indoor environmental quality and materials use [5]. As a result, other sources of data such as whole-building cleaning issues, waste stream water management programs, recycling programs, exterior maintenance programs, and systems upgrades will also be needed to perform facility management in buildings. New sustainability requirements affecting facility maintenance and operations include can be found in the Whole Building Design Guide [2] and the leadership in energy and environmental design (LEED) rating system for existing buildings operations & maintenance (LEED-EBOM) [5]. Although the requirements and amount of information to operate and maintain a facility is increasing, facility managers lack of a tool to help them organize knowledge on the various types of information generated during the building life-cycle. The purpose of integrating information is to enable all the documents produced during the design and construction phases to be stored in a single integrated database [1, 4]. The database contains the information generated in drawings and text documents. By accessing to the database, information on any particular building component can be retrieved and exchanged since data is standardized. In addition, information can be displayed in different formats allowing different parties to still use different software [2]. Representation of all the information needed to describe buildings throughout the whole design and construction process has been an objective for applying information technology (IT) in Buildings [6]. Informative case studies for BIM implementation for FM are detailed in [10-15, 18].

3 Building information modelling and COBie overview

The BIM is a tool for digital representation of physical and functional characteristics of a facility and it serves as a shared knowledge resource for information about a facility [7]. BIM represents real world elements as 3D objects. In addition to geometry details, other information is attached to these objects such as cost estimates, manufacturers, fire rating, and schedule among others [1, 4, 7]. Additionally, they have been used to solve constructability problems, conduct interference analysis and perform scheduling during the preconstruction phase [7]. These 3D models serve as a tool for communication between planning and design phases. However, BIM is rarely used during the post construction phase to address facility management issues [1, 7]. A substantial amount of information is still collected and transferred to the owner in boxes. Therefore, an approach to data collection that is incorporated into a BIM model is required.

Data collection can be completed using a COBie approach. The COBie is an approach to enter data just as it is created during design, construction and commissioning (Cx) phases. In other words, the information required by COBie is not different from the information already supplied in the design and construction contracts by all the parties. Since different parties use different software, they need to interact with COBie, as this information can be displayed in various formats [2]. All the formats provide an interoperable view of the underlying information specified by COBie and COBie can be customized to support specific requirements of an owner or a facility. Therefore, COBie allows having a one data set with different views enhancing the value of connection information and creating meaning since exchange is possible [2]. COBie's exchange specification is intended to transform existing deliverables into deliverables that contain the same information but in a new reusable format. COBie data includes spaces and zones of the facility, equipment and its location, submittals, instructions, tests, certificates, maintenance and safety protocols, start-up and shut-down procedure and resource data for the related activities [12]. Additionally, COBie data eliminates the reproduction cost for paper files, uses current software to deliver electronic handover information, ensures collaboration and integration of all project partners and improves the roll of construction submittals in construction handover [2, 7, 11].

4 Documentation process

The COBie approach begins early in the design phase and goes through the commissioning phase (see Figure 1). The starting point of COBie is when the owner determines the objectives of the facility and states the requirements. Once the specific requirements are determined, the design phase starts. In the early design, the facility naming and the vertical and horizontal spaces that are needed are defined. Additionally, the different types of systems to satisfy the function of each space such as ventilation, mechanical, plumbing and electrical are also defined. COBie information in the design planning stage is provided via a listing of facility, number of floors, spaces in each floor, functions of spaces, and product and equipment types for each space. After the design planning stage information is provided, the information of the coordinated design such as name of equipment, equipment systems, space zoning, space layout, and location is provided. At last, the information of the final design stage is provided which includes design document register, as-designed equipment properties, product and data schedules and the equipment connection model.

After the design phase information input is completed, the construction phase information takes place. Builders provide not only the approved submittal documents but also all the information to complete the equipment data such as component systems, manufacturer, model, serial number and tag numbers. Later in the commissioning phase, job plans, warranty and parts documents and resources are also provided. Additionally, updates space functions and area measurements and operations and maintenance documents complete the commissioning documentation. As noted in Figure 1, the information integration is cumulative. In other words, the information is transferred from the early phases of the process to the late phases to improve decision-making. Therefore, COBie database gathers the accumulated information produced in each phase. For all of the information provided to be integrated into COBie, COBie specifications have to be followed within the existing contract specification [8]. This specification requires the handover of COBie information in the spreadsheet XML format at each phase. The COBie specification is implemented within the context of the existing specifications or performance based. Performance based specifications deliver information not as a stand-alone data, but as data that can be further incorporated to measure and quantify the building's performance [8]. Quantifying the building's performance enhances architectural design since the facility is measured in terms of the owner's specific requirements [12, 17].

5 The integration approach

The decision on how to create COBie data is based according to the firm's software and in many cases other firms are contracted to create it. COBie can be created using COBie compliant software, development of transformations of existing data into a COBie compliant file and direct use of the COBie spreadsheet [8,13]. Due to the variety of parties, a combination of these methods is usually followed to create the COBie deliverables. If the first method is used, the use of the software must be combined with manual configuration of the BIM software. This process can be performed using two different approaches. The first approach consists of producing a COBie file that complies with the buildingSMART international's facility management handover model view (MVD) definition specification for industry foundation classes (IFC) building information model (BIM) files [12].

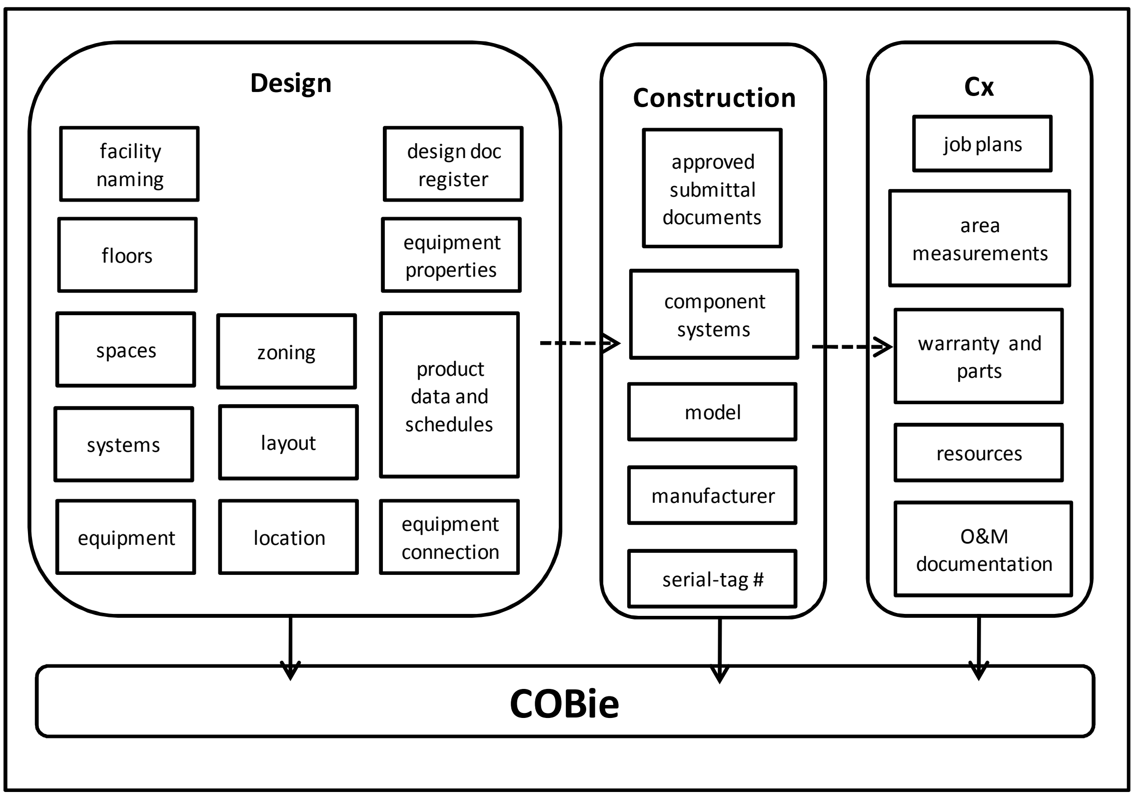

Figure 1. COBie approach. Adapted from WBDG, 2018.

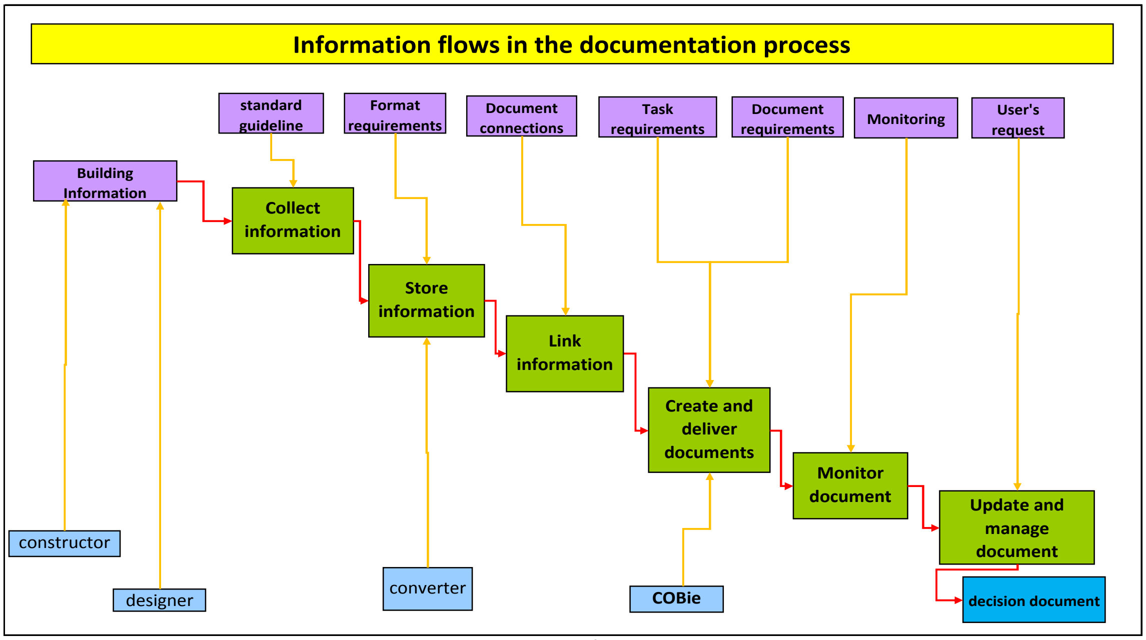

Figure 2. Adapted from Song et. al 2002

The COBie files produced have no technical difference with the MVD files, but to ensure compliance with the COBie contract language, the project parties must deliver the COBie formatted files. For that reason, a translation between the IFC files into a COBie formatted file is required [8]. The alternative approach needs the use of applications able of producing a file in the COBie spreadsheet format. The spreadsheet format of COBie is a modified version of Microsoft Excel spreadsheet which allows handling and saving of information as an Excel XML file format. As of December 2014, all software produced through the MVD will require some minimal manual adjustment to comply with COBie. Products from vendors who have completed COBie challenge can be found in the Whole Building Design Guide [2].

The second method to produce COBie files is based on capturing the information directly from the software tool in which it was created and the documents already containing the COBie information. For instance, applications containing equipment and room lists have most of the information required by COBie. For the case spreadsheets under a specific format are created, the spreadsheets' information is organized by hand or using other software. Afterwards, COBie information can be created using the exporting capabilities in the software. Finally, the third method is the input of the information in the COBie spreadsheet. By using this spreadsheet, the parties of the project can directly verify the accuracy of the information before submitting the COBie deliverable.

With all the information integrated into COBie, the COBie data is completed and can be used to support the facility management operations. Figure 2 shows the information flow in the documentation process. The building information is the initial input. This information is later collected, stored and linked (using COBie). COBie deliverables are the monitor document and this data set needs to be updated and managed to become the decision document.

The process model framework shown in Figure 3 supports the decision maker in the process of facility management planning. The framework illustrates how the process of data integration is supported by using tools and software. In the data input module information is collected, in the integration module the interoperability procedure and integration of documents into COBie occurs using an integration model of heterogeneous databases, then in the standardization module the translator is checked for compliance and finally in the operation module the standard format document is given to the owner or decision maker.

Since COBie data can be directly imported into the CMMS, no further standardization is needed and the complete facility operation and maintenance plan can be effectively controlled using the CMMS.

The integration module is the main enabler of this process model. This module uses an XML schema mapping using ifcXML (XML-based data interoperability) for querying and integration of data from heterogeneous data sources containing facility operations and maintenance information. The ifcXML is an implementation of the ISO-10303 Part 28 Edition 2 standard that provides an XML schema specification of the IFC schema through an automatic conversion from the IFC EXPRESS (ISO 10303 part 1) representation [22]. The integration framework for heterogeneous data sources has been the center of many database studies and the XML-based integration model dealing with transformation of heterogeneous data has proven to be effective in many prior studies [23, 24, 25]. The ifcXML schema provides both IFC interoperability features and XML-based data integration capabilities. Using ifcXML schema, data from diverse sources such as design, construction, and commissioning stage will be integrated and maintained in an XML-based database following IFC data model and will then be configured and mapped to COBie dataset.

6 Limits and benefits

Implementation of the process model described may be successful if parties involved in construction rethink and reorganize the building process throughout its life-cycle. Collecting and storing information in the minimum required format to then integrate it into COBie format might require new responsibilities and costs. The process of capturing information may need new personnel and training. It may also need agreement among the owner and AEC parties in the procedures to be implemented.

BIM has the potential to change the way construction is performed and documented. The transition requires a complete shift through all the phases of the building's life-cycle. BIM could become the data source of information including facilities management [16, 19]. The advantages of BIM include improvements in productivity as compared to other practices. Though, there are no reliable methods to measure the benefits of BIM and quantify the results of the new practices. Therefore, there may be some building participants who may still refuse to use BIM models and integrate information to improve the way construction is performed [17]. The process model described has demonstrated COBie data as a practical solution to the current problems of the as-built documents in order to support facility management. The benefits of using the process model include delivery of necessary and concise information, easy access to related information, enhanced collaboration between the parties, and provide reliability of information among others.

7 Discussion and conclusions

A number of studies on integration of information have been carried out, indicating the use of approaches to manage and compile facility operations and maintenance documents in a systematic way as well as models to integrate information and produce new formats. Although the integration of information has been approached by considering standards that may facilitate the input of information, the owner who is the final user of the format has not been considered. Owner's still receive information in boxes and have to gather and re-organize the information since it was usually produced by different parties using different software. In addition to the owner's need to translate information, the as-built documents are often poorly structured, missing, inaccessible or incomplete. Gathering this information is expensive and at the end is not a reliable database since it differs from the actual construction.

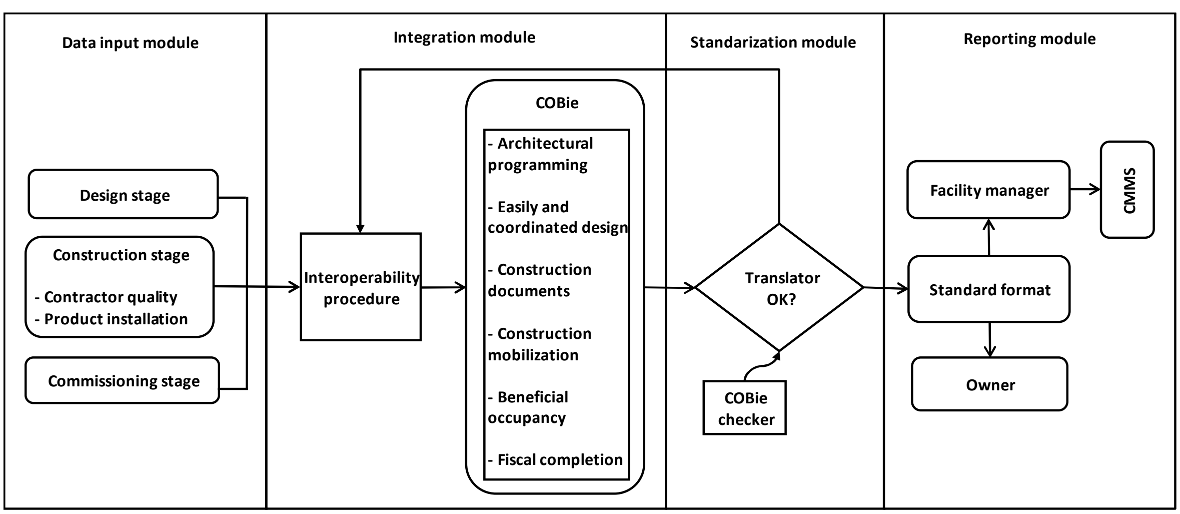

Figure 3. Process model framework

Therefore, an integration approach is needed to help owners support facility management operations with reliable data. COBie data set was developed to deliver accurate information to the owner in a format that can be used for facilities management.

The process model framework described in this study can help gather information and bring significant positive changes to the actual process of facility operations and maintenance activities. Its usefulness lies in the opportunity to include in the integration process information just as it is created in the design and construction phases. The possibility for all the different parties to include information from different software and different formats may help improve the quality of the as-built documents. As-built documents can be created and intended to reuse efficiently design and construction information to support operations and maintenance. Through COBie standards and the well-developed software products available in the market to transform documents into COBie documents, the benefits of information integration of a building can be realized. As a result, the process of facility management may be simplified and accelerated. COBie data set may broaden the capabilities of the decision-making process by allowing owners and facility managers to efficiently use reliable data without needing to gather and translate information.

The applied process model incorporates all the information of a building relevant to support facility management operations. The information is then integrated through an interoperability procedure to convert it into COBie information. Afterwards, a COBie check is run to verify the translators work properly. Once the check is concluded, the deliverables of COBie are ready to be used by owners to assist decision making in facility management operations. The implementation of the proposed process map and application case for indicating the actual uses of this process map is a future study.

As electronic environments increase, the range of document formats expands overwhelming users with information and making the retrieving information process effortful. Therefore, it is necessary to understand the information integration tools in order to help users benefit from all the information provided and successfully implement it to accomplish their tasks. The process model described in this study may contribute to benefit the integration of information for facility management operations. By investigating the products available that have applications capable of producing the format needed by the final user, information databases could become valuable tools to assist in operations in an ever-expanding range of options. As the use of smart technologies is becoming more common in buildings, there is a need to transform FM data so that it can be integrated with smart devices. This needs changes both in the schema level of COBie and data translation effort so that the FM data can be exchanged through a network instead of just spreadsheets or IFC files [9, 17, 20]. The understanding of demand and needs within building construction enhance consumer satisfaction contributing on how to make practices remain viable and useful for the construction sector.

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Trajectory Planning of Forces and Arm Tips for Tumbling Operation by Two Arms

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Abstract -

Rock-wise objects made after natural disasters must be removed by construction machines which are maneuvered by human beings. In that case, from the viewpoint of preventing a secondary disaster, the construction machines are preferable to carry out the task autonomously or by remote operation. We take aim at autonomous tumbling operation by a mobile robot with dual arms to move a rock-wise object. In previous study, a path planning algorithm for an object in tumbling operations had been presented. The order of the selected ridge line determines the path of the object. Next, trajectory planning of forces and arm tips of the robot is necessary for autonomous motion. In this paper, we present a method for determining the combination of action points by analyzing the tumbling operation. First, we derive relational expressions of force for the rotational motion of the object. Conditional expressions are set for making stable operation. Then, the problem is solved as a nonlinear optimization problem by evaluation function of force. The constructed algorithm derives optimal trajectory planning of forces and arm tips. Finally, the usefulness of the algorithm is shown by a numerical example.

Keywords -

Tumbling operation; Nonlinear optimization; Trajectory planning; Algorithm;

1 Introduction

After the wide-scale landslides are caused by a natural disaster such as an earthquake or a concentrated downpour, rock-wise objects generated by the disaster must be removed by construction machines which are maneuvered by human beings. In that case, from the viewpoint of preventing a secondary disaster, the construction machines are preferable to carry out the task autonomously or by remote operation. In this paper, we describe automation of removal work. Grasping and lifting-up motion are a common handling to remove objects, and easy to move the object. However, if the object is too large or heavy for the machine to grasp and carry, removal work by this operation is difficult. On the other hand, graspless manipulation such as pushing, tumbling, and pivoting are effective methods to handle the object in the case mentioned above [1]. Since these operations are performed while the object is in contact with the environment, they are not necessary to support all the weight of the object, and their energy is less than the energy of pick-and-place operation. In addition, pushing, tumbling and pivoting operations have different characteristics, so by combining these operations it is possible to flexibly manipulate the object. Therefore, many studies have been aimed at assisting the grasping operation or the pick-and-place operation for the assembly work of parts [2] [3] .

On the other hand, we take aim at autonomous tumbling operation by a mobile robot with dual arms to move rock-wise objects. In previous study, a path planning algorithm for an object in tumbling operations had been proposed [4] . The study dealt with a problem to move a rock-wise object approximated as a convex polyhedron around a desired position by tumbling operation. And a method for planning semi-optimal path represented as a selection order of the edge for a tumbling operation to minimize a predefined performance index was presented. Next, trajectory planning of forces and arm tips of the robot is necessary for autonomous motion. In this paper, we present a method for determining the combination of action points by analyzing the tumbling operation. The above method is possible to obtain the optimum trajectory planning that suppresses the excessive internal forces on the object.

In the next chapter, related studies are described. In the chapter 3, the initial setting of the problem and the coordinate system are explained. Derivation of relational expressions of force for the rotational motion of the object, and conditional expressions for making stable operation are described in the chapter 4. Determination of the combination of action points is solved as a nonlinear optimization problem by the derived equation and evaluation function of force. Also, we reduce variables to solve the problem of multivariable. For all combinations of action points, a convergence analysis is performed, and an algorithm is shown for deriving the optimal trajectory planning of forces and arm tips in the chapter 5. In the chapter 6, the usefulness of the algorithm is shown by a numerical example, and the conclusion and the future work are described in the chapter 7. However, the trajectory planning doesn't consider the characteristics of the robot except for two arms.

2 Related work

Sawazaki et al. analyzed three kinds of tumbling operations, and showed the feasibilities of them by carrying out the tumbling operation with multi-jointed robot fingers [5]. In contrast to the proposed method, which is an analysis based on a two-dimensional plane, this study extends the analysis to three dimensions in order to deal with the shape like a rock-wize object. Y. Maeda et al. proposed a method of motion planning of multiple robot fingertips for graspless manipulation including tumbling operations [6]. By considering whether each robot finger should be position-controlled or force-controlled, this method can obtain robust manipulation plans against external disturbances. Since large numbers of lattice points obtained by discretization of the configuration space are used as candidates of action points, it is theoretically possible to construct a plan for objects of any shape. However, in exchange for that, it takes a lot of calculation time. Therefor, in this paper, candidates of action point are narrowed down to cover a complicated shapes like a rock-wize object.

3 System initialization

3.1 Assumption

The assumptions in the tumbling operation are as follows.

- The operation is performed on a horizontal floor.
- The rotational motion of the object is slow and is regarded as quasi-static. Therefore, the inertia term is excluded for the motion of the object.
- The object is a convex polyhedron. Therefore, the object rotates around one ridge line on the bottom of the object.
- The friction coefficient generated at the contact portion is constant and it is possible to estimate approximate values from knowledge of the site.
- No-slip occur between the object and arm tips or a floor.
- The middle point of the ridge line is a position of action point. However, the middle point of the ridge line which is the bottom surface of the object is excluded from the action point.
- The initial state of the object is when the bottom surface and the floor surface are in contact with each other. Further, from Figure 1 the operation of rotating from the initial state to the other bottom surface and the floor surface around one ridge line is defined as "single tumbling operation".

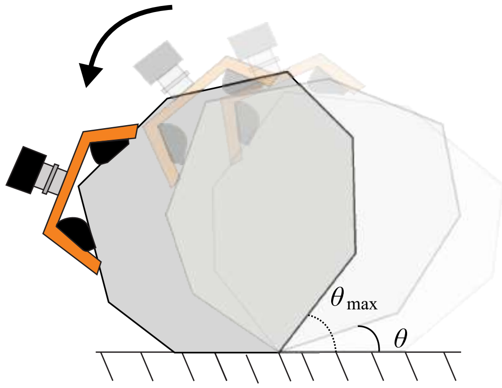

Figure 1. Single tumbling operation

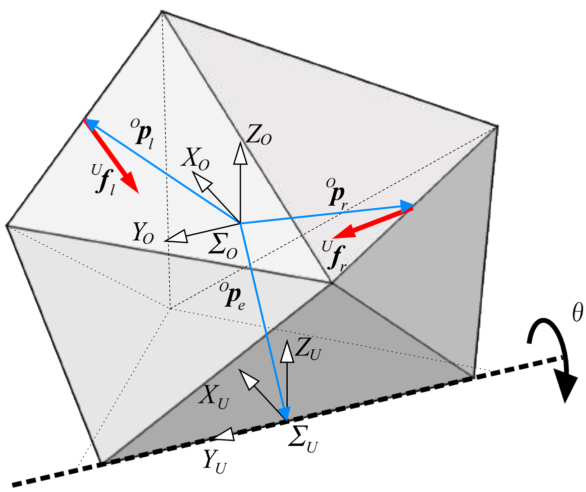

Figure 2. Coordinate system in object

3.2 Setting of the coordinate system

As shown in Figure 2, two coordinate systems, which are orthogonal and right-hand ones, are defined for calculation. The coordinate system Σ_O is fixed on the object, and its origin is located at the center of gravity of the object. The coordinate system $\Sigma_U(O_U - X_U Y_U Z_U)$ is defined with the middle point of the ridge line in the rotation axis as the origin. The Z_U axis is in the upper direction, and the X_U axis is in the advance direction of the robot. In the initial state of things, the postures of Σ_U and Σ_O are equal.

4 Problem formulation

4.1 Relational Expression of force

The external force on the object is denoted as ${}^U\boldsymbol{f}_i = \left[f_{ix}, f_{iy}, f_{iz}\right]^T$ $(i = r, l)$, where r and l indicate right and left quantities in the robot. Also, M is the mass of the object, $\boldsymbol{g} = [0, 0, g_z]^T$ is the gravitational acceleration, and $\boldsymbol{N} = \left[f_{fx}, f_{fy}, N_z\right]^T$ is the reaction force given from the floor surface. When two action points are selected and a tumbling operation is performed around the Y_U axis, relational expression of force is expressed as follows.

$$ {}^U\boldsymbol{f}_r + {}^U\boldsymbol{f}_l + M\boldsymbol{g} + \boldsymbol{N} = 0 \quad (1) $$

Further, the position of the action point is ${}^O\boldsymbol{p}_i = \left[{}^Op_{ix}, {}^Op_{iy}, {}^Op_{iz}\right]^T$ $(i = r, l)$, the position of the center of gravity is ${}^O\boldsymbol{p}_e = \left[{}^Op_{ex}, {}^Op_{ey}, {}^Op_{ez}\right]^T$, and the minute torque is $\boldsymbol{d\tau} = \left[0, d\tau_y, 0\right]^T$. Moreover, denoting the action point expressed in Σ_U as ${}^U\boldsymbol{p}_i = \left[p_{ix}, p_{iy}, p_{iz}\right]^T$ $(i = r, l)$, and the rotational matrix from Σ_O to Σ_U as ${}^U\boldsymbol{R}_O$,the equation of the torque on the tumbling operation is expressed as follows.

$$ {}^U\boldsymbol{p}_r \times {}^U\boldsymbol{f}_r + {}^U\boldsymbol{p}_l \times {}^U\boldsymbol{f}_l - {}^U\boldsymbol{R}_O{}^O\boldsymbol{p}_e \times M\boldsymbol{g} = \boldsymbol{d\tau} \quad (2) $$

$$ {}^U\boldsymbol{p}_i = {}^U\boldsymbol{R}_O({}^O\boldsymbol{p}_i - {}^O\boldsymbol{p}_e) \quad (3) $$

$$ {}^U\boldsymbol{R}_O = \begin{bmatrix} cos(\theta) & 0 & sin(\theta) \\ 0 & 1 & 0 \\ sin(\theta) & 0 & cos(\theta) \end{bmatrix} \quad (4) $$

Forces are applied from the arm tip to the object as shown on the left side of Figure 3. In this case, we assume that the resultant force of ${}^U\boldsymbol{f}_a$ and ${}^U\boldsymbol{f}_b$ is ${}^U\boldsymbol{f}_i$. Also, it is assumed that the plane and the ridge line are in contact. Therefore, the action of force around the ridge line is expressed as shown on the right side of Figure 3. The unit direction vector of bisector of the inner angle in ${}^U\boldsymbol{p}_i$ is ${}^U\boldsymbol{n}_i = \left[n_{ix}, n_{iy}, n_{iz}\right]^T$ $(i = r, l)$, and the coefficient of friction between the object and the arm is μ_{rob}. From the angle α between $\boldsymbol{f}_i$ and $\boldsymbol{n}_i$, the condition for not causing slip between the object and the arm tip is expressed by the following Equation (5).

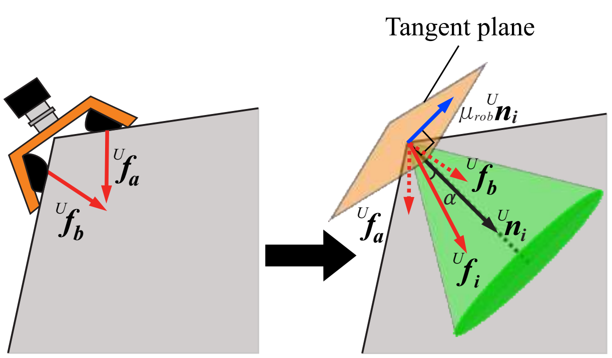

Figure 3. Relationship between force and friction cone at action point

$$ \frac{|{}^U\boldsymbol{n}_i||{}^U\boldsymbol{f}_i|}{\sqrt{1 + \mu_{rob}{}^2}} - {}^U\boldsymbol{n}_i \cdot {}^U\boldsymbol{f}_i \leq 0 \quad (5) $$

Further, the condition for not causing slip between the object and the floor surface is given by Equation (6) from the μ_{env} which is the friction coefficient between the object and the floor surface.

$$ \sqrt{f_{fx}{}^2 + f_{fy}{}^2} \leq |\mu_{env} N_z| \quad (6) $$

4.2 Formulation of problem to determine action points

In order to determine the optimal combination of action points, we define constraint equation and evaluation functions. The optimum solution in this paper means the combination of action points that can perform the tumbling operation with a force as small as possible. Therefore, the evaluation function on the magnitude of force is set as in Equation (7).

$$ f({}^U\boldsymbol{f}_r, {}^U\boldsymbol{f}_l) = |{}^U\boldsymbol{f}_r|^2 + |{}^U\boldsymbol{f}_l|^2 \quad (7) $$

By solving the nonlinear optimization problem shown in Equation (8), the problem of determining the action point is solved.

$$ \begin{array}{ll} \text{minimize} & f({}^U\boldsymbol{f}_r, {}^U\boldsymbol{f}_l) \\ \text{subject to} & h({}^U\boldsymbol{f}_r, {}^U\boldsymbol{f}_l) = 0 \\ & g({}^U\boldsymbol{f}_r, {}^U\boldsymbol{f}_l) \leq 0 \end{array} \quad (8) $$

$h({}^U\boldsymbol{f}_r, {}^U\boldsymbol{f}_l)$ and $g({}^U\boldsymbol{f}_r, {}^U\boldsymbol{f}_l)$ represent the equality constraints of Equation (1) and (2), respectively, or the inequality constraints of Equation (5) and (6).

However, it is desirable to improve computation efficiency as much as possible for multivariate analysis, so we will reduce variables. First, Equation (9) can be obtained by balancing the force in the Y_U axis direction of Equation (1) with only the external force related to the arm tips.

$$ f_{ly} = -f_{ry} \quad (9) $$

From Equation (9), one variable can be removed from the problem. Furthermore, there are five remaining variables, and there are three equations from Equation (2), so it is possible to reduce up to three variables.

For example, simultaneous equations for three variables are expressed as follows.

$$\begin{bmatrix} f_{rz} \\ f_{lx} \\ f_{lz} \end{bmatrix} = \boldsymbol{A}_0^{-1} \begin{bmatrix} -(p_{rz}-p_{lz})f_{ry} - Mp_{gy}g_z \\ -p_{rz}f_{rx} + Mp_{gx}g_z + d\tau_y \\ p_{ry}f_{rx} - (p_{rx}-p_{lx})f_{ry} \end{bmatrix} \quad (10)$$

Further, $\boldsymbol{A}_0$ is shown below.

$$\boldsymbol{A}_0 = \begin{bmatrix} p_{ry} & 0 & p_{ly} \\ -p_{rx} & p_{lz} & -p_{lx} \\ 0 & -p_{ly} & 0 \end{bmatrix}, |\det \boldsymbol{A}_0| \neq 0 \quad (11)$$

Three variables can be reduced by incorporating f_{rz}, f_{lx}, f_{lz} into the evaluation function or inequality constraint condition respectively. However, an inverse matrix of $\boldsymbol{A}_0$ is necessary for satisfying Equation (10). In a similar way, there are ten combinations when reducing three variables from five variables. Furthermore, determinants of $\boldsymbol{A}_{\mathrm{j}}(\mathrm{j} = 0, \ldots, 9)$ are as follows.

$$\begin{cases} \det \boldsymbol{A}_0 &= p_{ly}(p_{rx}p_{ly} - p_{lx}p_{ry}) \\ \det \boldsymbol{A}_1 &= p_{ry}(p_{lx}p_{ry} - p_{rx}p_{ly}) \\ \det \boldsymbol{A}_2 &= (p_{rx}-p_{lx})(p_{rx}p_{ly} - p_{lx}p_{ry}) \\ \det \boldsymbol{A}_3 &= p_{ly}(p_{ry}p_{lz} - p_{ly}p_{rz}) \\ \det \boldsymbol{A}_4 &= p_{ry}(p_{ly}p_{rz} - p_{ry}p_{lz}) \\ \det \boldsymbol{A}_5 &= (p_{rz}-p_{lz})(p_{ly}p_{rz} - p_{ry}p_{lz}) \\ \det \boldsymbol{A}_6 &= p_{ly}(p_{lx}p_{rz} - p_{rx}p_{lz}) \\ \det \boldsymbol{A}_7 &= p_{ry}(p_{rx}p_{lz} - p_{lx}p_{rz}) \\ \det \boldsymbol{A}_8 &= (p_{rx}-p_{lx})p_{ry}p_{lz} - (p_{rz}-p_{lz})p_{rx}p_{ly} \\ \det \boldsymbol{A}_9 &= (p_{rx}-p_{lx})p_{ly}p_{rz} - (p_{rz}-p_{lz})p_{lx}p_{ry} \end{cases} \quad (12)$$

However, when neither p_{ry} nor p_{ly} has a value, in other words when both Y_U components of the action point are included on the origin of Σ_U, variables can not be reduced by the method like equation (11). At that time, if we substitute $p_{ry} = 0$ and $p_{ly} = 0$ for Equation (2), f_{ry} is expressed by Equation (13).

$$f_{ry} = \begin{cases} \frac{Mp_{gy}g_z}{p_{rz}-p_{lz}} & (p_{rz}-p_{lz} \neq 0) \\ 0 & (p_{rx}-p_{lx} \neq 0) \end{cases} \quad (13)$$

In addition, in order to determine one variable, it is divided into two cases as follows.

$$f_{rx} = \frac{p_{rx}f_{rz} - p_{lz}f_{lx} + p_{lx}f_{lz} + Mp_{gx}g_z + d\tau_y}{p_{rz}} \quad (14)$$

$$|p_{rz}| \geq |p_{lz}|, p_{rz} \neq 0$$

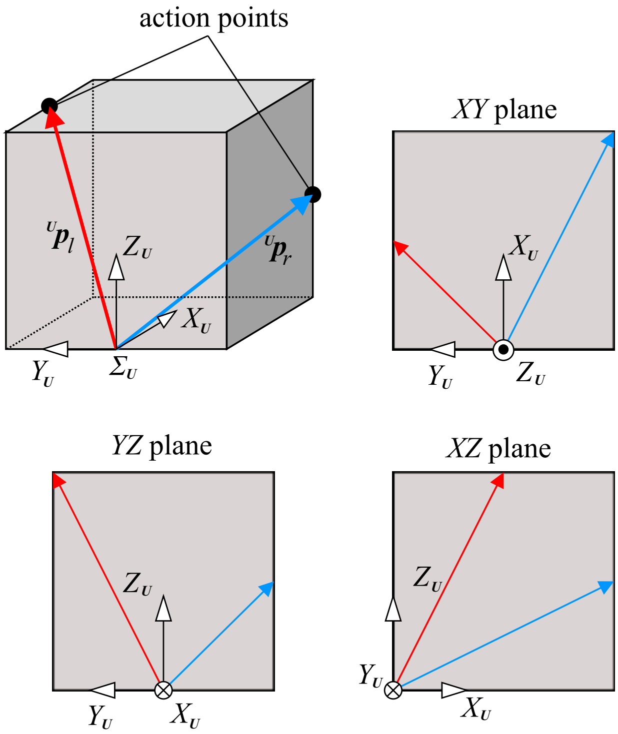

Figure 4. The positional relationship between the action point and the origin of Σ_U on each coordinate plane

$$f_{lx} = \frac{p_{rx}f_{rz} - p_{rz}f_{rx} + p_{lx}f_{lz} + Mp_{gx}g_z + d\tau_y}{p_{lz}} \quad (15)$$

$$|p_{lz}| \geq |p_{lz}|, p_{rz} \neq 0$$

Next, the case where the Y_U component of one of the at least two action points does not exist on the origin of Σ_U will be described. In this case the determinants of equation (12) are narrowed down by using the geometric characteristics of the object. As an example, suppose two action points are selected in a cubic object as shown in Figure 4. Also, in Figure 4, the positional relationship between the action point and the origin of Σ_U is shown using the projection of each coordinate plane. It can be seen that a part representing the outer product is included in part of the Equation (12). When no outer product exists, the two vectors overlap each other, or they are in a parallel relationship. Since there is a possibility of obtaining a singular point of a determinant by a combination of action points, conditional branching is necessary to reduce variables. In this case, we select the determinant taking the maximum value and reduce the variables. Furthermore, based on geometrical characteristics, the condition that no outer product exists in the coordinate plane is only when the action point of the same point is selected, so the determinant to be calculated can be narrowed down.

Therefore, reduction of variables are determined only by the determinant shown in Equation (16).

$$\begin{cases} \det \boldsymbol{A}_1 &= p_{ry}(p_{lx}p_{ry} - p_{rx}p_{ly}) \\ \det \boldsymbol{A}_3 &= p_{ly}(p_{ry}p_{lz} - p_{ly}p_{rz}) \\ \det \boldsymbol{A}_5 &= (p_{rz} - p_{lz})(p_{ly}p_{rz} - p_{ry}p_{lz}) \\ \det \boldsymbol{A}_7 &= p_{ry}(p_{rx}p_{lz} - p_{lx}p_{rz}) \end{cases} \tag{16}$$

In the Equation (16), we select the determinant that has the largest value of determinant and reduce the variable.

From the above, we solve Equation (8) after reducing variables. Furthermore, variables to be reduced depend on the position of action points. When solving based on the above method, it means that there is no feasibility of the tumbling operation unless equation (8) converges.

5 Algorithm of trajectory planning

An algorithm was constructed to determine optimal combination of action points from the problems described in the previous chapter. The flowchart is shown in Figure 5, and one ridge line which is the rotation axis of the object is set beforehand.

First, convergence calculation of Equation (8) is performed for the selected two action points. At this time, if an executable solution of the tumbling operation is not obtained, another combination of action points is selected. On the other hand, when Equation (8) is satisfied, 1[deg] is added to the rotational angle θ, and the convergence calculation of Equation (8) is performed again. When θ which is the rotation angle of the object reaches θ_{max}, this means that single tumbling operation can be executed to the end.

Then, by using the value of the evaluation function of Equation (7), the combination of the optimum action points is determined. The optimal combination is determined by comparing the sum of the evaluation functions obtained after the convergence calculation. However, the trajectory planning obtained by this algorithm does not include the operation of changing the action point in the middle of single tumbling operation.

6 Numerical example

Our planning algorithm is implemented on Windows using C language. We used IPOPT (Interior Point OPTimizer) [7] , which is a library suitable for large-scale continuous optimization problems. For the convex polyhedron shown in Figure 6, the combination of action points in single tumbling operation is determined. The object used in the experiment is a wooden polyhedron with size 0.32 × 0.29 × 0.28[m], M= 2.0[kg], g =

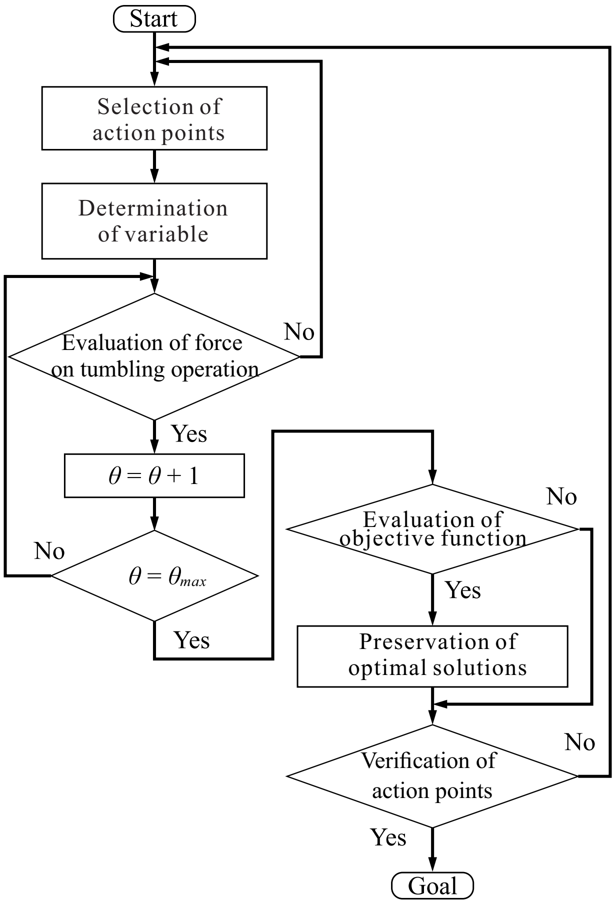

Figure 5. Flow chart for selection of action point

9.80665[m/s^2], θ_{max}=47.2[deg] and the friction coefficients are μ_{rob} = 0.5 and μ_{env} = 0.5, respectively. Figure 6 shows the object of a convex polyhedron. Since the object has twenty plane faces and the ridge line of the bottom surface is excluded, there are 27 action points. The combination of the action points obtained by the implemented algorithm is also shown in Figure 6.

Figure 7 shows the norms of force required for single tumbling operation for each θ, and Figure 8 is shown the planning trajectory of tumbling operation. In addition, as can be seen from Figure 7, when comparing the force acting on the object, the tumbling operation can manipulate the object with a smaller force than $Mg/2$ = 9.80665[N]. In the tumbling operation, it can be seen that the left and right forces fluctuate as θ increases.

We presented an impedance control of a mobile robot with dual arms for a three-dimensional tumbling operation [8] . Also, experimental verifications were conducted and its results were shown the effectiveness of the proposed algorithm. However, trajectory planning of this paper doesn't consider the characteristics of the mobile robot. Therefore, in the future, it is necessary to construct the

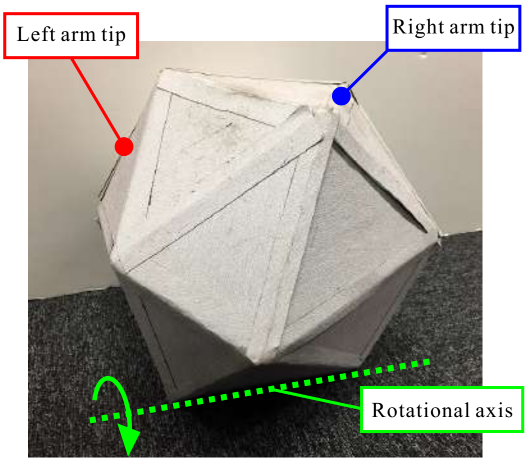

Figure 6. The appearance of the object

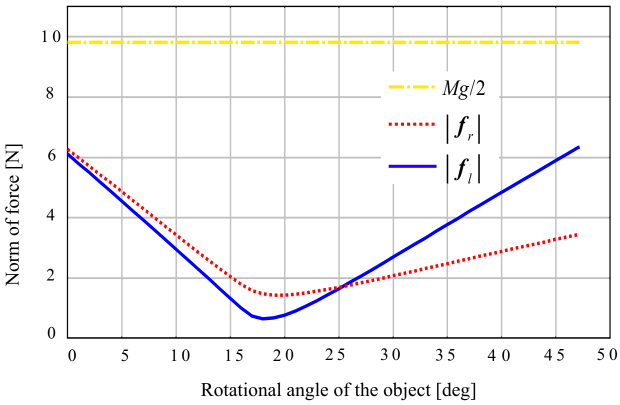

Figure 7. Result of tumbling operation and $Mg/2$

trajectory planning including characteristics of the robot.

7 Conclusion

In this paper, we presented the method for determining the combination of action points by analyzing the tumbling operation. We solved this problem as a nonlinear optimization problem by the evaluation function and the constraints on relational expression of force. From the characteristics of geometry, we showed effective reduction method of variable against multivariable problem. Finally, the usefulness of the algorithm was shown by a numerical example. As a future works, we will attempt to construct a trajectory planning that considers the robot's hand position and posture. Currently, we are trying verification experiments based on this algorithm by a mobile robot with dual arms.

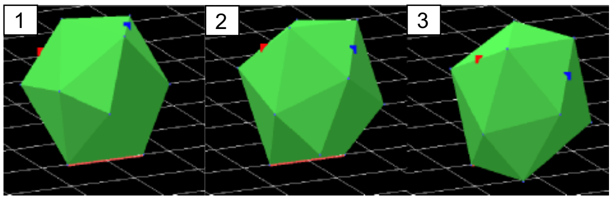

Figure 8. Planned tumbling operation

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Smart Facility Management Systems Utilizing Open BIM and Augmented/Virtual Reality

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Abstract

Building Information Modeling (BIM) is a technique in which a three-dimensional (3D) building model is constructed and designed in a computer. In recent years, BIM has been widely used in design and construction phases, but it has not been widely used in operation and maintenance phases, which account for the largest part of the building life cycle. The information required in BIM is different in each of the phases of design, construction, operation, and maintenance, and there are many pieces of reproduced information, making it difficult for managers to utilize the information. Although a number of studies have been conducted on combination of BIM with various technologies such as Internet of Things (IoT) and advanced sensing equipment in operation and maintenance, and interlinking of the obtained information with BIM information, there have been difficulties in commercialization and field application. This study aims to determine the problems found in previous studies and propose a fusion process in which new technologies adopt and utilize virtual reality techniques such as augmented reality (AR), mixed reality (MR), and head-mounted displays (HMDs) in existing maintenance work, thereby increasing maintenance work efficiency and further improving the utilization of BIM.

Keywords –
OpenBIM; Facility Management; Augmented reality; Virtual reality; Maintenance; Process Innovation

1 Introduction

1.1 Research Background and Purpose

The fourth industrial revolution (Industry 4.0) will bring about various technological changes in a variety of industries including the building industry, which has been affected by Industry 4.0 in many areas. According to ‘IoT Analytics’, seven main technologies that will lead Industry 4.0 are cyber physical systems, cloud computing, big data, system security, 3D printing, augmented reality (AR), and humanoid robots. The number of patent registrations for these technologies has increased by approximately 12 times between 2010 and 2015 [1]. The Gartner Hype Cycle for Emerging Technologies in 2017(Figure 1) reported that AR technology has already passed through ‘the peak of inflated expectations’ where excessive interests are concentrated and has entered the ‘trough of disillusionment’ where investments occur in corporations that own actual technologies, and it forecasts that virtual reality (VR) and AR will grow explosively until 2021 [2].

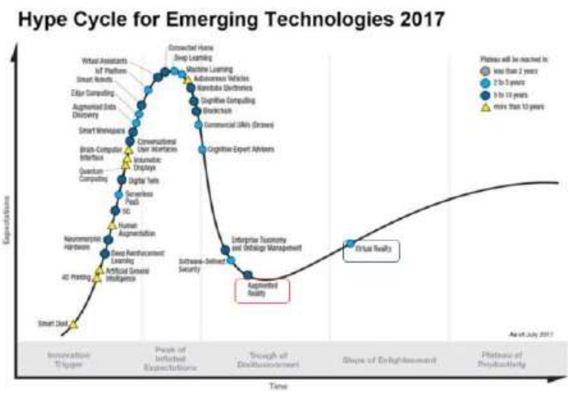


Figure 1. Augmented Reality / Virtual Reality in Hype Cycle (Panetta, 2018)

With the advancement of these technologies, a variety of new technologies have been combined in the building industry as well. Through the utilization of Building Information Modeling (BIM), information in the life cycle of building projects from design, construction, operation and maintenance, demolition, and remodeling can now be managed. To utilize this informatization model, requirements of BIM attribute information for each phase need to be specified and development and promotion of BIM libraries and standard formats are required. In addition, a process improvement for efficient BIM technology application is needed. In this regard, related studies have also been conducted actively. It is now time to consider how BIM information is efficiently created and fused with other new technologies (IoT, 3D printing, AR/VR) and utilized. Facility management (FM) accounts for 85% of the building life cycle cost (LCC) [3]. On-site facility data visualization and real-time collaboration function utilizing AR technology will change the maintenance work process and significantly benefit economy in terms of LCC viewpoints. Nonetheless, compared to the design and construction phases, few studies have been conducted on the applications of state-of-the-art technologies such as AR and VR to the maintenance work process.

Thus, this study identifies a trend of BIM and AR/VR technologies and determines an information linking method as one of the studies on smart FM for automation management and efficient execution of maintenance on facilities. It also proposes a smart maintenance work process that is applicable to smart FM systems by deriving user tasks where BIM and AR/VR technologies need to be applied in existing maintenance work.

1.2 Study method and procedure

This study adopts the following methods to enable smart FM work execution with applications of BIM and AR/VR technologies in FM of the building sector of public facilities. First, the existing maintenance work process is analyzed through a literature review. Through this analysis, the problems of existing processes are derived, and technical solution methods are searched. Second, component technologies of open BIM and AR/VR and Head Mounted Display (HMD) devices for visualization implementation are analyzed to derive applicable technologies and devices for smart FM. Third, a new work process for smart FM is proposed and detailed use cases for workers to execute the process are divided. Finally, the applicability of the technologies is determined through simple prototype implementation for each phase in the processes.

2 Research Trends

2.1 Building maintenance using BIM

The advantage of applying BIM to the maintenance phase is that it can utilize analysis data for purchase procurement of machine equipment, control systems, and other products and it can check whether all systems are correctly operating after buildings have been completed. It can also play a role as an interface for sensors and remote operation management of facilities, and real-time monitoring on control systems through providing accurate information about space and systems [4]. The BIM for FM is a sole information basis that provides a manual for building users. This can help the location of models such as facilities, attachments, and furniture to be recognized visually and can support contingency planning, security management, and scenario planning [5]. As described above, several studies have been conducted actively to draw out the advantages of BIM application to FM as much as possible.

A study by Yu et al. developed a data model, FMC, that can extract the required information from Industry Foundation Classes (IFC) for information compatibility of BIM data with FM [6]. A study by Mendez proposed functions that can be utilized by BIM in the maintenance phase and developed a web-based prototype to improve utilization of BIM data [7]. East and Brodt developed a spreadsheet-based data exchange format, COBie, to solve inefficiencies due to unnecessary information in maintenance among information sets created during design and construction phases [8]. A study by Burcin et al. defined a level of BIM recognition in the maintenance phase through expert interviews, applicable areas, required data and processes for successful implementation of BIM [9]. Lee et al. attempted to improve a facility maintenance system through benchmarking of the COBie system [10] and Choi et al. conducted a study to implement a FM system for sewage treatment based on COBie [11].

Most of the previous studies on FM utilizing BIM are focused on interoperability with FM systems and a measure to link data that are produced during design and construction phases, as well as being directed toward application of BIM to FM systems and commercialization.

2.2 Utilization of AR/VR technologies in the building industry

The trend of utilizing AR/VR technology in the building industry is reflected in the focus of most studies being on analysis of applicability of virtualization technology in the early days. Hammad presented the applicability of AR technology to field tasks of infrastructure [12] and Kwon analyzed considerations in the development of wireless technology-based AR-applied systems in terms of display, tracking, and servers. Afterward, a study on presentation of AR system prototype for inspection of steel column construction was conducted [13][14].

A variety of studies have also been conducted in relation to VR technology. For example, decision-making support through virtualization and simulation has been studied. Kim utilized VR technology in a system that evaluated a road scenery design and selected the final alternative based on superior scenery, technicality, and environmental criteria [15]. A study by Choi implemented a cloud-based BIM platform by which construction site environments could be experienced indirectly through simulations [16].

For studies on AR authoring tools, AR modeling through capturing and rendering of exterior structures in real time and a 3D modeling tool called 'Tinmith', which was manufactured to provide interaction between user and AR directly, can be found [17]. More recently, prototypes that can be applicable to real construction sites have been developed. For example, Dunston used a head mounted display (HMD) to represent a 3D computer-aided design (CAD) model on an actual real background, thereby conducting a study on AR-CAD that found a spatial interference on the drawings in the design phase [18]. Moon et al. implemented an AR prototype that can select the position of a tower crane appropriately in a high-rise building construction site and conducted a verification procedure through actual building drawings [19].

The analysis results in previous studies showed that the utilization of AR/VR technology in the building industry has enabled efficient construction management by recognizing design drawings intuitively by users. Four-dimensional (4D) BIM based on existing virtual environments has lacked reflection of actual construction site conditions. Thus, if AR technology that reduces a cognitive resistance is applied to maintenance sites, its value and utility would be significant in terms of productivity improvements.

3 Theoretical Discussion

3.1 Open BIM and IFC standards

In terms of commercial CAD systems, BIM technology has been advancing continuously. However, the most difficult limitation in BIM application is data compatibility. BIM platforms can share all information throughout the building life cycle in their unique data formats. However, the absence of standard formats and data access methods can create a problem in BIM data exchange between CAD systems. To overcome this problem, the Industry Foundation Classes (IFC) have been applied as a standard data format to exchange and share BIM data.

The IFC are a neutral data model rather than a proprietary model of a specific software vendor. They have been developed by the International Alliance for Interoperability (IAI), buildingSMART, to facilitate data compatibility for information sharing and exchange between application tools used in the building industries. They have been developed as standardized data sets for data compatibility between application tools. OpenBIM is an initiative of buildingSMART and several leading software vendors using the open buildingSMART Data Model [20]. Based on openBIM, several public project order issuing institutions in the USA and Europe require openBIM-standard-based delivery. The BIM-based public project orders in North America and Europe have been expanding throughout the world.

The AR/VR-based smart maintenance process proposed in this study utilizes openBIM for data interoperability.

3.2 AR/VR technology

The component technologies of AR applied to building industries that were analyzed in the previous studies can be summarized as follows.

- GPS-based technology: user location is recognized using GPS technology and registration to real environment can be done by projecting a 3D model to a pre-calculated location through the display.
- Vision-based technology: feature points are recognized based on images inputted to the camera and camera position is calculated to register a 3D model with a real environment.
- Real-time 3D recognition technology: real spaces are recognized and interpreted to align virtual objects in real spaces.
- Positional tracking technology: accurate tracking data values of user's position are reflected in the display in real time.
- Head tracking technology: can make a virtual object transit not only by position detection of the user according to movement in the real space but also by detection of head movements even when staying in the same position.
- Gaze (pupil) tracking technology: tracks the focal points of the pupils of eyes in real time using image processing, or can be implemented by a specific transmitter.
- High transparency technology: it overlays the view in the real space and the virtual object image naturally to project the light reflected in the real space to the retina.

The features, advantages, and disadvantages of AR/VR as virtualization technologies utilized in the building industries in construction sites are as follows.

- HMD hardware is needed to block the field of view in the real space as a technology that uses a 100% virtual image rather than a real image.

- It can provide various angles and stereoscopic effects through computer graphics, but it lacks site reality compared to AR.
- It is a technology that overlays 3D virtual images to real images. It requires a coordinate recognition technology of device medium or a rotation sensor to accurately overlay virtual images to positions in the real space.
- It has the advantage of delivering site-based selected information realistically, but has a limitation in recognition accuracy due to various site obstacles.
- It can be superior in providing indoor information of a completed building where the surrounding environment is stable.

This study aims to improve efficiency and productivity of maintenance work. To achieve this, it utilizes basic components and element technologies of AR/VR technologies.

4 OpenBIM-Based Smart FM

4.1 Overview of smart FM

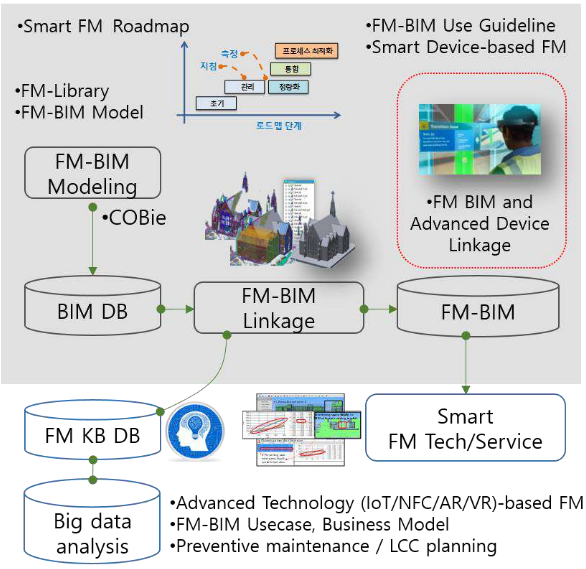


Figure 2. Smart FM technology development for advanced device and data analysis

The smart FM proposed in this study is a platform that employs the IoT, cloud, big data, and mobile (ICBM) basis technologies. It has the following major technologies.

- Scan/reverse design technology (SCAN-BIM, BIM model reverse design technology)
- Intelligent FM BIM technology (cloud/big data/intelligent model/BIM data analysis technology)
- Smart field FM BIM technology (IoT/VR/AR-based BIM FM)

The smart maintenance process proposed in this study is based on smart field FM BIM technology. It aims mainly to support site work. Figure 3 shows a diagram of the improved maintenance work flow.

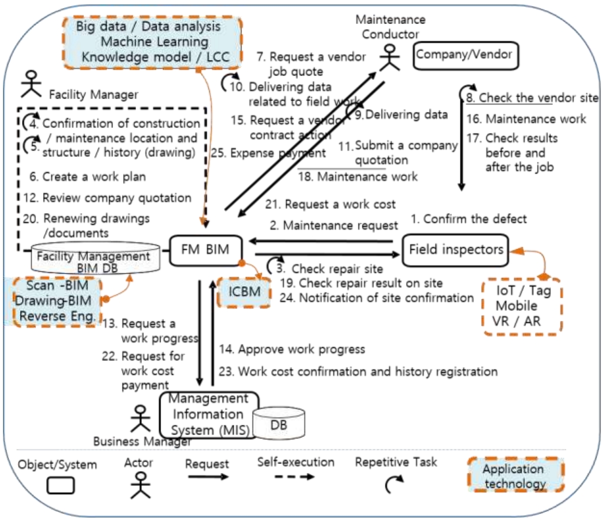


Figure 3. Maintenance work flow diagram in Smart FM

Through the ICBM platform-based FM BIM system that manages the facility management database in the center, variably distributed data can be gathered and processed as a hub for each request.

4.2 Existing maintenance work process

The routine maintenance inspection work processes of various facilities are investigated through a literature review and worker interviews. The maintenance work process differs depending on facility uses and sizes. Thus, this study limited the use and size to public facilities of less than five stories. The general maintenance work process is:

1. Establishment of inspection plan
2. Discovery/investigation of abnormality and defects
3. Determination of maintenance work schedule through safety diagnosis; and then if required
4. Repair work.

When utilizing BIM, histories of facility maintenance can be included and utilized in the BIM data. It is also differentiated from existing maintenance work processes by its process of automatic extraction of various statistical data and establishment of preventive repair plans as well as its conducting visualization simulations after repair work is complete. The as-is process of various maintenance works is divided into tasks for each user and is represented in Figure 4.

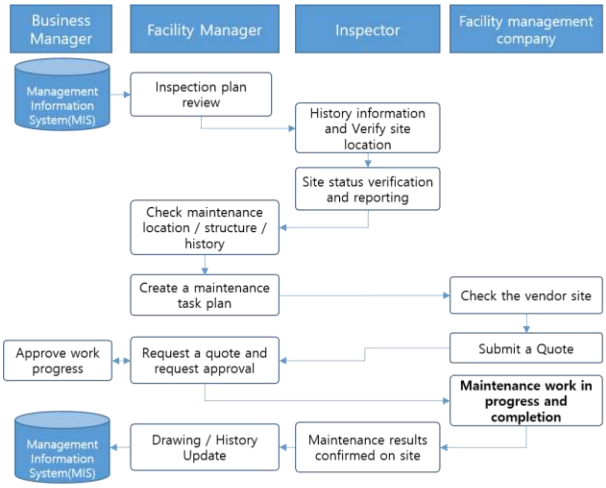


Figure 4. As-is process flow diagram of maintenance work

The facility manager then reviews the inspection plan and the inspector conducts inspection at the site based on the plan. Afterward, facility manager checks the history of maintenance and conducts maintenance, and the facility management company rechecks the site. When the facility management company submits a quote, the facility manager checks the quote. Once the executive manager approves the work, the facility management company can start the maintenance work.

4.3 Improvements in the AR/VR technology application process

Previously, data such as drawings, history information, and related documents were distributed and stored during facilities maintenance work. In addition, when facility defects occurred, it took a lot of time to search history information, drawings, company information, site location, and MIS history information. This was one of the main factors hindering work efficiency. The inefficient process with iterative tasks and sequential progress is improved through AR/VR technologies to produce an improved to-be process as shown in Figure 5.

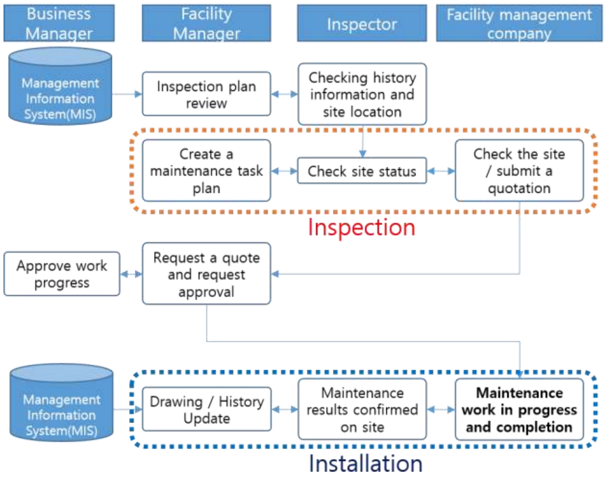


Figure 5. To-be process flow diagram of maintenance work

If VR virtualization technology utilizing BIM model spatial information is applied to review the work of the facility manager inspection plan, the inspector's history information and site position verification work can be done simultaneously. If AR technology is applied to a process when an inspector verifies a facility status at the site, the facility manager and facility management company can share the site conditions in real time and collaboration work for maintenance can be achieved. If AR technology is applied even when the facility management company does maintenance work, follow-up work of the inspector and facility manager can be done simultaneously. The utilization scenarios of the proposed system are shown in Figure 6 for different technical areas.

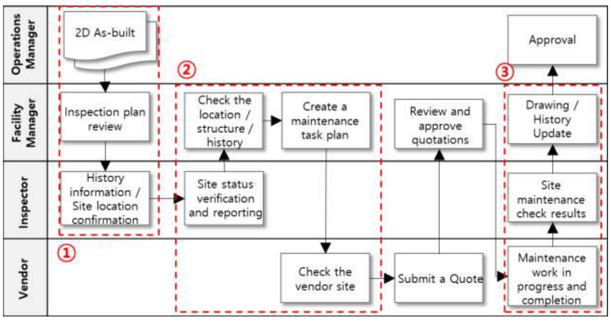


Figure 6. Utilization scenarios of the proposed system

The core technologies in the visualization process for each space through VR are as follows.

- Reference information system by phase
- Information division and information sharing process
- Indoor positioning technology

- Marker-indoor positioning integration technology

The core technology in the real-time collaboration process through AR visualization are as follows.

- VR/AR-based surveillance construction support technology
- 3D information + AR overlaying technology
- 3D data conversion technology for AR/VR

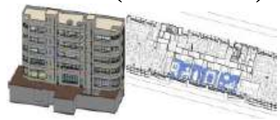
Table 1 Key issues and core technologies in the proposed maintenance work

① Space-specific visualization through VR	
Key issues	• Mapping of attribute information and mapping of necessary information to shape information • The user/manager side information process must be established & information control • Real-time management technology through history management based on current location information
Core technology	• Step-by-step reference information system • Information Segmentation and Information Sharing Process • Indoor Positioning Technology • Marker - Indoor positioning integrated technology
② Real-time collaboration through AR visualization	
Key issues	• The Inspector provides real-time information on the target location and history for checking the status of the object, • Real-time sharing of real-time information through 3D visualization
Core technology	• Surveillance-based support technology based on virtual / augmented reality • 3D Information + AR Overlaying Technology • 3D data conversion technology for AR / VR
③ Site-based update of historical information	
Key issues	• Check the real-time field status, upload and save the inspection contents, update historical information by each type of work • As-built model update through on-site information update
Core technology	• Data lightening support technology • 3D contents update process and technology based on reverse design • IoT information-based control technology for managers

4.4 Implementation of the improved process

An openBIM dataset of public facilities of five or fewer stories was utilized to implement the proposed AR/VR-based smart maintenance process. Table 2 shows the data and programs used to verify the applicability.

Table 2 Data and tools used for validation

Data and Tools	Programs and contents
BIM Dataset	Autodesk Revit(rvt), LOD500(BIM for FM)
Geometry models converted to IFC standards	
VR development tool	Unity
VR HMD	Microsoft Hololens
AR development tool	ARtoolkit, Android studio
AR HMD	Vuzix M100

To implement a VR virtualization prototype for prior inspection planning review and site location verification work (Figure 7), a model library for each maintenance target object should first be extracted from BIM information, and converted into model data for each space. The above process is required to use the 'Unity' VR implementation authoring tool. Any openBIM dataset can be acceptable. A VR prototype is complete for maintenance area visualization if spatial and object data are combined in Unity and camera and moving travel paths are set up followed by building into a preferred platform. To demonstrate this, Microsoft's 'Hololens' was used as an HMD.

For the implementation of AR technology-applied process, a maintenance history information overlay function and a real-time communication function were implemented through the open source programs 'ARtoolkit' and 'Vuzix M100', and Android SDK.

Figure 7. Validation of AR/VR based maintenance task through simple test

5 Conclusion

This paper proposed a process to apply AR/VR technologies to site maintenance work in the openBIM-based smart FM system. A survey analysis was conducted regarding existing BIM-based maintenance and AR/VR research in building industries. Along with surveys on openBIM and AR/VR technologies, a method to utilize them in maintenance work was derived. Finally, a process by workers and technology systems was proposed for AR/VR-applied maintenance work, and this was implemented as a prototype.

As a result, the utilization of AR/VR technologies in the maintenance work enabled fast and accurate decision making. With BIM data that can replace existing two-dimensional drawings and AR technology that can visualize information through overlay, inefficient re-work elements can be removed. In addition, since openBIM datasets created in the construction phase are utilized, it has the advantage of requireing little resource input for technical application. It can also improve accuracy and reliability of maintenance work results by minimizing interventions based on individual subjective judgments through real-time site circumstance sharing and collaboration functions via HMDs.

However, since the scope of this study was limited to the maintenance of public facilities of five or fewer stories in the building sector, the study results cannot be applied to other purposes and larger facilities. If maintenance work is extended to mechanical, electrical, and plumbing (MEP) facilities, the required BIM information can be extensive, and lightweight data are therefore needed. Thus, for future study, the following topics can be selected: definition of classes for attribute information visualization and BIM models for each facility of various sizes and uses, measures to link HMD and IoT sensing data, ensuring connectivity with actuators, and technical advancement of marker recognition with regard to maintenance targets.

Acknowledgment

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Resolution Enhancement for Thermographic Inspection in Industrial Plant Using Deep Convolutional Networks

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Abstract –

As the importance of maintainability for the energy efficiency of industrial plants is emphasized, thermographic inspection has been widely used as a key technique. However, the thermographic inspection cannot provide clear information due to the limitation of low resolution in inspecting wide areas where the worker cannot acquire data in close, such as hazardous environments and the ceiling with pipelines. Therefore, this paper proposes a resolution enhancement method for thermographic inspection in industrial plants based on deep convolutional network. The proposed network involves patch extraction and representation, non-linear mapping, and reconstruction. The proposed method was validated with 210 thermal images obtained from real cogeneration plants. Experimental results show that the method can provide the clear boundaries of instruments with an average PSNR of 32.51, which is superior than the bicubic interpolation of 29.92. The proposed method can be implemented in energy efficiency monitoring and automatic defect detection for thermal inspection in industrial plants by helping to detect defects that can be unchecked in low resolution images.

Keywords –

Thermographic inspection; Industrial plants; Resolution enhancement; Convolutional deep networks

1 Introduction

As demand for electricity increases, the importance of the energy efficiency of an industrial plant becomes a critical issue. Chen et al. [1] demonstrate that the energy efficiency of industrial plants can be achieved through efficient maintainability. With emphasis on the importance of maintainability of industrial plants, many non-destructive evaluation techniques have been proposed as an efficient maintenance method to detect defects in industrial instruments. However, as industrial plants become larger and more complex, most non-destructive evaluation techniques require significant labor resources for maintenance. This may result in insufficient information for evaluation, which makes it difficult to achieve corrective action for defects at optimal times [1]. In addition, most non-destructive evaluation techniques expose the worker to hazardous environments by requiring them to closely approach and inspect the instrument [2]. In this context, thermographic inspection enables short but reliable inspection by allowing the worker to inspect energy efficiency for many areas at a distance without needing to access instruments during maintenance [3, 4].

Despite the advantages of thermographic inspection, thermal images have limitations due to their low resolution. When inspecting areas of industrial plants where a number of instruments are installed, a thermal image with insufficient resolution cannot provide clear information on critical defects. This problem can cause the inspector to be unaware of a critical defect and leave the defect unchecked. Unchecked critical defects cannot only lead to energy losses of industrial plants, but also have far-reaching consequences. In order to ensure the resolution of the thermal data, acquiring data from close to the instruments is inefficient and impossible in pipelines installed on the ceiling or in hazardous environments that people cannot approach. In this context, it is necessary to enhance the resolution of the thermal image for thermographic inspection in industrial plants.

Over the past few years, some studies have been carried out to enhance the resolution of thermal images to address these low-resolution limitations [5-8]. Recently, with starting with a study by Dong et al. [9], the deep learning method has been successfully applied to improve the resolution of a single image, so many studies using deep convolutional networks have been actively conducted [10-12]. Choi et al. [12] have demonstrated that a convolution neural network can be successfully applied to thermal image enhancement.

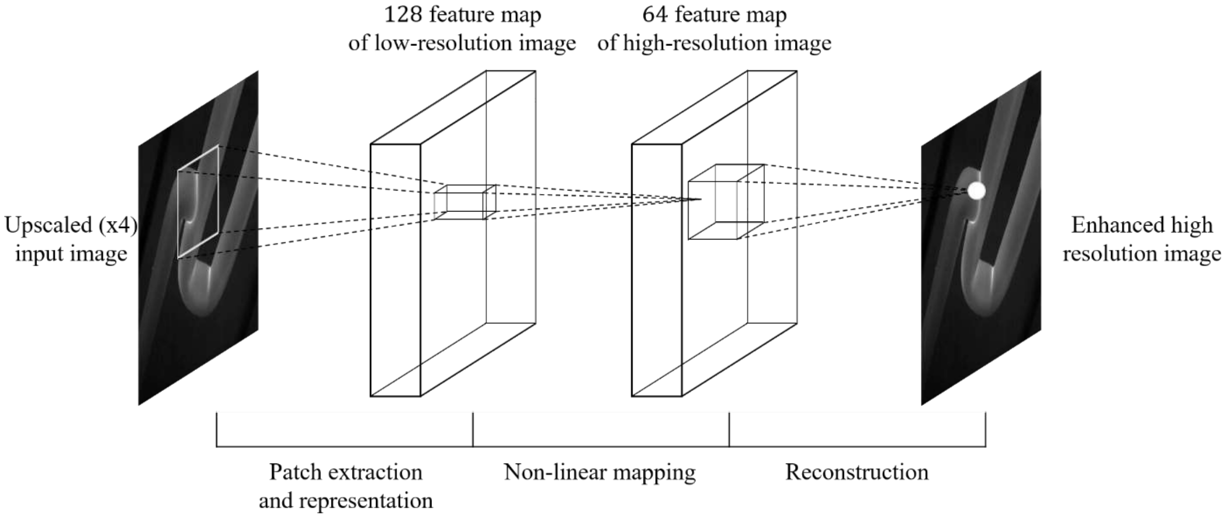

Figure 1. Network structure for super-resolution of thermographic inspection

However, Choi et al. [12] used an RGB (red-green-blue) dataset converted to gray scale as a training dataset. This process cannot be applied to thermographic inspection that utilizes the thermal value of acquired data, because it can distort acquired thermal values guided by the RGB image. Therefore, none have studied the method that can enhance the resolution of the thermal image for thermographic inspection in industrial plants. This study proposes a thermal image enhancement method for efficient thermographic inspection of industrial plants based on deep convolutional networks. The proposed method was evaluated by using a thermal dataset obtained from actual industrial plants.

2 Methodology

For resolution enhancement of thermographic inspection, this study uses a deep convolutional network inspired by C. Dong et al. [9, 10]. The configuration of the network is outlined in Fig. 1.

2.1 Proposed Networks

In pre-processing, the input image with low resolution is upscaled to the desired size of the high-resolution image using bicubic interpolation. This study used only gray channel for the input image by extracting temperature value from raw images. After pre-processing, there are three convolution layers that are patch extraction and representation, non-linear mapping, and reconstruction separately.

In the first layer, patch extraction and representation operation extracts overlapping patches from the upscaled image and represent each as high-dimensional vectors. In this paper, we use a larger network with the filter number of the first and second layers, because a superior performance can be achieved by a larger network [10]. We applied 128 filters with a size of 9 × 9 in the first layer. Therefore, output is generated as a 128-dimensional feature map. In this layer, the Rectified Linear Unit (ReLU) [13] is used as an activation function. In the second layer, each of the high-dimensional vectors from the first layer is mapped onto another high-dimensional vector. This operation is equivalent to applying filters with the size of 1×1. We set the number of filters as 64 in this operation. In the last layer, the enhanced output image is generated by aggregating the representations from the second layer. This layer operates as like the average pooling layer in traditional methods.

2.2 Training

This study used the 205 thermal images with resolution 640×480 taken from a cogeneration plant as training dataset. Figure 2 shows some examples of the training dataset. For training, the high-resolution ground truth images are cropped as sub-images with the size of 33×33 and the stride of 14. The sub-images are blurred using Gaussian kernel and sub-sampled by the upscaling factor of four. Finally, sub-images are generated by upscaling using bicubic interpolation with the same factor.

In the training phase, the parameters as weights and biases of filters are optimized in a way that minimizes loss. In this paper, mean squared error (MSE) is used as the loss function between input low-resolution images and the high-resolution images that are ground truths.

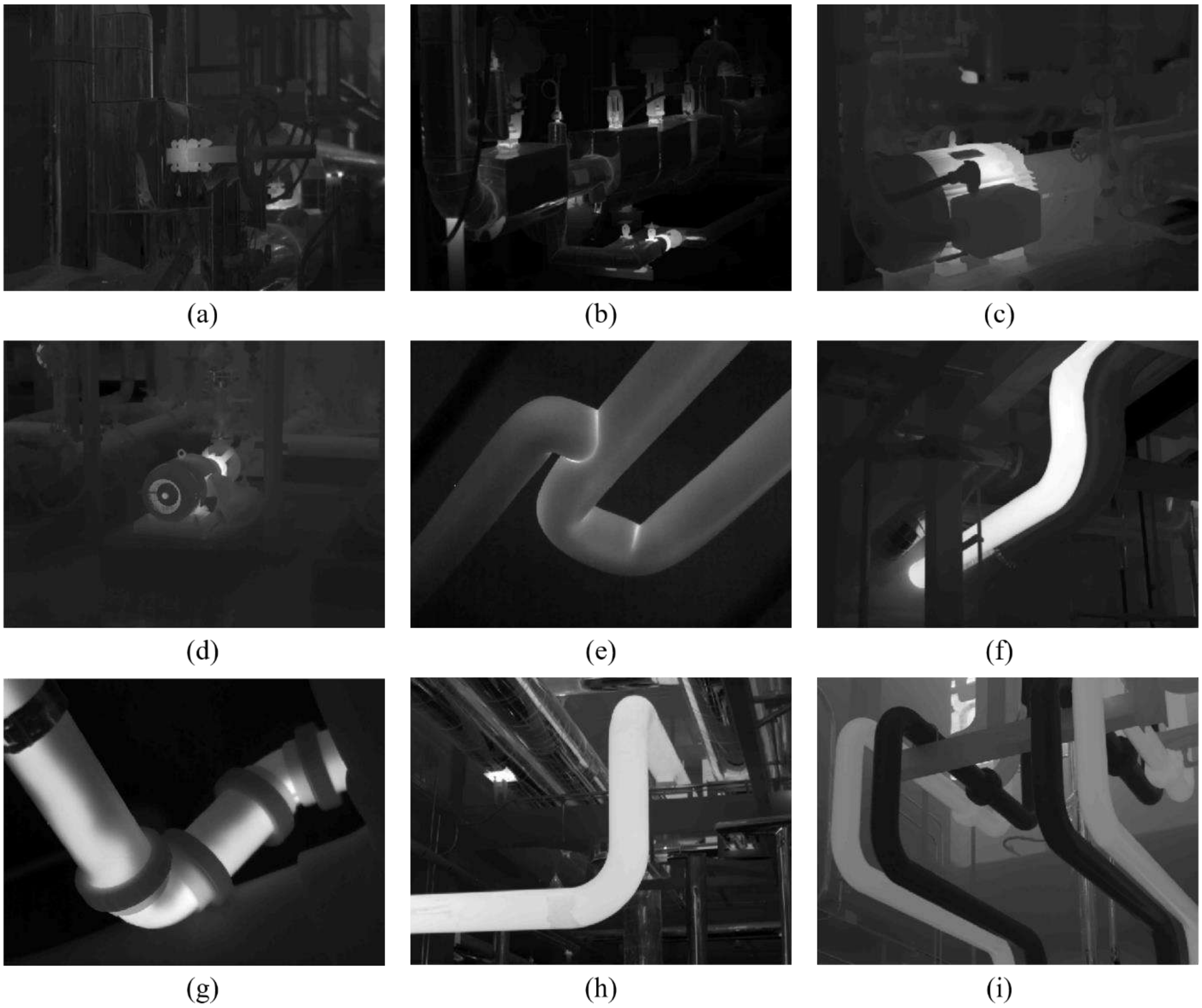

Figure 2. Examples of thermal image from cogeneration plant: (a) – (d) instruments; and (e) – (i) pipelines.

The loss function of MSE is below:

$$L(\theta) = \frac{1}{n}\sum_{i=1}^{n} \| F(X^i;\theta) - G^i \|^2 \qquad (1)$$

where θ is the parameters consisting weights and biases of filters, n is the number of training samples, $F(X^i;\theta)$ is i-th reconstructed image and G^i is a ground truth image. Therefore, the parameters are updated so that $F(X^i;\theta)$ is reconstructed close to G by calculating the loss every time it iterates from end to end. The parameter optimization is held by using stochastic gradient descent with back-propagation. We used a learning rate of 10^{-4} for the first and second layers. The smaller learning late of 10^{-5} is used for the last layer as suggested in Dong et al. [9].

3 Experimental Results

To measure the performance of the resolution enhancement, we employed peak signal-to-noise ratio (PSNR). The PSNR is the most common quantitative evaluation of resolution enhancement [11,12]. For evaluating the proposed method, five thermal images from real industrial plants were used a test dataset (Figure 3 (a)). We compared the performance of the proposed method with bicubic interpolation which is one of the baseline method in resolution enhancement [12,14].

Figure 3 shows the resolution enhancement results of the proposed method. We used the model obtained at 2×10^6 iteration of the proposed networks. As can be seen in Figure 3 (d), a much sharper image is produced using the proposed method compared to input image (b)

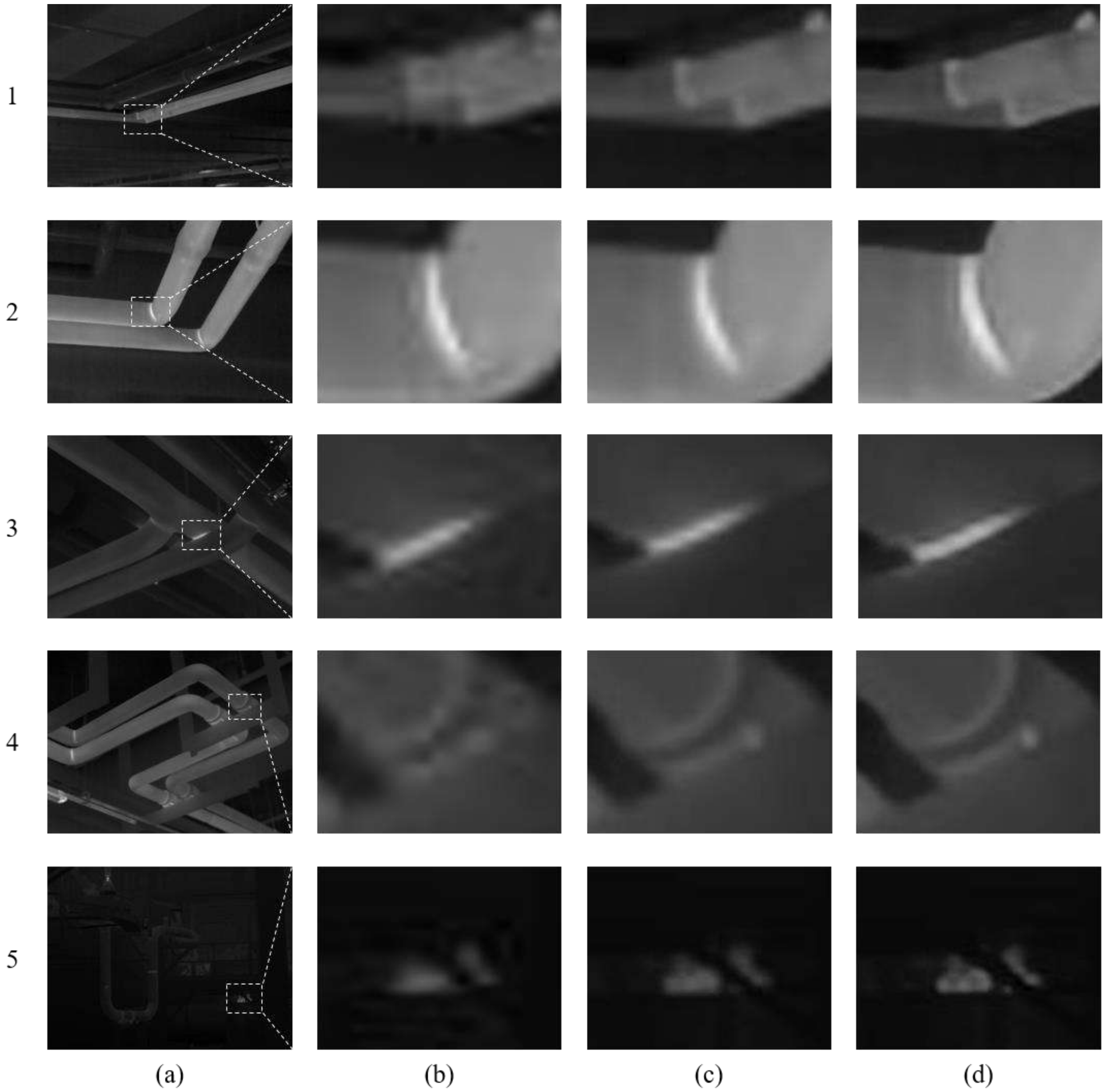

Figure 3. Resolution enhancement results of five test images: (a) ground truth; (b) input; (c) bicubic interpolation; and (d) proposed method

and bicubic interpolation (c). This shows that blurry boundaries of defects and other instruments in input low-resolution thermal images can changed to clear boundaries through the method proposed in this study. Table 1 shows the quantitative results as average PSNR for test dataset. For each test image, the PSNR of the proposed method shows the superior performance over bicubic interpolation. Therefore, the results show that the proposed method for resolution enhancement can be effectively applied in thermographic inspection for industrial plants.

Table 1 Resolution enhancement results (PSNR)

Test images	Bicubic	Proposed
1	38.88	41.23
2	38.33	40.94
3	42.52	44.39
4	39.03	40.89
5	45.59	46.33
Average	40.87	42.75

4 Conclusion

This study proposed a method for thermal image resolution enhancement using deep convolutional networks, with the goal of providing clear information about instruments installed in areas where it is impossible for workers to acquire data from nearby, such as pipelines on the ceiling or instruments in a hazardous environment. The experimental results show that the proposed method could produce a far clearer thermal image of actual industrial plants. The proposed method is expected to help identify the defects of instruments that may not show up in low-resolution thermal images. In future research, we will focus on automatically detecting defects based on the improved data using the proposed method.

Acknowledgements

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Stacked Hourglass Networks for Markerless Pose Estimation of Articulated Construction Robots

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Abstract –

The objective of this research is to evaluate vision-based pose estimation methods for on-site construction robots. The prospect of human-robot collaborative work on construction sites introduces new workplace hazards that must be mitigated to ensure safety. Human workers working on tasks alongside construction robots must perceive the interaction to be safe to ensure team identification and trust. Detecting the robot pose in real-time is thus a key requirement in order to inform the workers and to enable autonomous operation. Vision-based (marker-less, marker-based) and sensor-based (IMU, UWB) are two of the main methods for estimating robot pose. The marker-based and sensor-based methods require some additional preinstalled sensors or markers, whereas the marker-less method only requires an on-site camera system, which is common on modern construction sites. In this research, we develop a marker-less pose estimation system, which is based on a convolutional neural network (CNN) human pose estimation algorithm: stacked hourglass networks. The system is trained with image data collected from a factory setup environment and labels of excavator pose. We use a KUKA robot arm with a bucket mounted on the end-effector to represent a robotic excavator in our experiment. We evaluate the marker-less method and compare the result with the robot's ground truth pose. The preliminary results show that the marker-less method is capable of estimating the pose of the excavator based on a state-of-the-art human pose estimation algorithm.

Keywords –

Pose Estimation; Stacked Hourglass; Excavator

1 Introduction

Due to the hazardous working environment, construction site has a higher rate of fatalities and injuries throughout the industry [1]. On average, 53% of the fatal accidents that happen on construction sites are either struck by vehicle or equipment overturns and collisions [2], which causes almost $13 billion in extra cost per year [3]. Blind spots around the equipment are the main cause of such accidents [4]. When workers need to interact with the equipment on job sites, the equipment operator sometimes cannot locate all workers nearby and the workers also cannot locate the equipment components clearly. The prospect of collaborative human-robot teams on construction sites further heightens these concerns and highlights a need for developing on-site articulated equipment pose estimation methods. The pose of the construction equipment, such as an excavator, can be described as the angle between each component and the 6 degree-of-freedom (6 DOF) coordinates. Therefore, determining each joint location and the angle between each component is the primary goal of the machine pose estimation, as shown in Figure 1.

Figure 1. Excavator pose is determined by identifying its joints and components.

In the real practice, two types of pose estimation methods are used on construction equipment, namely non-visual sensor-based and vision-based pose estimation method. For sensor-based pose estimation methods, Inertial Measurement Unit (IMU), Global

Positioning System (GPS), Wireless Local Area Network (WLAN), Radio Frequency Identification (RFID), and Ultra-Wide Band (UWB) are mainly deployed on equipment and construction site. IMU sensors need to be mounted on excavator joint components to measure the angle [5], which has drift issues [6]. GPS is known for outdoor used only [7], which is not suitable for some indoor construction site. WLAN system requires significant amounts of effort for calibration [8]. RFID and UWB methods both require sufficient preinstalled tags and readers on equipment and infrastructure [9–11]. They generally suffer from missing data issues [12] and are inadequate for pose estimation [13]. In addition, most of these methods cannot provide orientation information directly, except for IMU, are not suitable for construction scenarios.

On the other hand, vision-based pose estimation methods are capable of analyzing position information as well as orientation information directly from input data, such as videos or point clouds. These methods generally recognize construction equipment on site [14–17], then estimate their 6 degrees-of-freedom (6 DOF) pose [18,19], which can be categorized to two different group: marker-based and marker-less pose estimation. The marker-based pose estimation method recognizes all the markers mounted on equipment and estimates the pose by their geometric relations [20,21], whereas the marker-less pose estimation method directly extracts image features and estimates the pose by them [18]. The marker-based method has been extensively applied in indoor localization and facility management [22,23]. Similar to sensor-based pose estimation method, they also require preinstalled markers on equipment and environment.

In addition to the marker-based method, the marker-less pose estimation method only requires an on-site camera system, which is common on modern construction sites. Feature descriptor based is the first type of marker-less pose estimation method, such as Histograms of Oriented Gradient (HOG) [16], 3D principal axes descriptor (PAD) [14], Iterative Closest Point (ICP) [24], or Viewpoint Feature Histogram (VFH) [18]. Convolutional Neural Networks (CNN) is another type of pose estimation method [25], which has higher performance (accuracy and speed) in comparison with all other vision-based methods, especially for human pose estimation. Therefore, in this study, a CNN based marker-less pose estimation system is presented, which can distinguish excavator joint components and estimate their poses in images. This system is built on a state-of-the-art human pose estimation network [26,27] and trained on an excavator image dataset collected in a factory setup lab environment. The excavator pose in this research is defined as the boom, stick, and bucket pixel-wise 2D location.

2 Marker-less Pose Estimation System

Our marker-less pose estimation system is developed based on a state-of-the-art human pose estimation algorithm, namely stacked hourglass network by Newell et al. [26,27]. This network scales the training image into different resolution and captures features, then combines the information together to predict the pose. Compared with the human pose, the construction equipment pose is much simpler, thus requires less information across different image resolutions. The detailed network architecture is further discussed in the next section.

2.1 System Network Architecture

We modify the stacked hourglass network to fit our target construction machine, mainly excavator. Unlike the complicated human skeleton, excavator pose only requires identifying three components, which are bucket, stick, and boom, as shown in Figure 1. Therefore, the complexity of the network needed is much less than the original network. Figure 2 shows the network architecture. Two convolutional layers followed by a max pooling layer are first applied to the training image, which shrinks the image down to the size of 64 pixels. Then three subsequent convolutional layers upscale the image to the size of 256 pixels before the hourglass module. Finally, three hourglass modules, output prediction modules, and residual link modules are used in the network. All the convolutional layers are followed by ReLu activation function, with stride 1 except the Conv1 layer with stride 2, and with batch normalization except the convolutional layers in the output prediction module.

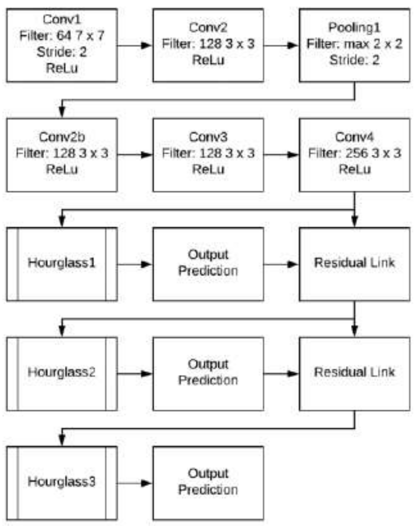

Figure 2. Full system network architecture, 3 hourglass modules are used in our system.

The hourglass module is the main part to collect features across different resolution, which is illustrated in Figure 3. The input passes into two parallel routes. In the first route, only one convolutional layer is applied to upscale the input to the size of 256 pixels. In the second route, one max pooling layer followed by three convolutional layers are applied to downscale the input to the size of 384 pixels, then resized to the size of 256 pixels, as the first route result. Finally, two route results are added together through elementwise summation to generate the output. This can preserve the global feature and capture the local feature as well. In the Hourglass2 and Hourglass3 module, we change the Conv_low2 layer to another hourglass module. This recursive hourglass module will increase the output size for more features.

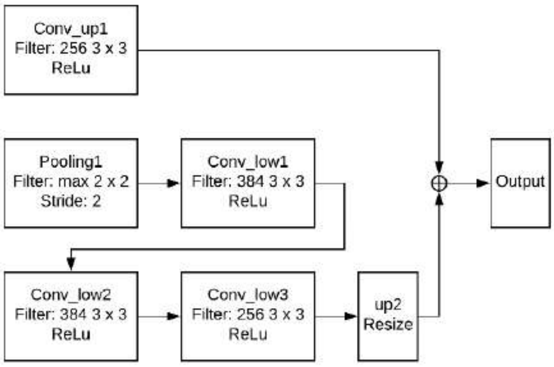

Figure 3. Hourglass module architecture, convolutional upscale and downscale layers are the main features of the hourglass shape.

The output prediction module and residual link module are applied after the hourglass module, as shown in Figure 4. Two convolutional layers are used in the output prediction module to generate the heat map of the possibility of the location of each joint. Figure 5 shows the concept of the prediction heat map. Each red dot represents the highest probability of each joint location from which we can estimate the pose, as shown in Figure 1. The final layer is a one-by-one convolutional layer, which aims to calculate the possibility across the depth of the output of the Conv5 layer. On the other hand, the residual link module combines the output from the previous hourglass and after the output prediction module to generate the input for next hourglass. The repeated hourglass and residual link module can preserve the spatial location and relation of each feature and apply to the final prediction step.

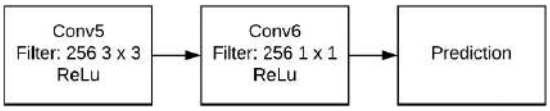

Figure 4. Output prediction layers, the previous hourglass prediction results are added with current output prediction.

Figure 5. The concept of the prediction heat map. Each red dot represents the highest probability of each joint location.

2.2 Training Details

We use the L_2-norm loss function to train our network, as shown in (1):

$$L_2(\hat{X}_p, X_L) = \sum \left(\hat{X}_p - G(X_L)\right)^2 \tag{1}$$

where $\hat{X}_p$ represents the predicted pose and X_L represents the labeled ground truth training data, $G(\cdot)$ represents the Gaussian kernel function with 1-pixel standard deviation. The loss function directly calculates the error between training and predicting image.

We implement the network system by modifying the original network using PyTorch [28] and the loss function described above. The network is trained on an excavator image dataset, which we collected from a factory setup lab environment with a simulated excavator and real construction site with real excavators. All the hyper-parameters are set the same as in [27]. The excavator dataset contains 1,000 training images and 500 testing images aligned with their pose annotating data. The detailed lab environment setup is discussed in section 3.

3 Experiment

We collect the image data from a factory setup lab environment and from real construction sites. The dataset is separated into training and testing groups. The algorithm is trained by the training group and evaluated by the testing dataset.

3.1 Implementation

We used a KUKA 7 DOF robot arm to simulate the excavator and capture the image of the robot arm with different poses. The upper arm represents the excavator stick and the lower arm represents the excavator boom. A bucket is mounted on the robot arm for a more realistic simulation. Figure 6 shows the simulated excavator in a factory setup lab environment. In order to control the robot as an excavator, the profile of the mounted bucket must remain perpendicular to the ground level. We controlled the robot arm to perform several excavator tasks such as digging, moving, or unloading.

Figure 6. The simulated excavator by a robot arm mounted with an excavator bucket.

We used a Point Grey camera to capture the image of the simulated excavator. The camera was deployed in 5 different location and orientation near the excavator to increase the variety of the dataset. A total of 1,000 images were collected; 750 of them were used as training images and 250 of them were used as testing images. Figure 7 shows an example of the simulated excavator dataset with different camera location and orientation. The joints of the simulated excavator were labeled in 2D pixel-wise location via MATLAB code. The structure of the annotation data is the same as the well-known human pose dataset (MPII) [25].

To increase the variety of the dataset and augmented the background of the dataset, we also collected image data from the real construction site with real excavators, as shown in Figure 1. A total of 500 images were collected; 250 of them were used as training images and 250 of them were used as testing images.

Figure 7. Example of the simulated excavator dataset with different camera location and orientation.

4 Results

We evaluate the proposed method by comparing the prediction results of the testing images and the ground truth. Figure 8 demonstrates the results of the excavator pose estimation. The green, blue, and red line are corresponding to the bucket, stick, and boom prediction. These two images are in the testing dataset. We also evaluate the Euclidean distance between the predicted joint location and the ground truth joint location, and the error percentage of the predicted component length and the ground truth, which can be seen in Table 1 and For the error percentage of the predicted component length and the ground truth, we only evaluated the lab dataset because the length of each robot arm component is known but the real site excavators are unknown. The result is shown in Table 2. The error percentage of the boom and stick is about 35% to 45%, and the bucket is 62%. The reason for the high error percentage in the bucket case is the occlusion issue. When the bucket is blocked or out of range, the predicted bucket location will be far away from its true location. In addition, the ground truth length of the bucket is short, which increases the differences between the ground truth and the false predicted result. Figure 9 shows two results of false prediction caused by occlusion.

Table 2. The average Euclidean distance between the lab testing dataset and ground truth is 50.05 pixels and between the real site testing dataset and the ground truth is 71.95 pixels. The bucket location has the highest error because the bucket is blocked (occluded) or out of range in some of the image. The model still tries to find the location in these cases, which increases the error

distance. The error in the real site dataset is higher than the lab dataset. This is because the real site dataset has a greater variety of excavators and backgrounds. Only some of these variations were included in the testing dataset, so this caused a decrease in accuracy.

Table 1. Results of the average Euclidean distance (pixel-wise) between the predicted and the ground truth joint location.

(pixels)	Lab Dataset	Real site dataset
Boom	42.01	67.12
Boom Stick	45.37	59.99
Stick Bucket	44.68	65.67
Bucket	68.13	95.03

Figure 8. The result of the excavator pose estimation. On the top is the simulated excavator and on the bottom is the real excavator.

For the error percentage of the predicted component length and the ground truth, we only evaluated the lab dataset because the length of each robot arm component is known but the real site excavators are unknown. The result is shown in Table 2. The error percentage of the boom and stick is about 35% to 45%, and the bucket is 62%. The reason for the high error percentage in the bucket case is the occlusion issue. When the bucket is blocked or out of range, the predicted bucket location will be far away from its true location. In addition, the ground truth length of the bucket is short, which increases the differences between the ground truth and the false predicted result. Figure 9 shows two results of false prediction caused by occlusion.

Table 2. Results of the error percentage of the predicted component length and the ground truth.

(%)	Lab Dataset
Boom	46.8
Stick	34.3
Bucket	62.8

Figure 9. The result of the false prediction, both are out of range (top) or blocked (bottom).

Based on the evaluation results, occlusion is the primary issue of the proposed system, which can be tackled by increasing the number and variety of the training dataset. Another problem is the multiple excavator situation. The proposed system can only identify one excavator pose. If there are two or more excavators in the image, the result will fail. We will design a new network or method for multiple excavator situation in the future work.

5 Conclusion

In this research, we proposed and evaluated a vision-based marker-less pose estimation system for construction robots, for which we used an excavator as our test-bed. The excavator boom, stick, and bucket joint positions are estimated with pixel-wise coordinates. We adapted and modified the state-of-the-art human pose estimation convolutional network, i.e., the stacked hourglass network, for our application. Three stacked hourglass modules and two residual links are included in the network. The network model is trained on an excavator dataset, which we collected and annotated from a factory setup lab environment with a KUKA robot arm representing an excavator from a real construction site. The results showed that the system can estimate the boom and stick joints but had higher estimation error for the bucket location due to the occlusion issue. Therefore, for the future work, more training image data with higher variety will be collected. We will also modify the proposed network to adapt to the multiple excavator situation. The comparison between the proposed system and the sensor-based system will be conducted as well.

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Robotics in the construction industry: state of the art and future opportunities

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Abstract -

This paper discusses the results of a survey regarding state of the art and possible future opportunities for the application of robotic technologies in the construction industry. The survey was conducted by submitting two distinct questionnaires to Arup's[1] most experienced technical and business leaders. The first questionnaire was designed in order to understand the state of the art of robotic technologies in the construction industry, while the second one aimed at identifying promising application scenarios from both the industry and the research point of view. The paper discusses how the questionnaires have been designed and presents the corresponding results.

Keywords -

Robotics; Construction industry; Construction Robots;

1 Introduction

The first applications of robotic technologies to the construction industry were designed in Japan during the 70's, in order to improve the quality of prefabricated elements for modular residential buildings. Since then, robots started spreading in the construction industry, slowly moving from factories to actual construction sites [1, 2, 3]. Differently from other industry fields, where the introduction of robotics technologies radically changed the way human workers operate, the construction industry has not fully experienced its "robotic revolution" yet. As a result, various operations that require high power and/or high accuracy (such as panel positioning, plumbing, material handling) are still manually performed by human workers in very inefficient and dangerous ways. Not by chance, some studies strongly suggest that productivity in the construction industry has been declining over the last decades [4] and that the conventional construction paradigm has reached its technological performance limit [5]. Even though the barriers that are preventing robots to spread within the construction industry are well known, some recently emerged trends started fostering the adoption of novel technologies.

As far as scientific research is concerned, there is no doubt that also the robotics community has demonstrated a growing interest towards applications in the construction industry in the last 15-20 years. Not by chance, the number of scientific publications targeting construction scenarios has experienced a significant growth over the last two decades, as it is demonstrated by Figure 1. From the application point of view, these scientific publications have confronted almost every construction-related application context. Naturally, heavy-duty operations have been tackled, like for instance façade installation [6, 7, 8], forestry [9], mining [10] and generic earthworks [11, 12]. Several solutions have also been developed in order to facilitate inspection of buildings and infrastructures [13, 14, 15]. Finally, in accordance with the trends that will be introduced in the following sections, more recent contributions tackled novel application contexts like for instance realization of wooden buildings [16], interior and exterior renovation [17, 18, 19, 20], additive manufacturing [21, 22] and also decommissioning of nuclear power plants [23, 24].

On the other hand, as far as research topics are concerned, construction-related contributions have explored both consolidated and recent topics in the robotics field: inverse kinematics calculations [25, 26], control architectures [27, 28, 29], trajectory planning algorithms [30], teleoperation strategies [31, 32], Human-Machine Interfaces (HMIs) [33, 34], autonomous vision [35, 36], [37], usage of Unmanned Aerial Vehicles (UAVs) [38]. Another topic that is worth mentioning is represented by the integration with Building Information Modelling (BIM) [39, 40, 41].

Given this scenario, it is clear that both a thorough review of the state of the art of robotic technologies in the construction industry and a detailed assessment of their implementation at different stages of the construction process could be beneficial to identify future research directions and to steer future development activities. With this in mind, the authors realized a survey in order to (i) draft a detailed picture of the state of the art, (ii) identify promising application contexts from both the industry and the research point of view and (iii) underline what skilled professionals expect from robotic technology in the con-

[1]Arup's website: `https://www.arup.com/`

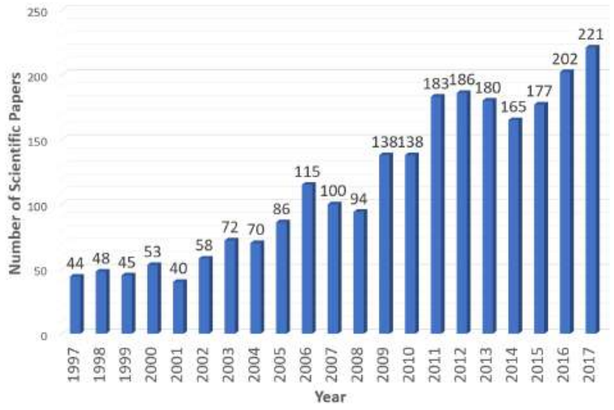

Figure 1. Number of publications labelled with the keywords “construction robotics” and/or “construction robot” over the last two decades. Data extracted from Google Scholar.

struction industry. In detail, the survey has been realised by submitting two distinct questionnaires to Arup’s most experienced technical and business leaders. The first questionnaire aimed at defining the current scenario, while the second one aimed at identifying possible future opportunities. This paper discusses how the questionnaires have been designed and presents the corresponding results. Section 2 deeply discusses barriers, drivers and trends that are influencing the adoption of robotic technologies in the construction industry. Then, Section 3 introduces the first survey and presents the corresponding results, while Section 4 describes the methodology and the results of the second survey. Finally, Section 5 reports some hypothesis regarding future opportunities.

2 Robotics in the Construction Industry

As mentioned before, the spreading of robotic technologies within the construction industry has historically encountered strong resistance, due to several well known barriers. Nowadays the situation is rapidly changing thanks to some recently emerged drivers that are accelerating innovation processes within the construction industry. Moreover, these drivers originated some clearly recognizable trends that are changing the way buildings are planned, built and maintained. In the remainder of this Section these barriers, drivers and trends are explained in detailed.

2.1 Barriers

The main factors that have prevented the spreading of robotic technologies in the construction industry can be listed as follows:

- **Site-related Challenges**: the inherently unstructured nature of construction sites prevents straightforward integration of robotic technologies already used in factories;
- **Sceptical Attitude**: the main stakeholders involved in the process (construction companies, clients and regulatory bodies) are characterized by a strong tendency to stick to well consolidated practices rather than to innovate and adopt novel technologies;
- **Complexity of the Supply Chain**: the number of different stakeholders and the fragmentation of the supply chain entails a strong inertia towards innovation due to extremely varying interests and needs;
- **Variety of the Markets**: regional markets have intrinsic differences (regulations, cost of materials, cost of workforce, quality requirements for products, etc.) that imply different requirements;
- **Variability of Buildings Typologies**: every building can be considered as unique due to the many differences that apply to its shape, materials, components used and locations. Consequently, flexible and easy to adapt technologies are required.

2.2 Drivers

Moving to the drivers that are fostering innovation processes within the construction, the following ones were identified:

- **Scarcity of Resources**: cost of materials traditionally used for construction purposes is increasing, while availability is decreasing;
- **Urbanization**: in order to build within densely populated urban areas it is necessary to rationalize the way buildings are designed and to employ compact and flexible machines in the construction process;
- **Ageing Workforce**: construction workers are rapidly ageing and technologies that can reduce physical effort and fatigue will be increasingly needed;
- **Connectivity and Convergence**: construction workers are becoming more and more used to new technologies, thus making it easier for them to adapt to the introduction of robots in their workplace;
- **Environmental Friendliness**: construction sites will need to progressively reduce polluting emissions, thus fostering the diffusion of electric powertrain systems;
- **Safety**: safety-oriented technologies will play a crucial role in reducing the number of accidents and injuries, in line with latest safety regulations.

2.3 Current Trends

Finally, robotics-related trends that are currently gaining momentum in the construction industry include:

- **Additive Manufacturing**: 3D printing simultaneously allows to rationalize the consumption of resources and to customize products to specific needs;
- **Internet of things**: the possibility to continuously acquire and share data is enabling novel paradigms, like for instance remote control of machines and predictive maintenance;
- **Integration with BIM**: the availability of 3D and 4D (time) information models will foster robotization of construction sites by making all the design information and the data collected on-site available in real-time to construction robots. As a result, quality of planning, construction and maintenance processes will increase, while execution time will decrease;
- **Augmented an Virtual Reality**: integration of AR an VR will improve training strategies and allow effective remote operations of robots [42, 43, 44];
- **Circular Economy**: construction industry is moving from a linear consumption model (use-consume-dispose) towards a circular one (use-recover-recycle). In this context automation and digitalization will act as key enablers.

3 First Survey: State of the Art for Robots in Construction

The first survey aimed at understanding the current occurrence of advanced construction machines and robots in key construction sectors, through the life-cycle of a project. To do so, a decomposition of the construction process life-cycle has been proposed, as well as six different application sectors have been prioritized for the investigation.

3.1 Construction Process Life-cycle

The default life-cycle of a construction project can be decomposed into the following main phases (see also Figure 2):

- **Site investigation**: this phase includes any action to assess the status of a construction site both for existing buildings/infrastructures and new built. It could include scanning of a building interior, inspection of basements as well as geotechnical survey;
- **Demolition**: this phase includes the set of actions needed to demolish a portion or a whole of a building/infrastructure. Might also include disassembly when possible and requested by the project;

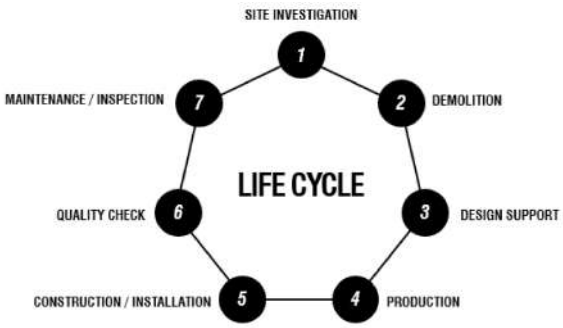

Figure 2. Construction Process Life-Cycle.

- **Design Support**: this phase includes actions to allow a more precise and actual design process, allowing the designer to know more details about any pre-existence at building/infrastructure or site level;
- **Production**: this phase includes the set of actions performed in the making at either the component or at the system level. For the purpose of this paper, we refer to production specifically for in-factory processes;
- **Construction / Installation**: this phase includes the set of actions performed during either the construction or the installation of a building/infrastructure portion or its whole. For the purpose of this paper, we refer to construction and installation referring to on-site processes;
- **Quality Check**: this phase refers to the actions performed at completion of the construction and installation process to assess the quality and the right execution of the process;
- **Maintenance / Inspection**: this phase includes the set of actions to assess the status of a building/infrastructure until its end of life.

These phases are seen as the most meaningful, and those ones where a construction robot could have a significant impact.

3.2 Priority Sectors for Application

On the basis of their experience and market knowledge, Arup's experts identified a set of high priority sectors for application in construction to be investigated within the survey. As shown in Figure 3, these sectors are:

- **Building Cladding**: this sector includes all the parts (components and systems) used at the level of the building envelope being this of any size, form and complexity, from small rain-screen panels to large unitized façade panels;

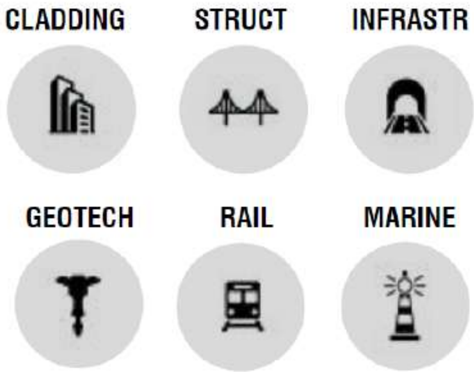

Figure 3. Priority Sectors for Application.

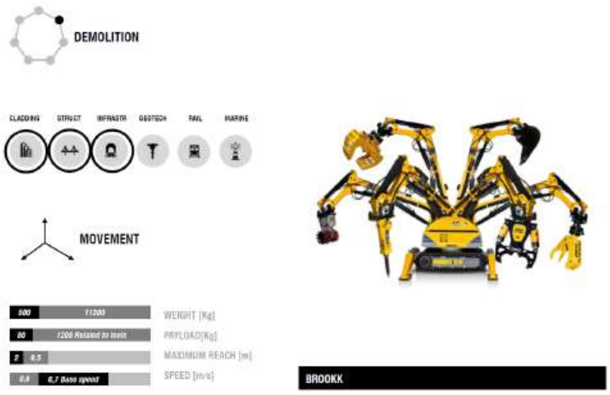

Figure 4. First Survey: remotely operated demolition machines produced by Brokk.

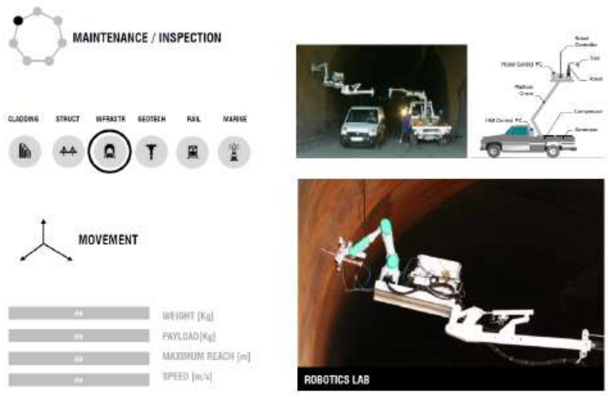

Figure 5. First Survey: Tunnel inspection robot developed by Universidad Carlos III de Madrid.

- **Building Structures**: this sector comprises all the parts (components and systems) used to provide adequate structural performance to a building;
- **Infrastructures**: for the purpose of present research, we considered this as the sum of the parts (components and systems) used to make a tunneling project;
- **Geotechnical Engineering**: for the purpose of present research, we considered this as the sum of the processes necessary to perform surveying and construction of underground areas or parts of a building/infrastructure;
- **Railway**: for the purpose of present research, we considered this as the sum of the parts (components and systems) used to make a railway project;
- **Marine Engineering**: for the purpose of present research, we considered this as the sum of the processes necessary to perform surveying and construction of marine and cost areas or parts of a submerged building/infrastructure.

3.3 Examples of Case Studies

In order to clarify the methodology used to conduct the survey, two distinct case studies have been reported here. The first example refers to the line of remotely operated demolition machines realized by Brokk[2]. Figure 4, shows some data regarding weight ($500 - 1300\ kg$), maximum payload ($80 - 1200\ kg$), maximum reach ($2.00 - 9.50\ m$) and travelling speed ($0.60 - 0.70\ m/s$) of the different machines. More interestingly, the diagram also reports the result of the survey in terms of mapping between the specific case study and life-cycle phases (in this case only demolition), and between the machine and the corresponding sector (cladding, structural and infrastructural engineering).

[2]Brokk's website: `http://www.brokk.com/`

A different case study is described by Figure 5, where an example of tunnel inspection robot is considered. Clearly, this case study robot has been matched with the maintenance/inspection phase and with the infrastructural engineering sector.

3.4 Survey Results

During the survey a total of 52 construction robots have been identified and categorized by Arup's consultants. Figure 6 shows the final results of the investigation from a tow-fold perspective. In the heptagon on the left, case studies were mapped to the different phases of the construction life-cycle. Data show that the vast majority of currently available construction robots are strongly focused on maintenance and installation tasks. As far as inspection tasks are concerned, the spreading of robots is almost surely due to the possibility to take advantage of high position accuracy in order to automate repetitive and specific tasks. Moving to installation tasks, the possibility

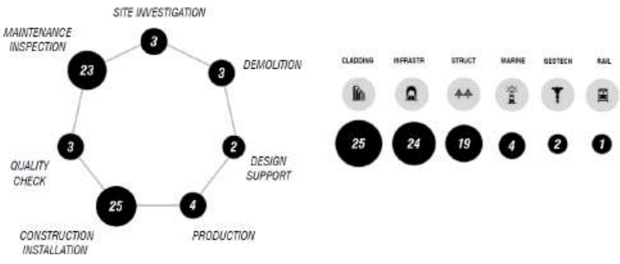

Figure 6. First Survey: overall results.

to move relatively low (high) payloads with high (limited) accuracy is particularly appealing. Notably, the survey identified a low number of robotic applications in the design support, production and in the quality check phases. This is possibly due to some of the aforementioned barriers: sceptical attitude towards new technologies, complexity of the supply chain and heavily unstructured nature of on-site operations.

Moving to the diagram on the right, where the identified case studies were mapped to the considered application sectors, it can be seen that several robots were found in the cladding, infrastructural, and structural sectors, while very few examples exist in geotechnical, railways, and marine engineering. A possible interpretation of these data consists in relating the number of technologies with the features of the corresponding working environment. In other words, the more the environment is unstructured and exposed to dust and weather conditions, the more difficult it is to realize robust and effective robots. It is worthwhile to mention that, as shown in Figure 4, a single robot can be mapped to one life-cycle phase (application sector) or more.

4 Second Survey: New opportunities in the construction industry

The second survey had a different ambition, namely to identify where the highest potential is currently seen within the building life-cycle and according to the six priority sectors identified before. To reach this goal, Arup's experts have been asked to assign a score to the relevance of robotic technologies, in the specific sector, at a specific life-cycle stage. Possible scores were:

- **High**: 3 points;
- **Medium**: 2 points;
- **Low**: 1 points;
- **Not Applicable**: 0 points.

Then, they were requested to evaluate, in each sector and using the same scale, the impact of robotic technologies on the following key indicators:

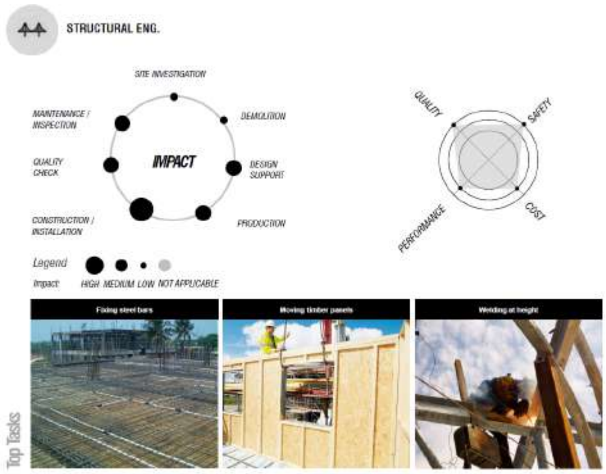

Figure 7. Second Survey: Structural Engineering sector.

- **Quality** of the construction;
- **Safety** within the construction site;
- **Cost** for the operations;
- **Performance** of the construction.

4.1 Examples of Application Sectors

In order to demonstrate how the authors conducted the second survey, data regarding two different application sectors are detailed in the following. The first one pertains the structural engineering sector. As it can be seen in Figure 7, the impact of novel robotic technologies in this sector is considered as "high" in the construction / installation phase, "medium" in design support, production, quality check and maintenance phases, and "low" for all the other phases. Arup's experts also evaluated a high impact in terms of safety and quality metrics, and a medium impact on cost and performance. As far as types of operations are concerned, some promising tasks identified in this sector are fixing of steel bars, placing of wooden elements and welding at height.

A different example is displayed in Figure 8, where the infrastructure sector is analysed. The impact of innovative technologies has been considered as "high" in almost all the phases, except production ("medium") and site investigation ("not applicable"). As far as key indicators are concerned, the result is the same with respect to the previous example. Finally, the most interesting tasks to automate are concrete spraying, tunnel inspection and tunnel boring.

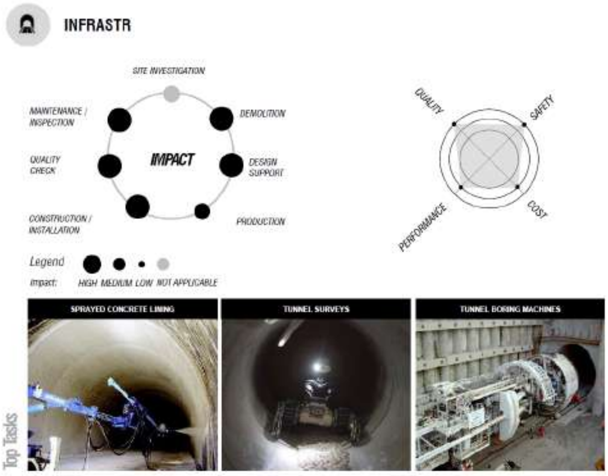

Figure 8. Second Survey: Infrastructure sector.

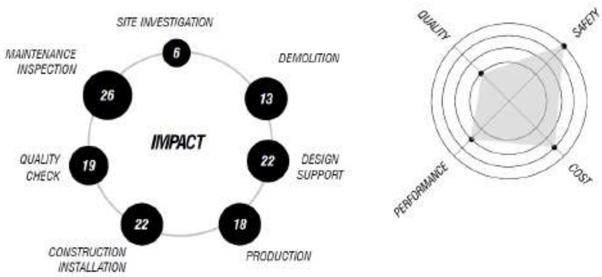

Figure 9. Second Survey: overall results.

4.2 Survey Results

In order to sum up the results of the second investigation, the two diagrams contained in Figure 9 have been realized. The one on the left shows the overall relevance of hypothetical new robotic applications to be implemented at the different stages of the construction life-cycle. Global scores have been computed by averaging the total scores assigned to each life-cycle stage over the different application sectors. Having in mind the results of the first survey (see Figure 6), the fact that maintenance and installation are confirmed to be the top-two phases comes at no surprise. Furthermore, the fact that a significant potential has been identified in the design support, production and quality check phases is in line with the conclusions of the first investigation. Finally, also demolition has been judged as an appealing stage since, in the context of a circular economy, the idea itself of demolition changes from destruction to de-construction, thus making position accuracy a valuable advantage.

On the other hand, the diagram on the right shows the average score assigned to each key indicator. According to Arup's experts, novel robotic technologies will have a substantial impact on safety and cost (which is quite straightforward). On the other hand, a lower impact is foreseen in terms of quality and performance, mainly because the capability to deal with heavily unstructured environments is still an open issue from both the research and the industry point of view.

5 Conclusions

This paper presents a survey activity aimed at defining a clearer picture of the current scenario of robotic in the construction industry. The investigation also intended to identify future opportunities for research and development activities. The survey involved Arup's most experienced technical and business leaders and was performed by means of two distinct questionnaires. The paper motivates the design of these questionnaires, presents some example of detailed analysis and discusses the overall results. In the end, Arup's experts identified demolition, design support, production and quality check as the construction phases where new robotic technologies could have larger impact in the next few years, in terms of improved safety and reduced costs and across several application sectors. Clearly, in order to develop such machines, the capability to robustly perform complex tasks inside heavily unstructured environments remains the most demanding challenge to tackle from the research point of view.

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Recognition and Positioning of SBCs in BIM Models Using a Geometric vs Colour Consensus Approach

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Abstract –

This paper proposes a new approach that recognizes different kinds of small objects that are commonly seen on walls and ceilings of buildings (Figure 1). The general idea supported in this paper is that such objects, called service building components (SBCs), should be inserted into the structure of the standard existing as-is BIM models, as they are automatically generated. But identifying these small building components within the vast dataset provided by the scanner is a difficult issue not solved yet. Our approach first processes a dense coloured point cloud and extracts global geometry and colour features to identify potential SBCs. A novel consensus algorithm between geometry and colour features is the basis to efficiently recognize and calculate the position of the existing small objects in the as-is BIM model of the building. The method has been tested in real and simulated environments providing encouraging results.

Keywords –
Object recognition; Scan-to-BIM; Automatic BIM; 3D data processing.

1 Small building service components: the last semantic level of a BIM model

Many researchers are currently working on the automatic creation of as-is BIM models at several semantic levels. This paper is framed into the methods that automatically obtain some sort of 3D building model from 3D data. Nowadays, and roughly speaking, we can distinguish between four semantic levels which go from a mere point cloud model to a detailed 3D CAD model of the building structure.

The first semantic level covers the set of automatic data acquisition algorithms that provide a rough point cloud of the building. This model usually has a poor-semantic content and most of the research efforts are focused on finding an efficient scan planning algorithm, which provides a complete dataset of the indoors [1], [2] or outdoors [3] of buildings.

Figure 1. The image represents a coloured point cloud and different objects recognized in a wall. Apart from the doors, our recognition algorithm identifies five service building components.

The second level is achieved after processing the initial point cloud of the scene. The data are usually segmented into a set of representative parts, which follows specific geometric patterns (e. g. vertical/horizontal flat regions), and the scene is finally represented by a B-rep model. Essentially, this is a polyhedral model with certain attributes (i.e. vertex, edge and face) and their corresponding relationships. Works at this level can be found in [4], [5].

In the third level the segment extracted in the second level are recognized as essential constructive elements of the building. This is a higher semantic level in which a meaning of the earlier data segments is introduced. At this level, the model contains primarily objects such as “wall”, “ceiling”, “floor” and “column” ([6], [7]).

The fourth level completes the previous level by adding other important elements which lie in the constructive elements, such as windows, doors and frames. Examples of models at this level are that of references [8]–[10]. Other works include pipes or scaffolding in the BIM models of industrial facilities ([11], [12]).

Beyond the fourth level, there are more components of a building that could be introduced in the BIM model as permanent or as-designed components. These small components are related with the habitability of the building, mainly related with power and security issues. As is argued in the abstract, from a constructive point of view, these components might have a relative importance, but are however essential for a safe and reliable life of the inhabitants of the building. Therefore, we propose a fifth level that includes such components which, from here on, we call service building components (SBCs). Previous work in the detection of SBCs is dealt in the next section.

2 Detection of SBCs: previous work.

Very few proposals achieve this level of detail in a 3D semantic building model and only partial solutions that recognise luminaries, sockets or other particular SBCs have been published to date. In addition, most of these works are framed in robot interaction applications.

Specific electrical equipment can be easily detected in thermal point clouds. For example, in [13] hot and cool regions are detected on ceilings. These regions are assumed to be electrical systems, heating, ventilation and air-conditioning components.

In [14], Díaz-Vilariño et al. process 2D coloured images of ceilings and identify two types of light fixtures. It is assumed that the segmented regions correspond to these objects, so that there is no proper recognition algorithm. Sockets and switches are also recognized in 2D images in [15]. Eruhimov et al. ([16]) classify between power holes, ground holes and the background in images acquired by a mobile robot. Meeussen et al. ([17]) recognize doors, door handles, electrical plugs and sockets, also under robotic applications.

Some authors provide more encouraging results. In [18], insulations, electrical outlets, studs and different states for drywall sheets are detected in 2D images. Unfortunately, the recognised objects are not positioned into a 3D model of the facility. The sensorial system presented by Bonanni et al. in [19] identifies - with the help of a human being- a set of usual small components, such as electrical outlets, fire extinguishers, hydrant boxes and printers. This is again a part of a human-robot system which is not related with the extraction of semantic models of buildings. The recognised small components are not therefore integrated into a 3D building model.

As is clear, the aforementioned SBCs detection methods are frequently associated with the recognition and pose estimation of objects in 2D images, which is not connected with an as-is semantically-rich 3D model of the building.

3 Justifying a new SBC recognition method in a BIM framework.

Recognition of SBCs in the BIM context is a difficult problem in which the origin and quality of the data to be processed plays an important role.

As is known, in general the problem of recognizing objects in 2D images has been extensively studied for many years and multitude of efficient solutions - including SIFT, SURF and others - have been proposed. All these algorithms commonly work on high quality images taken from medium/high resolution cameras, which signifies that the objects appear clear enough, with sufficient resolution and without significant superimposed noise. Nevertheless, object recognition in 2D images is restricted to merely identify, but not to estimate the position of the object in the 3D space (i.e. into a 3D indoor model).

Additionally, these techniques could yield frustrating results when applied to the raw scan data (the kind of data used for the construction of as-is 3D models), more precisely to the orthoimages generated from a coloured point cloud. Note that a balance between the resolution of the collected point cloud, the associated memory and the time requirements must be imposed in a building scanning process. On the other hand, in order to avoid occlusions, several scans must be taken (and later aligned) from different scanner positions. All this entails imprecisions on the coordinates of the registered data along with slight variations in the colour assigned to the surface of the potential SBCs (which have been viewed from different angles). Consequently, the orthoimages generated from the accumulated coloured point cloud are frequently, if not always, noisy and of a low resolution.

In practice, our automatic building scanning system generates orthoimages of 5mm/pixel. This resolution is achieved with an angular stepwidth of 0.065º, which yields 10 million points in 83 seconds per 360-scans. Of course, we can force the scanner up to a stepwidth of 0.0024º, but in this case, the system would become impractical.

To recognize a query (small) object in such a poor quality and low-resolution image (in fact, it is an orthoimage), new recognition methods need to be applied. The contributions of our approach lie in two pillars.

First, the geometry and colour data contained in the coloured point cloud are separately processed. Afterwards, the corresponding results are put in common by following an original consensus procedure. This is the most important issue of the paper, which is explained in detail in Section 4.

The second pillar consists of avoiding local features and descriptors in the recognition algorithms. Since the orthoimages might appear blurred and with a poor colour quality, we define a supervised learning algorithm that uses a pattern composed of global descriptors, which are invariant to scale and rotation. In the experimental section, we briefly refer to a particular feature pattern that has provided encouraging recognition results.

Figure 2 illustrates the poor quality and low resolution of the SBCs' images contained in the orthoimage of the frontal wall of Figure 1. Note the poor quality of the fire-alarm switch image with 26x26 pixels in size (13x13 cm).

Figure 2. Images corresponding to BSCs in the scene shown in Figure 1.

4 A consensus framework for SBC recognition

4.1 Assumptions and inputs

The objective of this paper is not to explain specific recognition algorithms, but to propose a new approach that identifies and calculate the position of SBCs by means of a consensus between geometric and colour-based recognition strategies. We therefore present a consensus approach by assuming that a number of 3D processing stages have already been completed.

Let us consider that previous pre-processing stages, such as data collection, registration, colour fusion and initial data segmentation have successfully been carried out. Let us also assume that the accumulated point cloud has been segmented into the essential constructive elements of the building, including openings. According to the earlier semantic building model classification presented in Section 1, we start our SBC recognition approach on the basis that the fourth semantic level is available. At this level, the coloured point cloud associated with an already detected and modelled wall is therefore available. The reader can obtain complete information about our mobile mapping system for digitization (MoPAD) and our last works on extraction of automatic BIM models in references [20]–[22].

The set of coloured data belonging to a wall is structured as a 4D orthoimage, J_{CD}, in which each pixel has colour (RGB) and depth (i.e. an orthonormal distance between the 3D points and the wall plane). The colour and depth components of J_{CD} are decomposed into J_C (colour) and J_D (depth), and two different geometric and colour-based algorithms are afterwards applied on the respective orthoimages J_C and J_D.

Let us assume that, as a result of the earlier processes, for each expected object O_i, $i = 1 \dots N$, two lists of candidates $\{C\}_{O_i}$ and $\{D\}_{O_i}$are identified in both images J_C and J_D .

4.2 The Recognition Coherence Matrix

Since there could be more than one instance of the object O_i in the wall, after the consensus between the lists $\{C\}_{O_i}$ and $\{D\}_{O_i}$, the output could be composed of several regions (RoIs) located on the wall.

In order to evaluate all possible combinations of $\{C\}_{O_i}$ and $\{D\}_{O_i}$, we define a *Recognition Coherence Matrix* Ψ . Each entry in Ψ_{O_i} is the *Recognition Coherence Level* α, which measures the coherence between a pair of RoIs found in images J_C and J_D . This parameter is ranged in the interval [0,1] and will be defined below.

The flowchart in Figure 3 explains how Ψ is built for each query object, N being the number of SBC classes lying on the wall. Symbols n_C and n_D are formally: $n_C = \langle\{C\}_{O_i}\rangle$ and $n_D = \langle\{D\}_{O_i}\rangle$, where $\langle A\rangle$ represents the cardinal of the set *A*.

The *Recognition Coherence Level* α between two candidates is calculated by assessing the overlap between a pair of RoIs, B_C^j and B_D^k (with centroid coordinates c_C^j and c_D^k respectively) found in the respective images J_C and J_D . There are three cases:

1. Partial Intersection. B_C^j and B_D^k overlap. In this case, α measures the relative overlap with respect to the bounding box B_{CD}^{jk} that encloses B_C^j and B_D^k. The expression of α is given in equation (1).

$$\alpha = \frac{\langle B_C^j\rangle \cup \langle B_D^k\rangle}{\langle B_{CD}^{jk}\rangle} \tag{1}$$

2. No intersection. B_C^j and B_D^k does not overlap. In this case, $\alpha = 0$.
3. Exclusive detection. $\nexists B_C^j$ or $\nexists B_D^k$. In this case, O_i is only recognized in J_C or in J_D, and $\alpha = 0.5$.

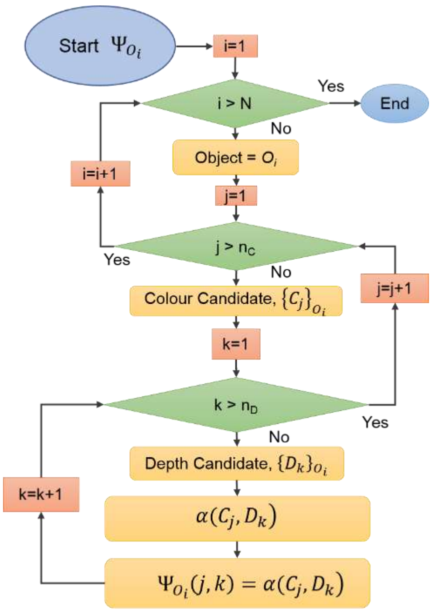


Figure 3. Algorithm for the construction of N *Recognition Coherence Matrices.*

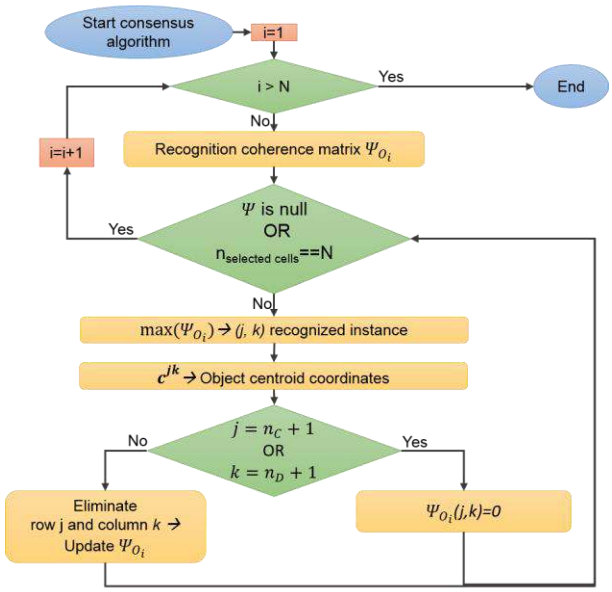


Figure 4. Recognition consensus algorithm.

4.3 Recognizing objects from the Recognition Coherence Matrix

The *Recognition Coherence Matrix* is completed with a new row and column, inserting the value 0.5 on them. The extra row and column are included because, besides the usual assignation of pairs of RoIs candidates, the exclusive detection by colour and depth is always considered in the resolution of the *Recognition Coherence Matrix*. In this way, Ψ_{O_i} is eventually a $(n_C + 1) \times (n_D + 1)$ matrix.

Once Ψ has been filled, the recognition consensus decision is solved iteratively following four steps (see Figure 4 for a better understanding):

4. The highest value of Ψ is selected and considered to be a recognized instance of the query object O_i.
5. The corresponding row and column of Ψ are eliminated, except when the selected cell corresponds to an exclusive detection case. In this case, only the corresponding cell is set to 0.
6. The coordinates of each recognized instance of the object O_i in the orthoimage J_{CD}, are calculated by means of a weighted mean of the corresponding RoIs centroid coordinates, $\boldsymbol{c}_C^j$ and $\boldsymbol{c}_D^k$.
7. Steps 1, 2 and 3 are iterated until Ψ is null or until the number of selected cells is equal to the number of expected instances of the query object in the wall.

Equation (2) shows two weights ρ_C^j and ρ_D^k that are defined depending on the specific geometric and colour based recognition algorithms used when the lists of candidates $\{C\}_{O_i}$ and $\{D\}_{O_i}$are obtained. In our case, we take ρ_D^k as the cross-correlation coefficient, which is obtained when correlating the RoI B_D^k with that of the depth model of object O_i. The weight ρ_C^j is a normalized distance coefficient that evaluates the goodness of the recognition algorithm when comparing B_C^j with the colour model of object O_i. This is a minimum distance classifier algorithm that compares patterns composed of global colour features.

$$c^{jk} = \frac{\rho_C^j \boldsymbol{c}_C^j + \rho_D^k \boldsymbol{c}_D^k}{\rho_C^j + \rho_D^k} \qquad (2)$$

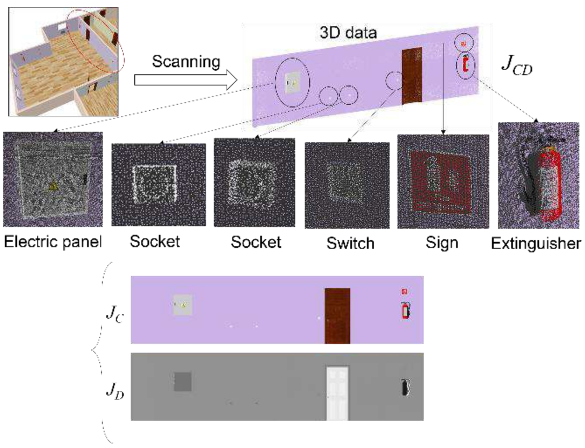
4.4 Showing a case of study

In this section we explain in detail the recognition procedure in a representative case of study. We have simulated the digitization of an indoor floor using the Blensor software [23]. This tool allows us to simulate a scanning process on a 3D building model by using the same scanner we have got in our lab.

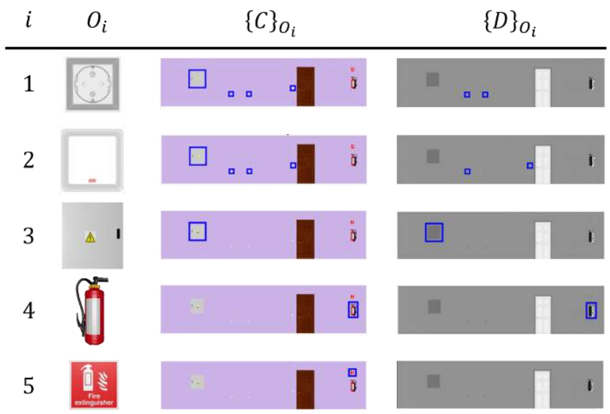
The indoor consists of several rooms with a wide set of SBCs lying on the walls. A representative wall of the room #4 has been taken to run our recognition strategy. This wall contains the following SBCs: an electric panel, two sockets, a switch, a fire extinguisher sign and an extinguisher (Figure 5 a)).

The orthoimage of the wall is decomposed into images J_C and J_D , and then processed separately. The results obtained from the colour and depth-based algorithms yield two lists of candidates $\{C\}_{O_i}$ and $\{D\}_{O_i}$. Figure 5 b) highlights in blue the RoI candidates in images J_C and J_D. Note that the first columns show the colour model of the query objects.

Initially, some surprising candidates are assigned at this stage, particularly in the case of the colour-based recognition. For example, note that the region that contains the electric panel is within the list of candidates of the objects "socket" and "switch". The explanation of this apparently strange result is that we identify the regions in which the query object could be located and, since we use global colour descriptors, the recognition algorithm is invariant to the scale. Obviously, some of the global colour descriptors of the socket could match with that of the regions in which the electric panel lies, and for this very reason, this could be included in the list of candidates $\{C\}_{O_i}$.



a)

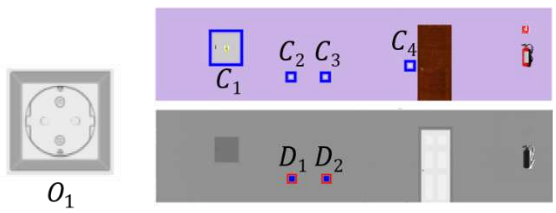


b)

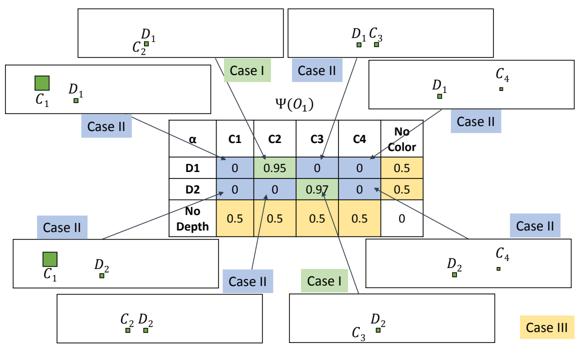
Figure 5. a) up) Representative wall of room #4 and the details of the coloured point clouds of the SBCs obtained from the virtual scanning. Down) Decomposition of the orthoimage J_{CD} into J_C (colour) and J_D (depth). b) The set of candidates $\{C\}_{O_i}$ and $\{D\}_{O_i}$ obtained after applying the recognition algorithms in images J_C and J_D. Candidate regions are highlighted in blue.

Since there are five different objects on the wall, five *Recognition Coherence Matrices* $\Psi_1, \Psi_2, \Psi_3, \Psi_4$ and Ψ_5 must be calculated. Figure 6 illustrates details of the Recognition Coherence Matrix Ψ_1 corresponding to the object "socket". Since $\langle\{C\}_{O_1}\rangle = 4$, $\langle\{D\}_{O_1}\rangle = 2$, Ψ_1 is a 5×3 matrix. The figure shows the positions of the candidates for each assigned pair and, according to the explained in Section 4.2, its corresponding overlapping type. Since we assume two instances of the object "socket" in the wall, the resolution process of Ψ_1 will take two iterations (See Figure 7).

As was explained in Section 4.3, the highest *Recognition Coherence Level* of Ψ_1 is taken as the first recognition result. This happens for the pair (C_3, D_2). The centre of the recognized instance of the object "socket" is then calculated according to equation (2). After deleting the corresponding row and column, the second assignation (C_2, D_1) is established and the same process follows. Since the number of selected cells is equal to the number of expected instances of the query object, the recognition process for the object "socket" comes to an end.



a)



b)

Figure 6. a) RoI candidates for the object "socket" in images J_C and J_D. b) The *Recognition Coherence Matrix* Ψ_1. Visualization of each pair of associated RoIs and the corresponding value of the *Recognition Coherence Level* in Ψ_1.

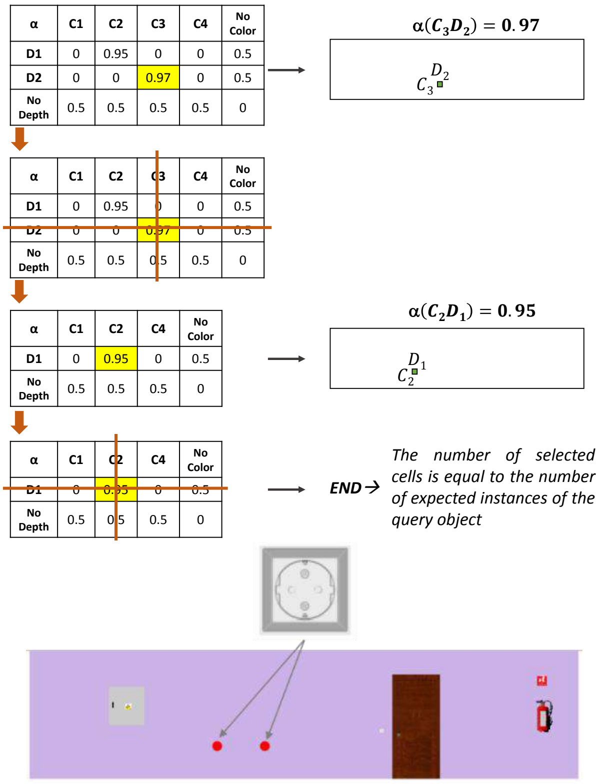


Figure 7. Solving the *Recognition Coherence Matrix* of the object “socket” and final recognition result.

5 Experimental test

This section is devoted to showing the efficiency of the geometric versus colour consensus approach in an experimental test. We simulated an indoor floor composed of 5 rooms containing 116 SBCs of 13 classes (See Figure 8). This scenario was virtually scanned with Blensor [23], which allows us to simulate the same real scanning process as with our Riegl VZ-400 3D laser scanner. In order to make the data acquisition process more realistic, noise to the position and colour of the collected point cloud was added.

The objective of this test is to compare the recognition results using, on one hand, separated colour-based and geometric-based algorithms (algorithm I and II in Table 1) and, on the other hand, the consensus approach (algorithm III in Table 1).

As mentioned in Section 4.3, our geometric-based recognition approach is a simple cross-correlation algorithm that compares the obtained RoIs B_D with that of the depth models of the objects existing on the wall. The colour-based recognition algorithm is a minimum distance classifier algorithm that takes some global colour features, such as the two principal saturation values in the HSV colour-space, the redness versus greenness and the yellowness versus blueness, which are parameters *a* and *b* in the Lab colour-space. Anyway, it is noteworthy to point out that the most important thing here is not in the specific geometric and colour-based algorithm applied, but in the efficiency of the consensus approach.

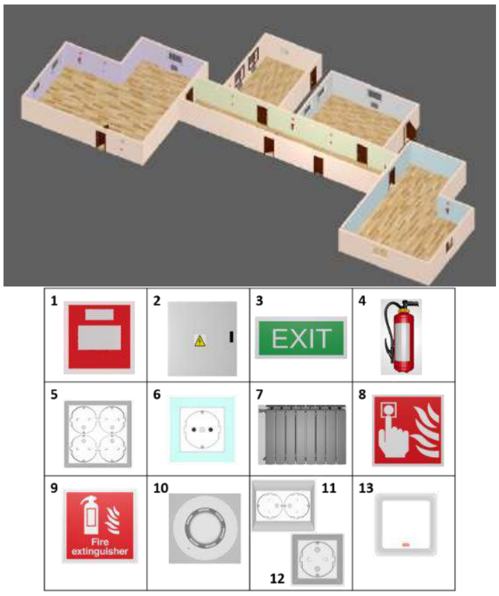


Figure 8. Simulated scenario used in the experimental test and the set of service building components included in the scenario.

Table 1. shows the recognition results after applying the aforementioned algorithms. The table includes the true positive cases (the algorithm recognizes successfully the query object), the false positive cases (the algorithm recognizes an object that is not the query object) and the false negative cases (the algorithm does not recognize the query object). Columns #1 to #5 refer to the five rooms of the scenario, column T is the total count and column Perc. signifies the recognition percentage.

The consensus algorithm achieves the greatest recognition percentages (90,5%) compared with algorithms I (83,6%) and II (41,4%). Although the geometric-based algorithm yields the lowest false positive percentage (5,2%), there is not a significant difference compared to that of the consensus algorithm (8,6%). In addition, the false positive rates are usually considered as the least important numbers in a recognition assessment. However, a more significant improvement can be seen in the figures concerning the false negative percentages. Clearly, the use of our consensus approach reduces the percentages yielded by the colour (16,4%) and the geometric-based (58,4%) approaches.

Figure 9 shows the extracted BIM model and the SBCs recognized after applying our algorithm. In this figure, each red spot represents the centroid of each recognized object.

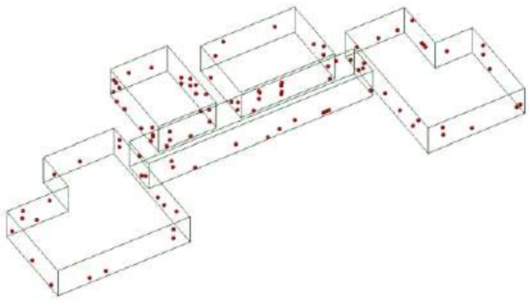


Figure 9. Recognition results superimposed onto the extracted as-is 3D model of the indoor floor. Red spots represent the recognized objects.

Table 2. provides more information about the false negative percentages for each one of the existing SBCs. In general, it can be stated that the objects with low-frequency colour/intensity components in the frequency domain (i. e. flat colour RoIs) are hardly detected by method I. Thus, the fire alarm switch (O_1), the electric panel (O_2) and the smoke detector (O_{10}) are not recognized in half of the cases. In regard to the method II, owing to the lack of depth discontinuity with respect to the wall, the regions with signs (e.g. O_8, O_9) and built-in sockets (e. g. O_6) are not detected as potential RoIs.

Note that the consensus algorithm decreases (or at least it is equal) the false negative percentages in all the cases. Significant improvements appear for the extinguisher (O_4), the socket x4 (O_5) and the smoke detector (O_{10}), in which both algorithms I and II fail. In O_4 and O_5, the false negative cases are eliminated and, in the case of O_{10}, the percentage in reduced up to 20%.

Table 1. SBC recognition results for the colour-based algorithm (I), the geometric-based algorithm (II) and the consensus approach (III). T=Total, Perc.=percentage

Algorithm		#1	#2	#3	#4	#5	T	Perc.
I	TP	20	24	18	21	14	97	83,6
	FP	4	1	5	5	1	16	13,8
	FN	4	3	5	5	2	19	16,4
II	TP	12	6	12	10	8	48	41,4
	FP	1	0	0	3	2	6	5,2
	FN	12	21	11	16	8	68	58,6
III	TP	23	25	21	22	14	105	90,5
	FP	1	1	2	4	2	10	8,6
	FN	1	2	2	4	2	11	9,5

Table 2. False negative percentages obtained per object.

Alg.	O_1	O_2	O_3	O_4	O_5	O_6	O_7
I	50,0	50,0	0	11,1	27,3	16,7	0
II	75,0	25,0	10,00	55,6	36,4	100	83,3
III	37,5	25,0	0	0	0	16,7	0
Alg.	O_8	O_9	O_{10}	O_{11}	O_{12}	O_{13}	Total
I	25,0	11,1	50,0	0	0	0	16,4
II	100	100	30,0	0	70,0	25,0	58,6
III	25,0	11,1	20,0	0	0	0	9,5

6 Conclusions

As is known, electric components (e. g. sockets and switches), fire devices (e. g. fire alarms and extinguishers) and a diversity of signs (e. g. exit signs and prohibition signs) are frequently placed inside the buildings, constituting a further but necessary part of the building. These small components, mostly related with the habitability of the building, should be included in the current as-is BIM models of buildings.

In order to recognize and estimate the position of such secondary components, this paper proposes a methodology that takes advantage of the geometric and colour information provided by the current 3D sensors (usually 3D laser scanners). But, owing to the poor quality and resolution of the orthoimages generated from the collected coloured point cloud, the SBC detection and its subsequent integration into the as-is 3D model of the building becomes a difficult problem, which needs to be addressed from new strategies.

The solution presented in this paper separates colour and geometric characteristics and proposes a consensus between the respective separated recognition results. This consensus has been implemented by means of the original concepts *Recognition Coherence Matrix* and the *Recognition Coherence Level*, which allows us to recognize multiple instances of the same object.

The method has successfully been tested on real and simulated data. The results yielded from the experimental work show that SBC recognition rates are greatly improved when our strategy is applied. These improvements signify that the use of the proposed consensus method makes the whole recognition process more robust and effective. In conclusion, our approach recognizes more objects and commits fewer identification failures, thus providing a rich fifth-level semantic 3D model of the building.

7 Acknowledgments

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Crane safety system with monocular and controlled zoom cameras

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Abstract -

In this paper, we propose an approach and workflow in order to detect humans in the environment around a crane with Monocular Images. The considered area is split up into a zone around the crane truck and one around the load. The load will be monitored with an optical zoom camera where we can control the zoom. We discretize the zoom levels and a Convolutional Neural Network for each zoom level is trained. Afterwards a Meta Convolutional Neural Network is trained in order to select the next zoom level. Since there are no public datasets available for this kind of task we propose to generate the needed data with a photorealistic simulation.

Keywords -

Crane; Safety; Human Detection; Deep Learning; CNN; Simulation

1 Introduction

In the construction site environment each human is exposed to many potentially dangerous objects. Common sources for injuries are heavy-duty commercial vehicles. The distribution of accidents in the example of an excavator can be seen in figure 1. As one can see most accidents happen in an area which is not visible to the operator, i.e., behind the vehicle or at the opposite site of the operator.

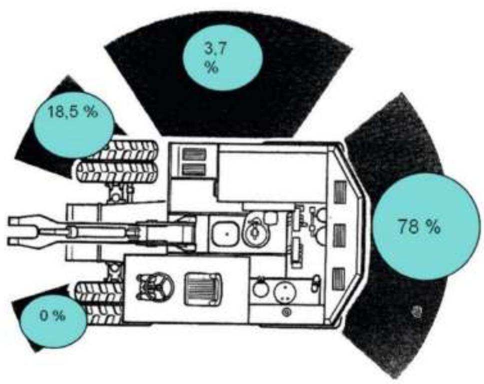


Figure 1. Distribution of fatal and critical accidents with excavators shown in the blue circles[14].

It is, therefore, necessary to support the operator of heavy-duty machines when the area around it is not closed off and humans can appear unexpectedly. Though the problem gets even worse with bigger machines where even bigger areas are occluded by the machine. Therefore there is a need to detect humans in the potential risk areas of a crane, which is definitely one of the biggest machines in a construction site environment. The work presented in this paper is focused on mobile cranes and caterpillar cranes, so specifically tower cranes are not considered. Universal usability for cranes of different manufactures is nonetheless important. We therefore do not make us of the internal crane data. When operating a crane there are two main areas which include a potential threat to humans, one is the crane truck itself and the other is the load of the crane. It is necessary to consider both parts for a reasonable approach.

We therefore propose a methodology which can be used to detect humans around the crane. It mostly relies on already tested *Deep Learning* approaches for object detection. Our methodology does not only detect humans around the crane but also around the load, which is more complicated due to some further restrictions. Additional challenging elements are due to the construction site environment. In road scenarios one can assume that the vehicles are in either a highway, city, urban or metropolitan area, while a construction machinery can operate in a mining field, building site, forest or even rough terrain. The environment effects type and activity of each object that the system is going to encounter during the detection task. One further handicap is that standard approaches for detecting humans around the load are not suitable. Since the shape and material of the load is not known in advance and the load can potentially be moved in a big area, which is also not necessarily planned beforehand. The only remaining possibility is to mount cameras on the crane itself. Because of the sheer size of the crane, off the shelf solutions for detecting humans are not applicable due to unusual perspectives and distances .

In the following sections we describe our approach in detail. The rest of the paper is organized as follows: Section 2 discusses the state-of-the-art of human detection algorithms split it up into the different perspectives which are used in the proposed approach. In section 3 the general structure of the proposed approach is described and again split up in the different zones of interest. Section 4 is considered with the generation of the needed datasets with a simulation tool. Section 5 takes a look at the network architectures chosen in section 3 to solve the detection tasks. Finally in section 6 we recap the proposed methodology.

2 Related work

In construction machines, safety systems mostly conduct without any automatic brake when possibility of a collision occurs. The system simply alarms the operator to brake manually. In some systems, the operator needs to acknowledge the alarm by e.g. touching the monitor screen. Traditionally, safety in construction sites is done by direct manual observation [17]. It mainly uses non vision-based sensors, e.g., RFID tag, ultrasonic or infrared sensors. The sensors can be attached on the workers' helmets or wristbands and inform the crane operator about their position. Due to the characteristics of proximity sensors, these safety systems are unable to predict a person's trajectory and absolute position due to an insufficient detection range. Most vision-based safety systems take advantage of specific cues of a persons appearance. In the construction site environment many such visual features can be used, e.g., hard helmet detection [26], detecting workers from reflective vest [19]. Even though dress code in construction site is strict, some people could unintentionally ignore it or do not realize the risk this poses.

2.1 Crane Truck View

For the detection of humans around the crane most state of the art Convolutional Neural Networks(CNNs) can be used as a basis. The perspectives are quite similar, even though the appearance of most humans is a lot more defined due to the presence of reflective vests and helmets. As a basis we refer for example to [24, 15, 23], which of course does not cover the whole extend of work in the field of human detection.

2.2 Load View

Most Detection algorithms for top view camera systems can be found in surveillance systems. Many different proposed methodologies have been proposed, however, these are not really suited to our needs. These approaches often times make use of the fact that either the camera itself is static [31, 33] or uses distinct features of the background, like a street [3]. Some methodologies use features which are prevalent even in top view images, like the head-shoulder shape [34], which may be different due to helmets or carried objects in an construction site environment. Some also simply try to estimate the number of persons in an image [13, 6]. Most are quite often not build to deal with images from a distance as far as in a crane scenario [22, 6, 30].

Another approach is to use a human detection algorithm which works for the front view case and adapt it in order to deal with different views and scenes [32, 1]. We do not only have to deal with the fact, that there is no fitting approach for our use-case but also no public available dataset. Recent advancements in the usage of simulated data for machine learning have been made in reinforcement learning [18], object detection via CNNs [21], viewpoint estimation via CNNs [20] and segmentation tasks [25]. Hence, there are many possibilities to tackle the introduced task, but additionally to the so far presented state-of-the-art it may be necessary to use domain adaptation techniques in order to improve the results as in [4, 16, 29, 35, 2]

3 Proposed Approach

The application seems to encourage an approach which is separated into the detection around the crane and around the load. In our approach we will follow this idea and deal with both problems in a separate manner. We start with the setup of the sensor system in each case. Afterwards we shortly talk about the used CNNs and how to train them specifically for our application scenario.

3.1 Human Detection Crane Truck

In this subpart of our Application scenario we use a camera setup which roughly looks like presented in figure 2.

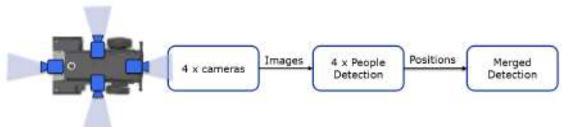
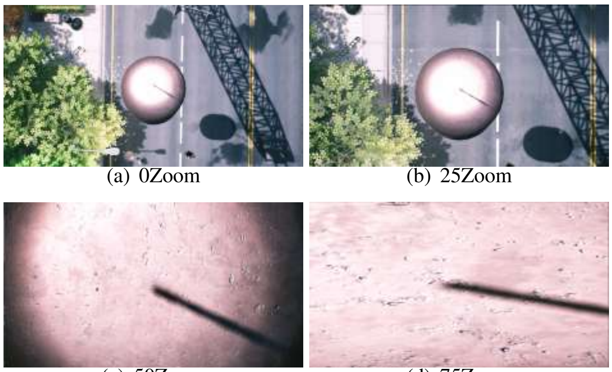


Figure 2. Sketch of camera setup at the crane truck

We have a couple of cameras mounted on the crane truck. They look into different directions in order to have the possibility to detect humans in the blind spot of the operator. In the crane scenario the blind spots are not static, due to the revolving superstructure. We are then able to work on each camera image individually and then merge the results. In order to detect humans in each of the images we use a Neural Network. Like already elaborated in section 2, CNNs yield solid performances when dealing with human detection for such frontal views. As for the explicit architecture of the used CNN we refer to [15], since we do not adapt the actual structure to much, still some additional work is needed. Off the shelf trained networks will not yield perfect results since the construction site environment differs from most available training data. Going into a construction site environment and collecting enough labeled data of typical workers to train such a network from scratch is very time consuming. We therefore use a pretrained Network as initialization. Afterwards we apply transfer learning with some examples from construction site environment workers. We also will use simulated data since we will need to generate it anyway, as explained further below. The workflow will be similar to figure 4, but keep in mind that we start with a pretrained network and do not need to train from scratch. With this in hand we have all the necessary parts to combine it into a human detection algorithm around the crane truck.



(a) 0Zoom (b) 25Zoom

(c) 50Zoom (d) 75Zoom

Figure 3. View of different levels of zoom

3.2 Human Detection Load

The detection of humans around the load is more involved. The first problem is how and where to mount the camera system. The possibility of putting, e.g., cameras on tripods on the ground and then merging the images is not feasible due to the fact that the exact trajectory the load will take is often times adapted during the hoisting process. Therefore constant rearrangement of the tripods would be needed, which is not feasible. Another possibility would be to mount a mobile camera below the load, which is only practical with a wireless connection. This is also not feasible due to most loads containing lots of metal parts and therefore greatly interfering with the data transmission. Additionally one needs to consider the fact that a complete hoisting cycle may take up to several hours, which further solidifies the need for a wired connection because of the battery capacity of wireless cameras. So the only possibility which is left is to mount a camera on the crane itself. Of course many cameras could be mounted on the crane boom. We selected the boom top as a first choice, since for other locations at the boom additional need for an alignment with the load is present. This is not the case for the boom top due to the load being approximately perpendicular to the ground.

There are however some other problems arising from mounting the camera on the boom top. A crane can easily reach a height of $100m$, but the boom top may also be close to the ground depending on the hoisting process. So we have to deal with many different perspectives and distances to the ground. This greatly affects the size of the humans in the image. Therefore there is a reasonable necessity for a camera with controllable optical zoom in order to deal with these differing camera heights.

If however one has such a controllable zoom additional effort needs to be made in order to chose the zoom value accordingly. Of course a high zoom value is desirable since then the size of a human in the images is bigger. On the other hand a low zoom value gives us a wider view of the scene. Specifically for the crane scenario an additional limitation is the occlusion due to the position of the load. This occlusion will always be present, so we need to try and optimize the occlusion by adjusting the zoom level accordingly. The optimal zoom level is not only dependent on the pose of the boom but also on the position of the load, see figure 3. We therefore propose the following approach. We split up the zoom levels in discrete parts, for simplicity we here take the zoom levels of $0\%, 25\%, 50\%, 75\%$. For each of the zoom levels we want to individually train a CNN, called $Zoom0$, $Zoom25$, $Zoom50$, $Zoom75$. Each of the networks take images as inputs and we choose the same architecture for each of the networks. Training for each network will be done with its one appropriate dataset. We so to speak need a $DatasetZoom0$, $DatasetZoom25$, $DatasetZoom50$ and $DatasetZoom75$. Since such datasets are not publicly available we follow the workflow proposed in figure 4 for each network individually.

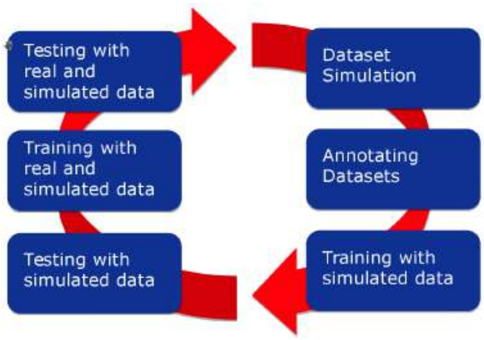


Figure 4. Proposed workflow for each individual network

Assuming this training is finished we take an additional network which we will call MetaNetwork, which differs in its architecture. See section 5 for a closer look at the architecture and the training process. This MetaNetwork will take the current image and the corresponding zoom level as input. Its output is then the proposed number of human each of the four Networks will detect. The idea here is, that the MetaNetwork can, e.g., due to a uniform texture, see figure 3, detect when the zoom level is too high and we have a lot of occlusion. On the other hand the MetaNetwork may notice that only a small amount of occlusion is present, but we are far away from the ground and therefore may say that a bigger zoom level may detect more pedestrians due to bigger humans. Then a deciding algorithm should determine what the appropriate zoom level is and also select the network accordingly. The whole architecture is presented in figure 5.

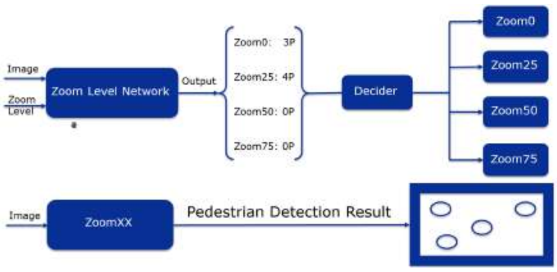


Figure 5. Complete architecture

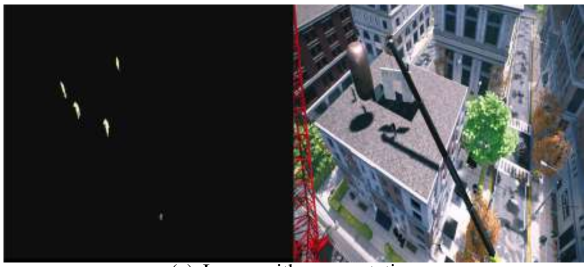
In its easiest form such a Decider could just take the network with the highest proposed number of detected humans. Also more sophisticated versions are possible, e.g., only switch after a certain amount of time has past to prevent constant switching or do not directly switch between *Zoom*0 and *Zoom*75. If all this is put into place we have an algorithm which gives an educated guess which zoom level to choose and then puts a detection network in charge which is specialized to exactly this zoom level.

4 Dataset Generation

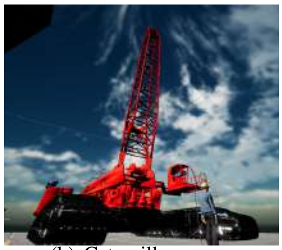
A common problem for Machine Learning in the context of commercial vehicles is the very small number of public datasets. A huge volume of image data is needed. The common datasets and benchmarks which are used in learning process of classification or object detection tasks, e.g., KITTI [12], Daimler [8, 11, 27], Caltech [7], INRIA [5], PASCAL [10], ETHZ [9] are not really applicable to our situation. So in order to generate the needed data we exploit a simulation tool, Unreal Engine 4. The idea of the approach is similar to [28]. Instead of training the human detector using only real-world image data. The Unreal Engine can produce realistic images of a construction site environment e.g different workers, different kinds of weather conditions such as snow, rain, cloud. For such effects see figure 6.

Also different times of day and therefore different lightning conditions are easily simulated. In the case of the construction worker, the tool allows us to create desired character appearance, motion or posture, based on motion capture data. Also different perspectives of the same situation, at the same time are possible. As we will see in section 5 we need to have the exact same situation with different zoom levels in order to get an objective ground truth for training the MetaNetwork. Data gathered in real-life would not be able to fulfill this constraint, since either the timing or the perspective of each zoom level would be slightly off.

The annotation of the synthetic data can be automatically achieved by an object instance mask plugin. In a dataset which is annotated by hand there is always a concern left, that the data may be annotated in a wrong manner. Manual annotation is a tedious task so one can not be sure to, e.g., not miss a human in the image or have slight errors in the localization of an object. All these concerns vanish with the use of automatic annotated data, since the simulation environment knows the ground truth and is therefore inherently objective.



(a) Image with segmentation



(b) Caterpillar crane

(c) Rain and snow

Figure 6. Examples of synthetic data generated from UE4: (a) Hoisting with the appropriate segmentation by the object instance mask, (b) and (c) are scene in construction site.

5 Learning Framework

In the proposed approach a couple of networks are involved. For the detection in each of the zoom levels and around the crane we just use a state of the art object detection network and adjust the trained weights with transfer learning, see [15] for a detailed look on the base architecture. The MetaNetwork needs to be constructed in a different manner. Since it does not only take the image but also the current zoom level as an input we can not simply use a standard architecture but have to adapt to this format. The proposed architecture can be seen in figure 7

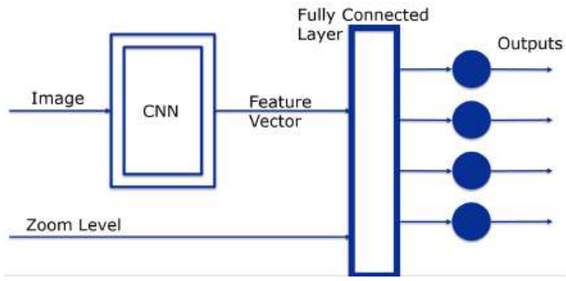


Figure 7. Network architecture of the MetaNetwork

So as we can see we first have a CNN, with nearly the same architecture as in the detection networks for each zoom level. We remove the last layers in order to just pass on the feature vector which is normally evaluated in the last layers of a network. We then connect this feature vector and the zoom level, encoded simply as an integer value, with a fully connected layer. Then the result of this fully connected layer will be given to our four desired outputs. The idea is that this MetaNetwork will deduce similar information as the detection networks but take the current zoom level into account and by that help to chose a suitable network. The training process will differ slightly from a normal CNN. Since the ground truth is the actual number of humans each of the networks detects, the dataset needs to reflect that. Therefore the dataset needs to contain 4 images, one for each zoom level, while the ground truth is the actual evaluation of each image by the corresponding zoom network. Then during training one of the four contained images can be chosen arbitrarily and the zoom level input needs to be passed on accordingly. This means that before we can train the MetaNetwork each of the specialized ZoomNetworks has to be trained sufficiently.

6 Conclusion and Future Work

Let us recap the approach presented in this paper. We defined a sensor setup which is able to detect humans around the crane truck and around the load. This camera setup contains standard monocular cameras and a zoom camera with a controllable zoom. Additionally we presented a CNN structure which is used for each of the mounted cameras individually. Then a meta algorithm, which is itself again a neural network yields a first estimation what an appropriate zoom level would be. According to this estimate the zoom level and the specialized network is chosen. After the proposed approach is evaluated a prototype system which is able to inform the crane operator about humans or other potentially endangered objects entering the working area is being developed

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BIM-based Surface-specific Solar Simulation of Buildings

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Abstract -

Photovoltaic (PV) solar energy is rapidly growing as an attractive alternative to fossil fuels. PV panels can harvest the solar power and turn it into a clean source of electricity. Traditionally, PV panels are only used on the rooftops of buildings. However, with the emergence of building-integrated solar panels in recent years, other surfaces on the building façade can be considered for the installation of PV panels. Given that different panels have different cost and performance profiles, it is of a cardinal importance to properly design the PV panels on the building facades to ensure a maximum benefit-cost ratio.

Existing simulation and optimization methods do not discriminate between different types of surfaces of the building and treat the building envelope as a set of polygons. This can result in under- or over- design since there is a strong relationship between the type of the surfaces and the type of PV panels that can be attached to them or integrated with them. The advent of Building Information Modeling (BIM) in recent years has provided a rich platform for object-based evaluation and analysis of buildings. Nonetheless, currently, BIM is not used for a detailed and surface-specific simulation of building surfaces.

In this research, a BIM-based method is developed for a detailed simulation of a building envelope using its surface properties. A prototype is developed using Dynamo visual programming platform to demonstrate the feasibility of the proposed method, and a case study is presented for a building in Montreal, Canada. In the light of the result of the case study, it can be concluded that the proposed method is promising in terms of providing the input for a comprehensive planning of the solar panel layout.

Keywords -
BIM; Solar Simulation; Building Façade

1 Introduction

The exacerbating global warming issues, on one hand, and the depleting fossil energy resources, on the other hand, are making the need for sustainable energy resources progressively palpable and vital. As one of the most promising options, photovoltaic (PV) solar energy is gaining growing popularity in recent years [1]. PV energy can be harvested using solar panels, and then transformed into a clean source of electricity that can be used in different industries. According to International Energy Agency (IEA) analysis, solar energy will provide 20-25% of the world electricity supply by 2050 [2].

Buildings account for up to 40% of the total energy use [3]. Therefore, the effective use of solar energy in buildings can tremendously contribute to the reduction of fossil energy. The increasing availability, affordability, and efficacy of PV panels are rendering them an attractive option for use in buildings. Traditionally, PV panels are only used on the rooftops of buildings. However, with the emergence of Building Integrated Photovoltaic (BIPV) in recent years, other surfaces of the building envelop can be considered for the installation of PV panels/films, as shown in Figure 1.

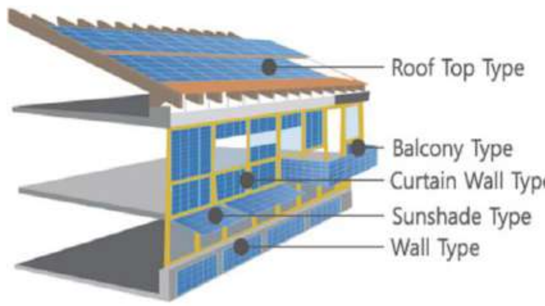


Figure 1. Different types of solar panels that can be used on building envelop

For example, using PV panels on balcony fences, or applying semi-transparent modules for designing glass ceilings or facades can improve the aesthetical aspects [4]. Some PV products such as amorphous silicon tiles can replace the common tiles on roofs. Other PV materials can be applied as shading panels or semi-transparent fenestration films in the design process of new buildings or the renovation of existing buildings. Given that different panels/films have different cost and performance profiles, it is of a cardinal importance to properly design their installation on building surfaces to ensure a maximum benefit-cost ratio.

The ultimate goal of the building solar design is to determine the number, type, location, and orientation of the solar modules on the building exterior surfaces considering the lifecycle cost of the modules. Many researchers have addressed the problem of PV panel layout design and optimization in recent years [5~10]. Nevertheless, the prerequisite to a reliable layout design/optimization is an accurate solar radiation model for estimating the amount of the annual solar energy that each surface on the building envelop can potentially generate [11, 12]. This model should capture the context of a building (i.e., location, orientation, geometry, surrounding buildings and vegetation, season, and weather conditions), to simulate the radiation potential. There are many different approaches for the simulation of the buildings' solar potential [13~17]. However, the majority of the available models work with either (1) 2D footprint of the buildings, or (2) approximated façades generated by the extrusion of 2D footprints. Both of these approaches are suitable for the design of PV panels for the horizontal surfaces (e.g., rooftops), and cannot be used for detailed analysis of vertical surfaces of the building. RADIANCE, Daysim, SORAM, SolarFlux, r.sun, ArcGIS Solar Analyst, and Sky View Factor are some examples of these radiation models [15].

The available methods are not suitable for a detailed planning of PV panels because the accurate 3D representation of the building envelop is not available; and thus, the radiation potential on the actual vertical surfaces cannot be calculated. In recent years, some researchers started to use 3D city models to consider the vertical facades [18, 19]. Nonetheless, while these methods can be used for the 3D simulation of the solar radiation, they are essentially geometric solutions that work with polygons and do not have the specific properties of the building objects. The disadvantage of these methods is that the distinction between different objects on the façade (e.g., balconies, curtain walls, windows, etc.) cannot be made easily. Accordingly, a detailed planning and optimization of PV modules where surface-specific characteristics are considered in a holistic way are not feasible.

On the other hand, the advent of Building Information Modeling (BIM) in recent years has paved the way for the integrated management of building data throughout its lifecycle [20]. Since BIM provides easy access to information of various elements of the building, it can be best used for various types of simulations such as daylight, energy performance, and solar radiation simulations [21~24]. In a recent project, an open BIM-based platform is developed for designing and simulating energy efficient buildings to integrate the simulations in the virtual design office [25]. Also a research project in Germany is trying to integrate the energy active components into the building envelope based on the methodology of the Building Information Modelling [26]. There are several software packages for solar analysis, such as ECOTECT [27] and Insight [28]. However, these packages transform the BIM 3D objects to a polygon mesh. During this process, the semantic information about different objects is lost. As a result, they treat the entire building envelope as a set of polygons with no distinction based on the object types. Consequently, the current tools are not geared toward the surface-specific solar analysis of the building, which is essential for a comprehensive design of PV solar modules.

Accordingly, the main objective of this paper is to develop a method for surface-specific solar simulation of buildings that can later be used for a comprehensive planning and design of PV modules. In this method, BIM and City Geographic Markup Language (CityGML) are integrated to capture both the object properties of a certain building and the surroundings of this building.

The remainder of this paper is structured as follows: first, the proposed method is explained in detail in Section 2. Then, the implementation and case study are presented in Section 3. Finally, the conclusions and future work are presented in Section 4.

2 Proposed Method

Figure 2 presents the overview of the proposed method. The main assumption of this method is that the BIM model of the target building and the CityGML model of the area are available.

This method focuses on the application of off-the-shelf solar simulation software. As a result, the goal is not to develop a new BIM-based simulation tool that can use the object properties and attributes directly in the simulation. Instead, the focus is on creating classes of surfaces that associate with different types of building objects (e.g., exterior walls, roofs, curtain walls, windows, etc.) using BIM capabilities. These classes can be used to run the existing simulation tools on the different classes of surfaces, and thus enable surface-specific simulation of the solar potential.

The BIM model can be available either at the design stage or use as-is modeling. Given that as-is BIM models

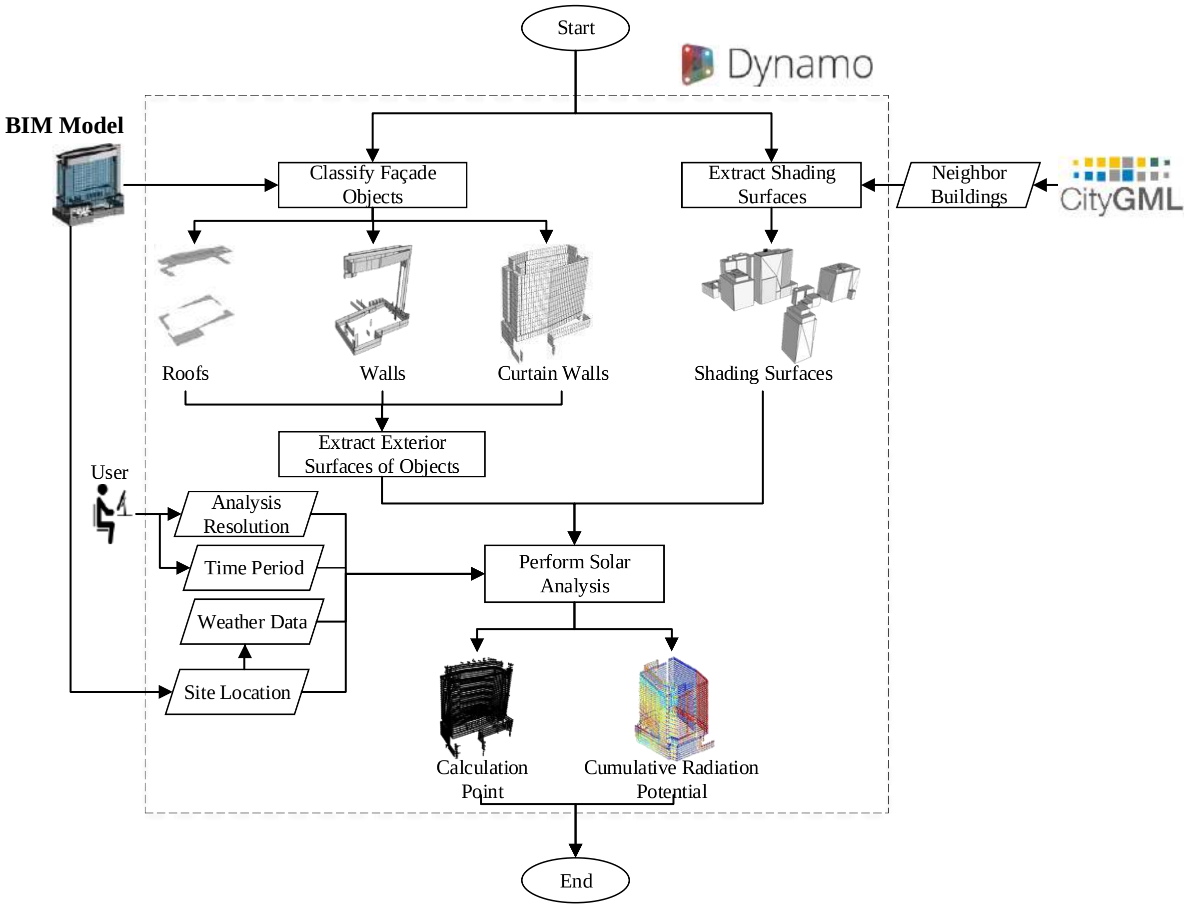


Figure 2. Overview of the proposed method

are not available for many of the existing buildings, as-is modeling is becoming popular in recent years using new technologies such as Light Detection and Ranging (LiDAR). Point cloud data captured by LiDAR can be converted into an object-based model manually or semi-automatically [29]. Although it is possible to scan the entire building (i.e., interior and exterior elements) with LiDAR and generate a complete as-is BIM model, it is -sufficient to generate the 3D model of only the exterior of the building for the purpose of solar potential simulation and PV panel optimization. This can expedite the preparation of the BIM model required for the proposed method. Unmanned Ariel Vehicle (UAV)-mounted LiDAR can be used to further facilitate this process [30].

For the purpose of PV panel planning and design, the Level of Detail (LoD) 200 would be sufficient. At this level of detail, the type and geometry (i.e., size, shape, location, and orientation) of building objects are known [31]. As per this criterion, the basic object detection and classification of the point clouds that can classify different object types (e.g., windows, curtain walls, etc.) and approximate their dimensions can be satisfactory. This allows the use of scan-to-BIM solutions, which reduce the amount of manual efforts required for the generation of BIM models [32, 33].

As shown in Figure 3, the BIM model provides the basis for the classification of different objects of the façade of the building. Depending on the types of the considered PV modules, the classification can be further expanded using the attributes of the elements.

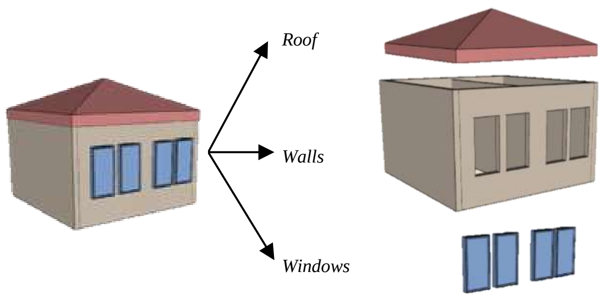


Figure 3. BIM-based classification of façade objects

For instance, the length and width of windows can be used to classify the windows into sub-categories based on their sizes. Such detailed classification helps to select suitable PV modules for the objects based on the materials or sizes of the objects. However, the consideration of detailed attributes in the BIM model (e.g., materials) may necessitate higher LoDs of the BIM model.

After the classification, all the objects in each class are decomposed into the constituent surfaces. For each object, only the exterior surface is kept and the remaining surfaces are filtered out as they are irrelevant for the solar analysis, as shown in Figure 4.

On the other hand, CityGML can be used to capture the surrounding of the building. As shown in Figure 5(a) many cities are already using CityGML to provide high-quality geo-referenced semantic models of their jurisdictions [34, 35]. Therefore, these models are becoming increasingly available for different areas.

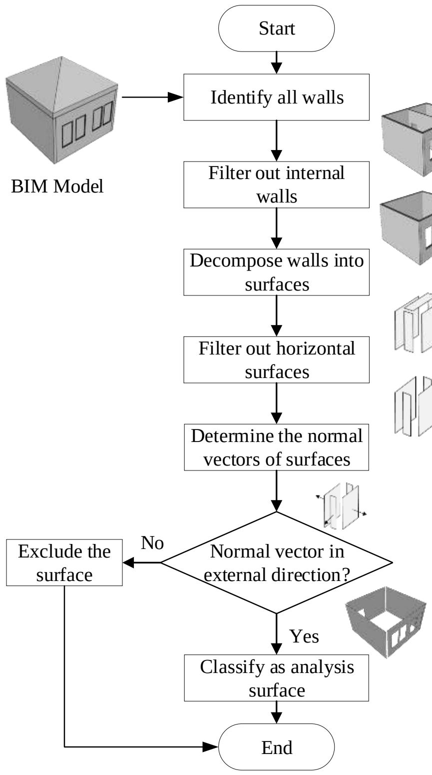
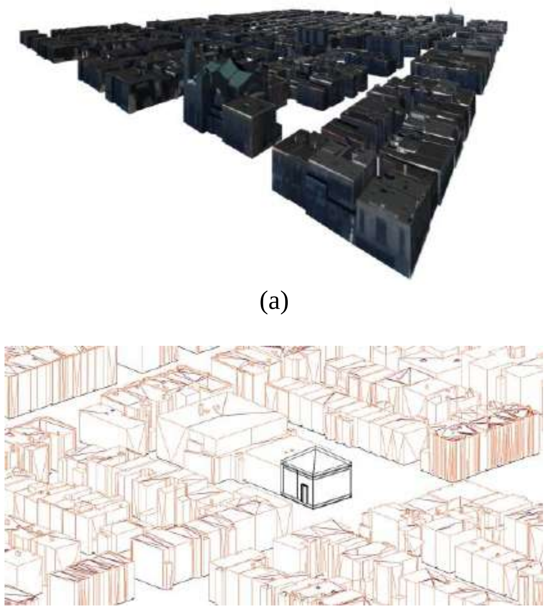


Figure 4. Flowchart for extraction of exterior surfaces from wall objects

The surrounding buildings are used to represent the objects that have shading effect on the study building. The CityGML model should be trimmed to include only buildings in the effective region of the building under consideration in order to reduce the computational effort of the simulation.



(a)

(b)

Figure 5. (a) An example of CityGML file of Montreal, (b) BIM and CityGML integration

The boundaries of the effective region are marked by the furthest buildings in different directions that can cast a shadow on the building under consideration. Whether or not a building has a shadow effect on the target building is a function of the height ratio of both buildings, the distance between the buildings, in-between obstacles, and their heights, and the orientation of buildings with respect to the true north. This calculation can be done in Geographic Information System (GIS) platforms, but it is outside the scope of the present research. Then, the CityGML model is merged with the BIM model of the building under consideration, as shown in Figure 5(b).

The next step after merging the surfaces of the buildings in one model is to run the solar simulation using off-the-shelf software (e.g., Autodesk Insight). In this step, a series of input from the user is required. Firstly, the resolution of the analysis should be specified, as shown in Figure 6(a). The resolution specifies how many calculation points on each study surface should be considered. The resolution should be selected based on the minimum size of the PV modules that are considered for the analysis and the available computational power.

The user needs to specify the time period of the simulation. While this period can be for any length and from any starting date, since the majority of PV panel optimization and design procedures are based on the annual solar potential, it is recommended to use a whole year for the time period. The site location can be obtained from the coordinates of the BIM model. Based on the location of the building, the weather data can be retrieved from national meteorological databases. Figure 6(b) presents an example of surface-specific simulation of solar potentials.

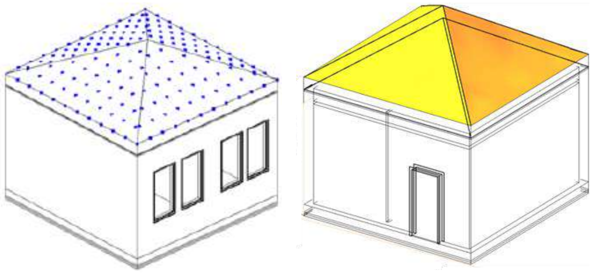


Figure 6. (a) Schematic representation of analysis resolution on the roof, (b) Surface-specific simulation of solar potentials

3 Implementation and Case Study

The proposed method is developed in a prototype implementation. In this implementation, Revit [35] is used as the platform for the BIM model. In order to implement the method in Revit, Dynamo visual programming is used [37]. Dynamo runs within Revit and works as an Application Programming Interface (API). As a result, Dynamo ensures a seamless integration with Revit. Also, it allows rapid coding within Revit and provides a seamless integration between the Revit model and various simulation tools. As an example, Figure 7 shows the implementation of wall object detection and surface extraction shown in Figure 4.

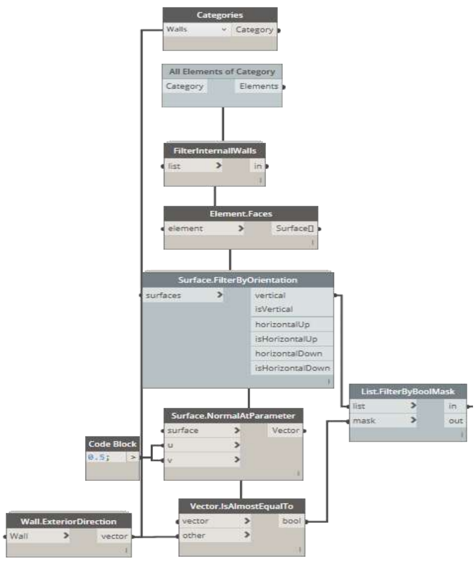


Figure 7. Implementation of wall detection and surface extraction in Dynamo

Similar codes are developed for other parts of the flowchart presented in Figure 2. It is worth noting that some of the nodes, e.g., FilterInternalWalls, are custom nodes that are developed by the authors. To test and validate the developed implementation, a case study is conducted. As shown in Figure 8(a), the case study is performed on Sir George William (SGW) campus of Concordia University in downtown Montreal. The building of John Molson School of Business (JM) is selected for the analysis because of its specific architecture, which includes curtain walls, windows, walls, rooftops, and projected horizontal surfaces at different levels. This complex architecture requires a detailed and surface-specific simulation of the building envelope. The BIM model of JM building is created and imported into Revit. Then, Revit Solar Analyst was used for simulating the solar radiation on the building surfaces. For this purpose, it is necessary to set the geographical location of the study area and define the true north of the buildings.

As shown in Figure 8(b), the city blocks around the JM building is extracted from CityGML model provided by the city of Montreal [32]. CityGML file is converted into a .fbx file and later merged with the BIM model as a unique *site* family in Revit.

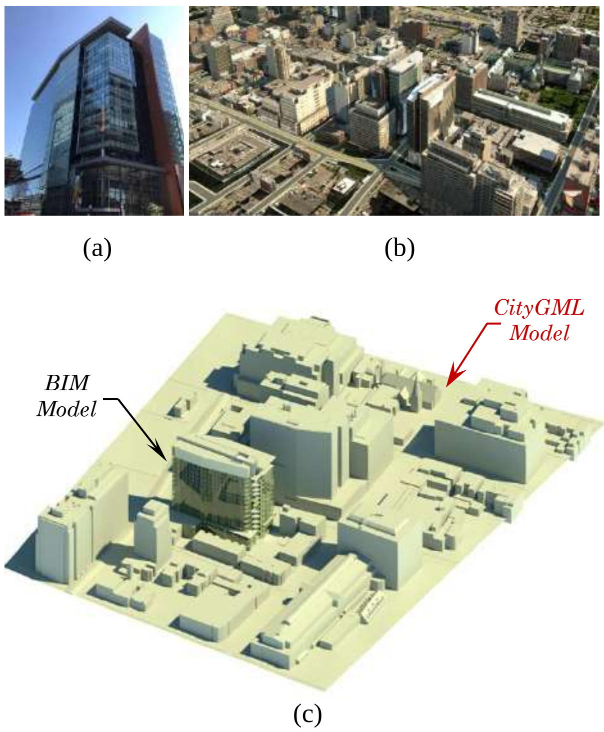


Figure 8. (a) JM building in downtown Montreal, (b) CityGML model of Concordia SGW campus, and (c) integration of the BIM Model and CityGML in Revit

Three classes of objects are considered for this case study, namely, roofs, walls, and curtain walls. Figure 9 shows the external surfaces of these elements. It is important for the implementation that elements are modeled using appropriate families and attributes in the BIM model. For the resolution of the simulation analysis, a grid with the spacing of 1 m is used, as shown in Figure 9(d, e, and f). The weather data is automatically determined based on the site location and the annual solar radiation is calculated for one year.

In the next step, the solar analysis is applied in Dynamo using the predefined node. The radiation value is then calculated for every single point on the grid of the classified surfaces. The corresponding values of the annual solar radiation for each surface type are then stored in a separate Excel sheet. These values are then imported into MATLAB to visualize the simulation results. The results of the simulation for each class of surface are shown in Figure 10. As shown in this figure, in line with the expectations, the higher floors received more radiation. Additionally, the backside of the building which was overshadowed by the surrounding buildings is receiving less radiation than the front side.

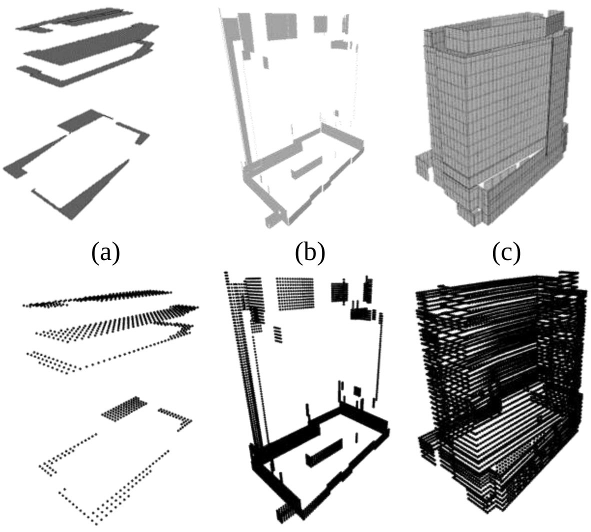


Figure 9. Extraction of external surfaces of (a) roofs, (b) walls, (c) curtain walls, and resolution of simulation analysis for (d) roofs, (e) walls, and (f) curtain walls

4 Discussion

Integration of the simulation results with Matlab to visualize the radiation values will facilitate the next step of the project to optimize the PV panel installation. Although this paper focused on a single building to perform the radiation analysis, analyzing multiple buildings can be done by combining several BIM models. In order to do that it is necessary to index each building based on its address to allow identification of building-specific surfaces.

5 Conclusions and Future work

In this paper, a BIM-based method is developed for a detailed simulation of a building envelope using its surface properties. The BIM model provided the basis for creating different categories of surfaces associated with different types of building objects such as exterior walls, roofs, curtain walls, and windows.

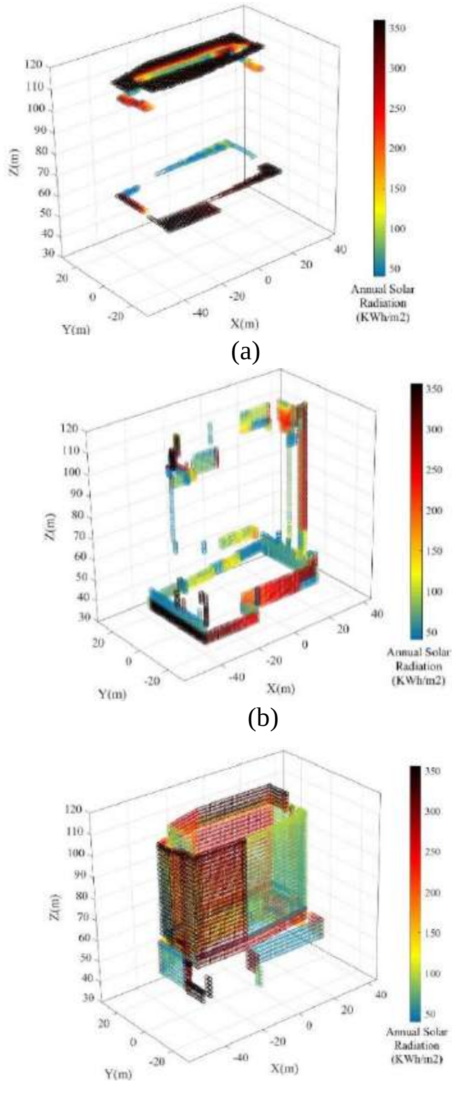


Figure 10. Visualized results of the solar radiation simulation for (a) roofs, (b) walls, and (c) curtain walls

A prototype is developed using Revit and Dynamo visual programming platform, and a case study is presented for a building in Montreal, Canada, to demonstrate the feasibility of the proposed method.

In the light of the result of the case study, it can be concluded that the proposed method is promising in terms of providing the input for a comprehensive planning of the solar panel layout. Future work will aim to optimize the installation of PV modules on building surfaces considering maximum energy generation and minimum life cycle cost of the modules.

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Automated progress monitoring of masonry activity using photogrammetric point cloud

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Abstract

Information retrieval and automated progress estimation of on-going construction projects have been an area of interest for researchers in the field of civil engineering. It is done using 3D point cloud as-built and as-planned model. Advancements in the field of photogrammetry and computer vision have made 3D reconstruction of buildings easy and affordable. But the high variability of construction sites, in terms of lighting conditions, material appearance, etc. and error-prone data collection techniques tend to make the reconstructed 3D model erroneous and incorrect representation of the actual site. This eventually affects the result of progress estimation step. To overcome these limitations, this paper presents a novel approach for improving the results of 3D reconstruction of a construction site by employing two-step process for the reconstruction as compared to the traditional approach. In the proposed method, the first step is to obtain an as-built 3D model of the construction site using 3D scanning techniques or photogrammetry in the form of point cloud data. In the second step, the model is passed through pre-trained machine learning binary classification model for identifying and removing erroneous data points in the captured point cloud. Erroneous points are removed by identifying the correct building points. This processed as-built model is compared with an as-planned model for progress estimation. Based on the proposed method, experiments are carried out using commercially available stereo vision camera for 3D reconstruction.

Keywords –

3D reconstruction, point cloud, as-built, as-planned, progress estimate

1 Introduction

Traditional monitoring of construction projects has always been manually driven process involving visual inspection and human judgment. This makes these methods slow and inaccurate, reducing the ability of infrastructure managers to monitor project performance indicators, including schedule and cost. These poor monitoring techniques are comprehended as one of the reasons for cost and time overruns in construction projects [1]. Importance of accurate and efficient progress monitoring have been reiterated by several researchers. Research establishes project monitoring as a critical success factor for in-budget completion of a construction project [2]. The time taken for identification of inconsistency between the as-built and as-planned model is proportional to the cost overrun and increased difficulty in implementation of the corrective measures in a project [3].

In the past, several automated methods of progress monitoring have been developed and tested by researchers and practitioners to enable better monitoring. Automated progress monitoring can be divided into four steps: (1) Data acquisition, which is capturing digital representation of as-built scenes, (2) information retrieval, this refers to extraction of useful information from the data collected without loss of any information required for accurate progress estimation, (3) progress estimation, this is a comparison between as-built model and as-planned model in order to determine the state of progress, (4) visualization of the results obtained via previous steps [4].

Recent advancements in the field of reality capture technologies, like, 3D imaging, laser scanning, in-situ sensing equipment, onboard instrumentation and electronic tagging, has made data acquisition possible for automated progress estimation. Moreover, developments in the field of machine learning and computer vision have made analysis of the acquired data efficient. While the impacts of these advancements are compelling, numerous challenges continue to persist. [5][6] These challenges prevent them from maturing into technologies that could be deployed to an on-going construction site for monitoring without human intervention. It can be alleged that there are no practices which offer automated analysis of construction data to estimate progress [4].

Thus, the goal of the study is to improve the result of progress estimate of a construction by generating a correct 3D reconstruction of construction. Considering the high variability in site conditions and data collection techniques, the method should be robust to these variations for any given site.

It should be noted that 3D reconstructed point cloud model is obtained using commercially available stereo vision camera. The process of 3D registration of images to produce point cloud is known to be error-prone, producing erroneous points with no correspondence in actual site [7][8]. Thus, data pre-processing becomes of paramount importance, involving outlier removal and noise filtering. But these methods are preliminary in nature and erroneous points continue to exist in the point cloud data. Therefore, there is need to identify these error points.

In this study, we work to improve the results of progress estimate of construction calculated by comparing as-built model, obtained using a commercially available stereo vision camera, and as-planned model. The research employs machine learning techniques for processing and refining 3D point cloud model before progress estimation is made. The processing involves detection of the masonry followed by its distinction from erroneous points. This is done to obtain a more accurate representation of the captured scene as compared to the output of 3D reconstruction. Subsequently, this processed as-built model is used for progress estimation by comparing it with the as-planned model.

In this paper, a novel method is proposed to classify between normal and erroneous points using machine learning techniques. "Normal" class representing points which correspond to constructed parts in the 3D point cloud model whereas "erroneous" class represents points which have no correspondence or correspond to parts other than constructed elements. In this method, a supervised binary classifier is built by training it over data collected. This trained classifier is used for identifying masonry points and thereby removing erroneous points from a point cloud, eventually producing better progress estimate. The study has been done for masonry construction, but can be extended to other types of construction.

2 Problem Statement

The aim of the paper is to develop an approach to reduce erroneous points generated in 3D reconstruction. Thus, it trains a classifier to reduce false positive in the 3D point cloud model reconstructed. The study also deals with the impact of the different site conditions like lighting, and different data collection parameters, like the speed of capture, yaw of the camera, the pitch of camera, etc. on the 3D reconstruction and progress estimate. The methodology developed needs to be independent of these parameters.

3 Review of the literature

Laser scanning and photogrammetry are two popular techniques for obtaining as-built point cloud of a construction site. Although laser scanning produces dense point clouds capturing tiniest details of the site, it is very costly. On the other hand, though the camera has the drawback of lower geometric accuracy; flexibility to use and cost-effectiveness makes them a favorable choice. Bohn & Teizer have explored advantages and challenges of camera-based progress monitoring [9]. The efficacy of stereo vision cameras to obtain as-built point cloud model using 2D images and depth map has been studied and proved by various researchers. [10]–[12]. Thus, imaging (stereo vision camera) system is used to obtain input for the as-built modeling stage.

The accuracy of reconstruction has a crucial impact on the progress estimate. The reconstructed models are highly corrupted with outliers and missing values because of imperfect conditions in which scanning is done, for instance, the motion of the object, multiple reflections, object occlusion, etc. Therefore, the output of the data acquisition step, that is reconstructed point cloud model, needs to be processed and analyzed before feeding to the next step of information retrieval and progress estimation. The standard tasks involved in pre-processing of point cloud data are (1) Outlier removal, (2) Handling missing value and (3) Reducing noise (or smoothening) of data [13]. For large point clouds, downsampling through voxelization is done, in order to reduce the computational time and cost.

Outlier removal for point cloud is a non-trivial task because of following reasons: geometrical discontinuities, no apriori knowledge of outlier distribution, and varying local point density [14]. Outlier removal methods in literature are mostly based on local properties of points, popularly calculated using density-based approach [15] and distance based approach [16]. Some of the local statistics are local point density, nearest neighbor distance, eigenvalues of the local covariance matrix, etc. [17]. Wang et.al, proposed connectivity-based and clustering approach for detection of outliers [14]. Similarly, the point cloud is processed for noise smoothening, involving noise filtering and point update.

The processed as-built point cloud is to be compared to as-planned BIM model for progress estimate. There are two ways to do the comparison: (1) convert the point cloud model in BIM model (involving semantic segmentation and object recognition) and compare, (2) convert the as-planned model to point cloud format and compare. In this paper, latter is adopted progress estimation.

It is worthy to note that in almost every data pre-processing techniques, no apriori knowledge of error (i.e. outliers) distribution is used. Thus, though these techniques help in cleaning data to an extent, they cannot

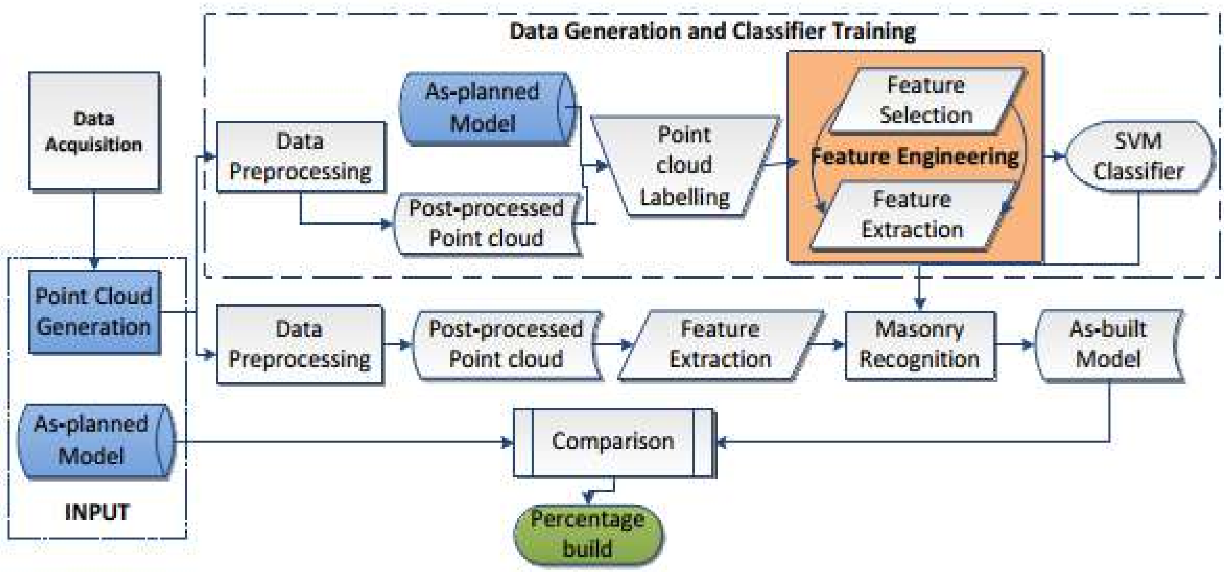


Figure 1. Proposed Methodology

remove incorrectly reconstructed points which are dependent on the methodology followed for reconstruction, data collection technique, and site conditions. In this paper, we propose a method to learn the characteristics of the construction materials and elements and use this knowledge to detect the same, and thereby removing the erroneous points. The erroneous points are detected using machine learning technique. This detection is posed as standard binary classification problem to classify between normal and erroneous points, which is solved by training a classifier based on local and contextual features (which are discussed in detail in later sections).

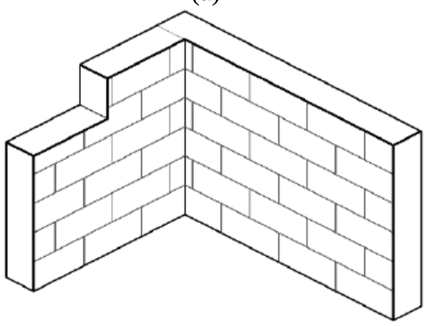
4 Methodology of Research

In this research, we focus to improve the as-built model reconstruction accuracy. In addition to, data pre-processing, the point cloud is subjected to supervised binary classification for construction material detection. This detection method has two-fold advantages – First, it eliminates the need to manually assign threshold values, which requires expertise. Second, it enhances the ability to scale the method, as this can be easily re-implemented after re-training. The proposed methodology excluding data acquisition and pre-processing (outlier removal and noise smoothing), can be divided into four components: (1) Data generation, (2) Feature Engineering, (3) masonry recognition using machine learning based supervised classification, (4) progress estimation and evaluation. Each of the above components are discussed in detail in the following sub-sections:

4.1 Data generation

This is the first step in the proposed framework. The input to this method is point cloud data and corresponding BIM model. The point cloud is annotated

(a)



(b)

Figure 2. A sample of 3D models used for data generation (a) as-built model showing erroneous points marked in yellow (b) as-planned model corresponding to the model in figure 2(a).

using BIM model as ground truth. Instead of following the common strategy for point cloud labeling, which involves over-segmenting the data and then assigning labels to segments. The data is annotated pointwise, considering two-fold advantages – (1) to avoid inheritance of error from segmentation step (2) to prevent classifier from learning hand-crafted rules of segmentation algorithm, when used for training [18].

3D annotation is done by manually comparing the point cloud model with the BIM model. The two models are overlapped and annotation is done view-by-view. A view is fixed and in this view, all the points lying within the boundary of BIM model, with a small tolerance value, are marked as normal while the rest of the points are marked as erroneous. This process is iteratively repeated for different views until all the possible views are covered. The problem with this way of annotation is that, same points appear in different views, appearing erroneous in one view and normal in another. To tackle this problem, a point is marked normal if it appears normal from all possible views and erroneous if it appears as erroneous from any possible view. Eventually, the point cloud is separated and labeled into two classes – “normal” and “erroneous”.

4.2 Feature Engineering

Performance of any machine algorithm is only as good as the ability of the features (or parameters) used to distinctly define the underlying distribution. In this regard, we attempt to learn a list of features which can be used to identify point corresponding to masonry in a point cloud. Rashidi et.al., realized three categories of construction materials depending upon appearance and color features[19]. Thus, discriminating features are learned for masonry data through an iterative process of, feature extraction and feature selection. The types of features learned are spatial and color, which are discussed below:

4.2.1 Spatial Features

These features are used to model the geometrical properties, like angles, distances, and angular variations, of masonry data. In a 3D point cloud, these features for a point in space is calculated by considering the spatial arrangements of data points in the neighborhood. The neighborhood can be assumed to spherical [20] or cylindrical [21] with a fixed radius. The neighborhood can also be selected based on k-nearest neighbor, depending on 3D-distance from the query point, where $k \in N$ [22]. For classification, spatial features were calculated for fixed radius spherical neighborhood. In order to obtain appropriate and uniform features across different data models, features are calculated at a fixed scale.

Neighboring points in a 3D model are known to be correlated and interdependent [23]. And therefore in order to capture this correlation, apart from individual features, some of the features are obtained which take this interdependency into consideration. Some of the features which are used are:

- **Individual**: Normal, local point density
- **Contextual**: Fast point feature histogram (FPFH) descriptor

FPFH descriptor is calculated in two steps: (1) for every point p, relationships are calculated between the neighbor and the query point, this histogram is named as simplified point feature histogram, SPFH. (2) In this step, for each of the query point, its nearest k neighbors are found, and FPFH is calculated using equation (1)

$$\mathrm{FPFH}(p)=\mathrm{SPFH}(p)+\frac{1}{k}\sum_{i=1}^{k}\frac{\mathrm{SPFH}(p_k)}{w_k} \quad (1)$$

where, k represents the number of nearest neighbors to a query point, w_k represents the distance between the query and the neighboring point.

Figure 3 illustrates the influence diagram of a point and highlights the neighborhood of a point which contributes the feature at that point [24]. These features are computed using Point cloud library [25].

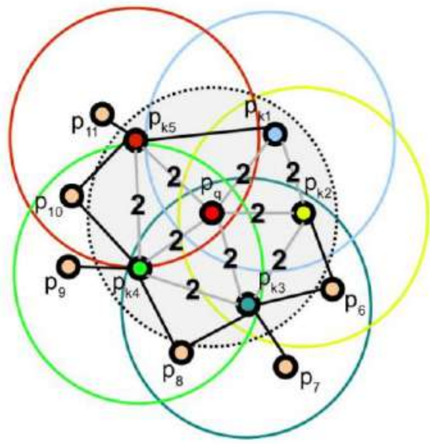


Figure 3. Influence diagram of FPFH to capture the interdependence of the neighboring points in the 3D point cloud [24]

4.2.2 Color Features

For the recognition of masonry, color values are very effective feature given its distinctive bright red color. It serves as an effective indicator for differentiating masonry from rest of the objects found on a construction site. However, it is worthy to note here that though the color value for a given does not vary drastically in a given point cloud, it might vary significantly when the same material is compared from two different point clouds, captured for different site conditions. This is illustrated in figure 4.

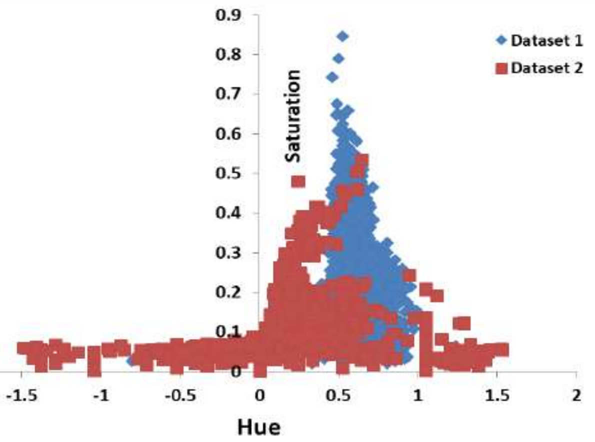


Figure 4. Hue and Saturation plot for two different datasets, collected under different conditions

The color values are obtained in the RGB space. Though these are most widely used color space, these RGB values are susceptible to a high variation on exposure to the same object under different illumination. And since illumination is an uncontrolled construction environment is ought to vary, dealing with these variations is highly important to produce effective results. Therefore, in this study, we have transformed the color space from RGB to HSI. It is compelling to make this transformation because: (1) it is very intuitive as it is similar to the way in which color is perceived by humans, (2) it separates the chrominance (color) and luminance (intensity) information, which has proved to be advantageous in image processing application. Hue (H) and Saturation (S) correspond to the color component of the RGB space, whereas Intensity (I) represents the illuminance-dependent part. Therefore, hue and saturation provide a good parameter for classifying masonry points from the rest. The color is changed from RGB to HSI using following equations:

$$H = \arctan \frac{\sqrt{3}\,(G-B)}{(R-G)+(R-B)} \tag{1}$$

$$S = 1 - 3\frac{\min(R,G,B)}{R+G+B} \tag{2}$$

$$I = \frac{1}{3}(R+G+B) \tag{3}$$

4.3 Masonry recognition

For the recognition of masonry in the point cloud, the pre-trained binary classifier is used. The following sub-sections explain the details of the classification.

4.3.1 Classifier training

An SVM classifier is trained over a training dataset generated using the method explained in data generation step. Instead of using voxel-based approach for training, a point-based approach is used. Despite the computationally costly and time-consuming nature of point-wise training, it is acceptable because: (1) it helps in improving recall values while detecting concrete points, (2) training is a one-time process, to be done during the setting up of the system. Hence, selection of the approach was done based on accuracy rather than computational cost.

Since the classification boundary was non-linear, Radial Basis Function (RBF) kernel was used. The parameters C and γ are to be determined for RBF kernel SVM model. C is regularization parameter and γ is kernel parameter [26]. In order to validate the results obtained using the training set, an independent validation set is used, which was obtained using a method similar to training data.

4.3.2 Masonry detection

The classifier obtained in section 4.3.1 is used for detection of points corresponding to masonry points in the post-processed point cloud. Features are extracted from the input 3D point cloud data (different from the data used for classifier training) depending on which classification is done. The point cloud is separated and classified as in two classes: “normal” and “erroneous".

4.4 Evaluation

For evaluating the performance of the system, two popular measures – Precision and recall are used.

$$\text{Precision} = \frac{TP}{TP + FP} \tag{4}$$

$$\text{Recall} = \frac{TP}{TP + FN} \tag{5}$$

Where, TP represents true positives, a number of points that are correctly predicted, belonging to the normal class, FP represents false positive, points which are predicted as normal but are actually erroneous, FN represents false negative, points which are erroneous but are predicted as normal.

5 Preliminary results

Based on the study, it is observed that colour features are distinctly different for both classes and therefore contribute most to the classification results. This is attributed to rich colour properties of a masonry construction. The erroneous points are observed to have low values of hue and saturation. The performance of the system with only colour features used for the training of the classifier is 69% in precision and 72% in recall. This result of colour acting as dominating feature in masonry detection is in coherence with different studies done in the past [12] [27].

The value of the evaluation metrics obtained in the preliminary study is given in Table 1. These results were obtained using all the features discussed in Section 4.2. The precision and recall values obtained are low in comparison to other studies which were conducted using 2D images as the dataset. These low values are the result of low point density in comparison to a high pixel density of an image. Moreover, training dataset used for training of the classifier was small in number. Therefore, these values need be improved further by using a larger training dataset, which is representative of the entire population of variations causing erroneous points reconstruction.

Table 1. Precision and recall value obtained from the test dataset

Metric	Percentage (%)
Precision	73.1
Recall	77.3

6 Conclusion and Future work

This study has presented an automatic system for information retrieval and progress estimation, with a goal to improve progress estimate by introducing a step of construction elements/material recognition. Masonry brick wall is used as a construction element in the study. The work needs to be extended to other construction materials/elements. A larger dataset needs to developed which can be used produce better results by employing data-intensive machine learning techniques, like tree family algorithms and deep learning algorithms. In future work, apart from geometric and colour features, texture features and other local geometric features needs to be explored in order to obtain better results. Although stereo vision-based imaging was employed for the study, the proposed methodology is expected to perform equally well irrespective of the technique used for data collection, as long as inputs are in the form of 3D point cloud with colour features. Moreover, detection of construction material can help in case of occluded scenes, where the building is to be separated from the rest of surrounding.

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Key Factors of an Initial BIM Implementation Framework for Small and Medium-sized Enterprises (SMEs)

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Abstract –

Building Information Modeling is the process and the technology transition from a traditional single sequential form to a modern multiple parallel form of data integration. BIM is the process of data sharing and distribution with the ability to employ the data via numerous applications for managing several multidimensional tasks and activities of AEC/OM (Architecture, Engineering, Construction/ Operation and Maintenance) throughout the building lifecycle. Indeed, employing BIM technology not only seems vital for small and medium-sized enterprises (SMEs) who are active in the construction sector of the building industry but also it is unavoidable for the firms who are seeking to increase their competitiveness and even their existence in the future era of the industry. The era of automation, robotics and 3D printing is coming faster due to the extraordinary developments and innovations in the digitalization and automation sectors, absence of desire productivity and efficiency in the building industry where BIM can efficiently provide the required information and accurate data to be used for model simulation and machine control in robotic construction.

However, most of the active SME contractors are not aware of building information modeling, nor are they familiar with the BIM implementation framework and its key factors. Therefore, the main aim of this article is to provide realistic key factors for an initial BIM implementation framework that can help the SMEs, who are working in the construction sector of the building industry such as contractors, to understand BIM as modeling and employ it with less costs and more efficiency.

Keywords –

Building Information Modeling (BIM); Building lifecycle; SMEs; Competitiveness; Building industry; BIM implementation framework; Automation and robotics;

1 Introduction

This research study encompasses a background on building information modeling (BIM), its importance for the building industry, the construction and particularly SME contractors. The importance of BIM in automation and robotics will be discussed too. Next, the problem and the research focus will be explained. Followed by, the research methodology covers the most relevant studies about BIM implementation, published in the last decade. Finally, key factors and an initial BIM implementation framework will be presented.

1.1 Background of BIM

What is BIM? A common question with numerous answers and definitions! BIM as a context is not a new phenomenon. In 1975 a building description system (BDS) was introduced by Eastman [1]. However, after popularity of the term "BIM", several definitions and explanations for building information modeling have been introduced. For instance, Laiserin indicated BIM as a process and not a software [2], while, Woo described BIM as a new methodology for building design and documentation that provides faster and easier construction process for all involved parties [3]. Similarly, Penttilä defined BIM as a methodology but for managing the digital format of design and project data during the building lifecycle [4]. Furthermore, Eastman et al defined BIM as a technology that allows the building digital and virtual models to support design process phases by the accurate geometry and data. This not only will support the fabrication, procurement and construction phases but also will be used for other phases and activities of the building lifecycle. Thus, BIM can facilitate a form of integrated design and process that marks higher quality and reduces costs and time of the project [5]. Furthermore, in 2007 the US National Building Information Modeling Standard (NBIMS) defined BIM as "BIM is a digital representation of physical and functional characteristics of a facility" [6]. Azhar [7] expressed BIM as a pattern within AEC industry that can boost integration of all stakeholders on a project.

Although there is not a common consensus among researchers, software developers and practitioners, it is possible to distinguish an immediate difference between BIM as "modeling" and BIM as "a model". Nevertheless, BIM as a model can be derived a product of building information modeling. BIM as modeling is the process and the technology transition from a traditional single sequential form to a modern multiple parallel form of communication and data integration. In addition, building information modeling is the process of data distribution and data sharing with the ability to employ the data via numerous applications and tools for managing several multidimensional tasks and activities throughout the building lifecycle. A related point to consider is that in practice, current building information modeling and BIM software as well as BIM tools have their own limitations and challenges particularly for existing buildings and renovation that requires more research and development activities [8] [9].

1.2 Importance of BIM

There are familiar questions that the industry practitioners, specially contractors, ask such as "Why should we employ BIM?" or " What are the benefits of BIM?". In this section and through the next paragraphs, the BIM importance and its impacts on the building industry as well as its future use for the automation and robotics will be discussed.

1.2.1 BIM and the Building Industry

It is well known that the building industry is a late majority adopter or even the laggard adopter of new technologies, processes and methods in comparison with, for instance, the aviation industry. This lack of willingness to change, throughout the past decades, have created significant levels of time waste, quality decrease and profit loss as well as duplicating activities and repeating mistakes for the industry [7]. In addition, the construction industry has not been fully employing new innovative opportunities [10]. A very good example of the industry's hesitation to use the latest technologies, which is significant to be addressed, is BIM implementation, particularly, in the SMEs.

However, the building industry in general and the SMEs in particular demand for an effective and more integrated management during the initiation phase to the closing phase of a project. In addition, construction industry should seek for productive time, higher quality and fewer costs as well as try to avoid the parallel and unnecessary activities. Furthermore, eventually, the industry will ask for automation as unique solution to the lack of sufficient efficiency, mass production, labors and professional workers. Finally, the industry should intensely consider reducing waste materials and using recycled products and materials.

Although BIM has been introduced for years, for many the SMEs in the building and construction sectors BIM is yet to be recognized as a modern 3D software. On the other hand, BIM has several direct and indirect impacts on the building industry. Same as any other new technology, BIM brings advantages and disadvantages for its users. However, it has been confirmed that employing BIM will increase a firm's ROI (Return of Investment) which means more profit for the company in a long term [11]. Additionally, Barlish and Sullivan (2012) [12] developed a method for analyzing and quantifying BIM benefits, value, impacts and outcomes. The metrics, investment and cost, were tested against multiple cases on BIM based projects and traditional based projects. The results reveal that actual ROI varies depended on each project but for BIM based projects, there is a high potential of benefits. In addition, according to the NISB report, only in the national level, an estimated cost of inadequate data interoperability in the US capital facilities industry is approximately $15.8 billion dollars annually [13].

Furthermore, in a project level, the lack of interoperability increases costs of projects up to 3,1% of total project costs in the building industry [5] which is shown in Figure 1. Nonetheless, this is likely to be a small portion of the cost showing only the top of the industry's cost "iceberg". Consequently, it is not far from reality that the costs of inadequate and poor data management and interoperability consist billions of dollars of many countries' GDPs per year, globally. Furthermore, the study of using BIM in different stages of a building lifecycle shows that BIM is mostly used just in early stages and the use of BIM decreases while a project is progressing to the next stages. It is also found that BIM collaboration and process create positive impacts on projects. Also, clients as well as facility managers can benefit from BIM [14, 15].

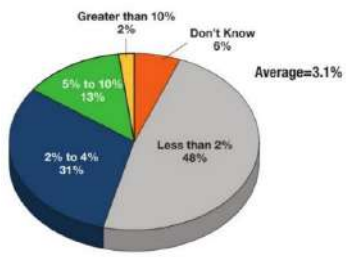

Figure 1. Total AEC/OM cost of non-interoperability, adopted from [5]

Thus, BIM is an essential technology for the future construction processes and the SMEs who have started to employ BIM will experience a higher level of competitiveness and technical improvements. Besides, BIM users will experience faster delivery, enhanced quality and efficiency in the projects [16] [17]. On the other hand, employing BIM requires new investments and some changes of the firms' organizational structure and culture [12, 18]. Possibly, in the long term BIM may change the industry's lifecycle management too. However, the indirect impact of BIM can benefit and help a wide range of other fields such as saving energy, waste materials, CO_2 emission and natural recourses and it can increase sustainability [17] [19].

1.2.2 BIM and Automation

The building industry is seeking potential solutions to the current problems. Problems such as high costs, traditional time consuming tools and methods, low quality, high waste, labor difficulties, high risk, inefficiency, low sustainability and low productivity [20]. Alternatively, the developments and innovations in the ICT, digitalization and automation sectors of the building industry are visible such as automated equipment and methods [21]. Thus, based on that, it is not out of imagination that inevitably the industry will employ more automated processes and automatic machines in the near future for mass production too. However, while BIM and digitalization are booming among the industry practitioners, automation and employing robotic technology as well as 3D printing are scaling. This will gradually motivate and seize attention of more contractors and innovation organizations who are active in the construction section.

On the other hand, dimensional control and identification are required for exploiting automation [22] and BIM can efficiently provide the required information and accurate data to be used for model simulation and machine control in construction automation and robotic construction. Therefore, BIM's importance and effects on the future usage of automation and robotics in the industry not only appear strong but also, in the long run, they are inevitable for the firms who are seeking to increase their competitiveness [20], productivity [23] and even their existence in the future era of the building industry.

1.3 Problem Statement and Aims

Regardless of considerable development of BIM based tools, still AEC/OM firms, particularly the SMEs, hesitate to employ BIM so its technical and financial benefits are not fully employed [16] [24]. On the other hand, according to the EU user guide to the SME definition, about 90% of enterprises and over 67% of jobs are generated by the SMEs. The SMEs include a broad category of companies from micro to small and medium-sized enterprises comprising less than 250 employees and a turnover of less than 50 million Euros annually [25]. Thus, due to the significant number, role and effect of the SMEs on the building industry in general and the construction market in particular, it is essential to address the issues, the BIM technology and its implementation framework to the SMEs.

The problem is that most of the active SME contractors are not aware of building information modeling, nor are they familiar with the BIM implementation framework and its key factors to increase their competitiveness. Thus, the main aim of this article is to provide the realistic key factors for an initial BIM implementation framework that can help the SMEs, who are working in the construction sector of the building industry such as contractors and sub-contractors, to understand BIM as modeling and employ it with less costs and more efficiency.

2 Methodology of the Study

This study is mainly based on a literature review on BIM implementation in the AEC sectors of the building industry with more emphasis on BIM adoption for contractors in the construction sector of the AEC/OM industry. In order to achieve the goal successfully, first the most related factors of a successful BIM implementation will be explored through the literature review from the past decade publications. Then a proposed solution as an implementation framework will be provided in order to increase the practitioners' general knowledge of BIM and the factors related to BIM implementation. This must be mentioned that likewise any other research, the framework is limited to and will focus on SME contractors in the construction section. Figure 2 illustrates the general view of the study structure including the problem statement, the aims, methodology and anticipated output.

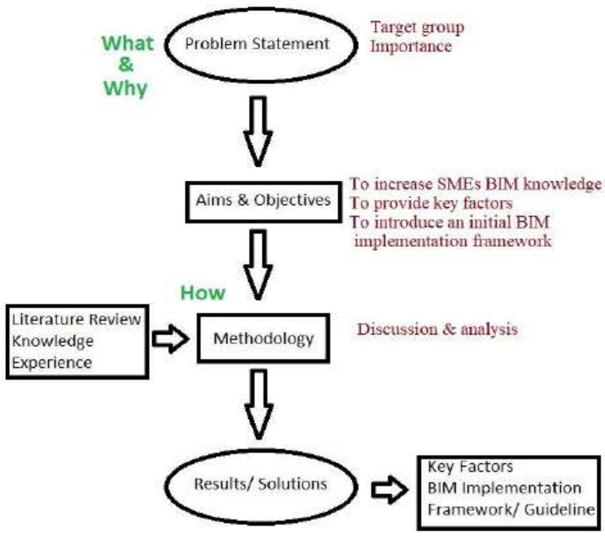

Figure 2. The research structure

2.1 Literature Review

To establish a related context of this study on BIM implementation, a selected literature review of the most relevant publications of the last decade of BIM implementation and adoption studies is provided. Table 1 illustrates a summary of the literature review.

In 2006, Brucker et al [18] offered a strategic BIM implementation plan for USACE (the U.S. Army Corps of Engineers) in order to improve the processes of design, planning and construction. The proposed BIM implementation plan, for the designing phase, is as follows:

- Gather up the current design team including the managers and the designers to define the current process and the responsibilities for the transition
- Assign a BIM team, including the design team and the lead technicians, to create and organize a BIM action plan including tasks, processes, metrics, expectations, BIM vision and team's needs
- Technical and organizational training by workshops based on the staff's role and responsibilities are required

Arayici et al (2009) [26] identified the BIM implementation challenges and factors by surveys in the UK and interviews in Finland with the construction stakeholders and academics. The study indicates that BIM implementation requests considerable changes of organizations and processes. However, in order to decrease resistance to change and build the process of implementation, training of BIM technology and BIM based tools are essential. This also, includes the change of redefining HR (Human Resource) system of the organizations, their responsibilities and the working processes. According to the study, the main challenges and barriers for BIM implementation are as follows:

- Lack of sufficient knowledge of BIM technology and BIM definition
- Unwillingness to employ the new technology and train/ lack of trained staff
- Lack of demand
- High costs of implementing that cannot cover the costs and make benefit
- Low rate of return of investment (ROI) which requires longer time to make BIM beneficial

Nonetheless, a paper published by Succar (2009) [27] describes an ontology of the BIM domain concepts and identifies the conceptual parts of BIM and main BIM activity fields. The main BIM activity fields are introduced as process, technology and policy that partially share deliverables (e.g. regulations, standards, construction products and services, software, hardware and equipment) and players (e.g. designers, engineers, contractors, manufacturers, technology developers, owners, operators, legal bodies, researchers).

In addition, Gu and London (2010) [28] conducted a FGIs (Focus Group Interviews) research study on the focused group of architects, engineers, contractors, BIM consultants, academics and software vendors for BIM adoption in the building industry. They found that besides various implementation levels, based on practical knowledge of BIM, there are mainly two types of issues as technical and non-technical that can affect BIM adoption and technology diffusion among the building industry. The technical issues comprise technical tools and software whereas the non-technical issues are related to work practices, strategies and processes.

Jung and Joo (2011) [29] addressed the variables for a BIM framework consisting of three main dimensions as BIM technology (dividing into four categories including standards, data properties, relation and utilization), BIM perspective (of industry, organization and project) and construction business function (design, contracts, estimation, scheduling, planning, materials, safety, quality, administration, finance, HR, cost control, sales and R&D).

Besides, Khosrowshahi and Arayici (2012) [30] provided a roadmap for BIM implementation in the UK to be used at operational and managerial levels. According to their suggestions, in BIM implementation, firms should consider three factors, including organizational culture, information management and training.

Following, Eadie et al (2013) [14] established an analysis of BIM implementation showing that BIM can be used throughout all stages of a building lifecycle. They found that the stakeholder collaboration aspect is the most effective factor following the process, as it is more important than software besides training. The two barriers are the lack of training and the industry experience of BIM. Takim et al (2013) [31] studied factors of BIM implementation in the AEC industry at two levels, the national level and organizational level in Malaysia. The study revealed several factors can create gaps for the implementation such as product limitation and interoperability, technical support and process change, economic demand and people acceptance, perceived usefulness and ease of use.

An analytical study by Miettinen and Paavola (2014) [32] presented that local experimentation, continued learning, standards and guidelines have a main role in BIM implementation. In addition, for BIM implementation, Morlhon et al (2014) [33] established an interaction model based on some critical factors such as reengineering business process, standardization, external stakeholders involvement, education whether technical and or information management as well as system selection process. Meanwhile, Peter Smith (2014) [34] examined the issues of BIM implementation in the construction industry. The results of the study show that leadership and government support, national and global standards, liability and legal issues, research, education and training as well as business impacts and opportunities have critical role on BIM implementation.

In 2015, Lindblad and Vass [35] investigated the changes, in three areas of product (model), organization (resources) and process (work practices), required for BIM implementation initiating in a large public infrastructure organization in Sweden. Furthermore, Son et al (2015) [36] studied the drivers of BIM adoption in design organizations of AEC industry aiming to examine the factors enabling the adoption process by the architects. What they found show that computer self-efficiency, top management support and subjective norms are the critical factors to make the adoption useful and ease for the architects. Risto Tulenheimo (2015) [37] introduced several key challenges and obstacles of BIM implementation generated by customers/ clients (demand, procurement skills and contracts), companies/managers (vision and strategy, management's will and competence, and ROI), organizational behavior (change resistance, education and training, project organization) and technologies (such as hardware, software) in Finnish construction industry.

Table 1. A summary from the literature review

Fields	Technology	Process	People		Organization		Policy
Factors/ equivalnt parameters	Tools (software & hardware)	Work process & team collaboration	Training & need (HR, organizatioan)	Resistance to changee	Investment (costs, ROI)	Risks & Challenges	Standards, Regulations , legal issues
Brucker et al, 2006 [18]	○	○	○			○	
Arayici et al, 2009 [26]		○	○	○	○	○	
Succar, 2009 [27]	○	○	○				○
Gu and London, 2010 [28]	○	○				○	
Azhar, 2011 [7]	○	○	○	○	○	○	○
Jung and Joo (2011) [29]	○	○	○		○	○	○
Eastman et al, 2011 [8]	○	○	○	○	○	○	○
Khosrowshahi and Arayici (2012) [30]	○	○	○	○	○	○	○
Eadie et al (2013) [14]	○	○	○				
Takim et al (2013) [31]	○	○		○	○		
Miettinen and Paavola (2014) [32]			○				○
Morlhon et al (2014) [33]		○	○			○	○
Peter Smith (2014) [34]			○		○	○	○
Lindblad and Vass (2015) [35]		○					
Son et al (2015) [36]	○					○	
Tulenheimo (2015) [37]	○	○	○	○	○	○	
Bui et al (2016) [38]			○		○		○
Cao et al (2016) [39]			○		○	○	
Hosseini et al (2016) [40]					○	○	
Ghaffarianhosein et al (2017) [16]	○	○	○		○	○	

Bui et al (2016) [38] studied the issues preventing BIM implementation in developing countries. The factors of current BIM adoption are mentioned as technical, perspective (including lack of standards and professionals, legal issues and governmental support) and construction business function (including unclear benefits of BIM). Cao et al (2016) [39] conducted a research on social and economic motivations for BIM adoption in construction industry projects in mainland China. They suggested that BIM users will experience more economic motivation while BIM is maturing. Also, there is relation between organizational ownership and BIM implementation motivations. Additionally, Hosseini et al (2016) [40] studied that the main obstacles to BIM implementation is the lack of clients' and subcontractors' interests and that the SMEs' key stakeholders recognize higher risk of investment and uncertain ROI. However, it is indicated that in Australia the main barrier is not lack of resources and knowledge.

Finally, in 2017, Ghaffarianhoseini et al [16] studied current BIM adoption, its benefits, risks and challenges. The study revealed that lack of adoption is due to factors such as cost, ROI, demand and interoperability issues (software, skills and experience). They suggest that in order to have a successful BIM implementation, firms need to invest in training, software, hardware, an internal process development and business development based on BIM technology. Table 1 shows a summary of the BIM implementation key factors adopted and or are equivalent from the literature review.

3 Discussion on the Key Factors

In order to understand the challenges and issues, we define fields and factors or equivalent parameters. Each field points a group of factors addressing challenges and essential needs that can affect BIM implementation. Although the BIM implementation studies show various approaches and viewpoints of challenges and factors by the researchers, the most cited factors can be divided into five main fields as people, technology, process, organization and policy. The first four fields are showing inner layer factors of firms and the policy field shows an outer layer field that indicates the influences that other organizations and enterprises can make on firms, such as policy makers and governments covering e.g. legal issues, national standards and guidelines.

Figure 3 shows the BIM implementation key factors distribution cited in the literature review and their frequent citations in percentage. The most cited factors are belonged to the organization field, the people field, the process field, and the technology field followed by policy field including standards, regulations and legal issues with 32%, 25%, 17%, 15% and 9% respectively.

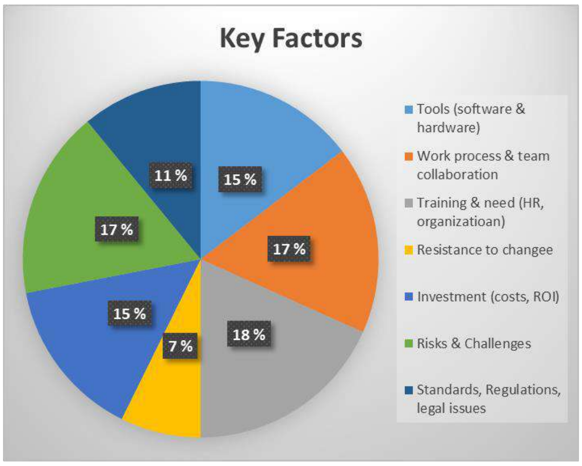

Figure 3. BIM implementation Key factors distribution

The people field includes training human resources (HR), organizational culture and change management issues. The factors of people are challenging parameters that can affect a successful adoption too. The process field is the roadmap of how the technology and people execute the activities and tasks. The technology field indicates the factors including tools, software and hardware. Without appropriate hardware and required software BIM implementation cannot be practically executed. Nonetheless, people, technology and process fields are parts of organizations that decision makers are involved with financial factors such as investments, costs and ROI as well as organizational risks, challenges of business changes and processes.

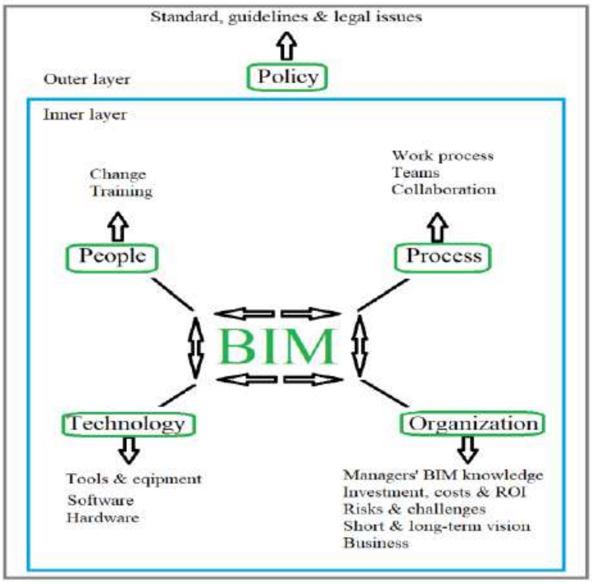

Figure 4. The key factors and BIM fields

Figure 4 illustrates how BIM is centered in the inner layer creating a common source and the outer layer as policy. However, the four internal fields are interconnected and can affect each other.

4 BIM Implementation Framework

BIM implementation is a complex process, due to the mentioned various factors being involved in the implementation process. This article attempts to point out the common aspects applicable to SME contractors. Regarding the similarities and differences between design, construction and service firms, the other firms, with some modifications, can also benefit the presented system to design their own frameworks.

Figure 5 shows an initial BIM implementation framework presented by this study for the SMEs. The framework consists of three main steps and each main step includes some sub-steps addressing challenges, activities, planning, communication, integration and collaboration under the fields of organization, people, process and technology. The first step consist two parts. The first part is targeting that managing directors, boards and shareholders of the SMEs fully understand BIM challenges and impacts. They are ready to change the firms' long-term strategy from the current form to an integrated form, invest in the BIM based business, and work model. The second part is related to the middle level mangers such as directors and managers of technical sectors, ICT sectors, business sectors and financial sectors. They are responsible for change management in their sections, addressing challenges, legal issues, security issues and discovering new business opportunities as well as short-term targets for the firms and assigning BIM teams.

The second step is planning step and the BIM team including current team members should analyze current processes of activities, human resources and tools in order to design new processes based on BIM technology and tools. This is crucial to communicate the progress of this step and send the feedbacks to the organizations for adopting and supporting new decisions aligned with the short and long-term strategies. This step also can benefit current available standards and guidelines for BIM implementation, depends on their availability.

The third step is piloting what has been planned in the second step. The output of second step supports people, process and technology to be employed in real work places. For instance, during bidding phase the teams can prepare quantity takeoff list (QTL) and cost estimation by the 3D parametric models and BIM based software instead of using traditional means. However, constructability and clash detection are feasible and an accurate construction plan can be obtained. In the execution phase, work activities, timetable and scheduling as well as site and risk management are considered more accurate by using BIM based project managing software and other tools like virtual reality (VR) and augmented reality (AR). For the monitoring phase tracking activities, verification and guidance are covered. In order to review and reorganize the involved processes, people and technology for each piloting step the feedback and results as well as challenges should be reported to the BIM team. The circulation of information, feedbacks and knowledge between the three steps supports the system to improve the framework and acquires more advantages from it.

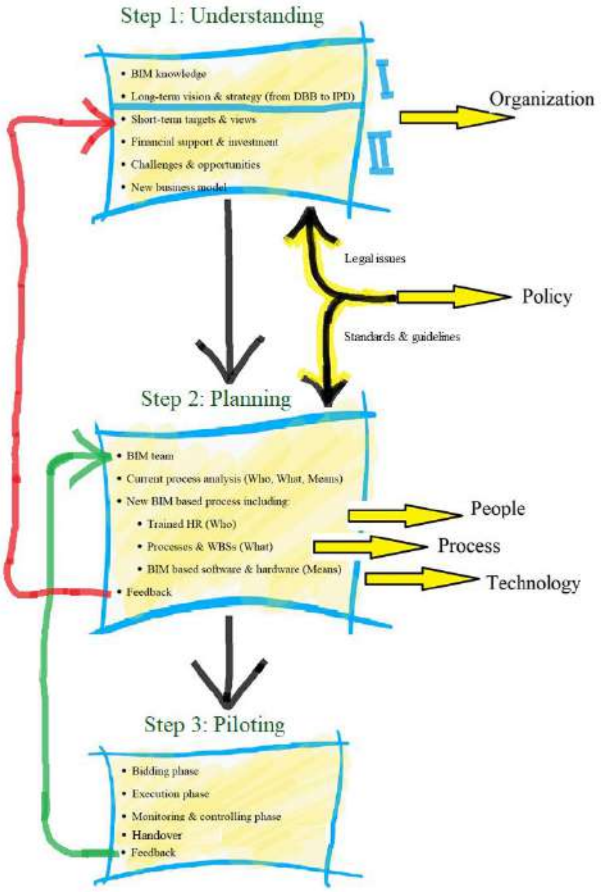

Figure 5. Initial BIM implementation framework

5 Conclusion

In this article, the authors have tried to define and introduce BIM as a modeling system, which can increase ROI and competitiveness of the SMEs and in the near future will be an essential approach and tool in the building industry. Additionally, BIM in the building industry and the current necessity of BIM implementation as well as the future role of BIM in automation and robotic construction were discussed. However, as the main aim of this article, a simplified initial implementation framework for SME contractors was introduced. The authors expect that this article to help the SMEs to understand BIM as modeling and employ BIM with less costs and more efficiency by knowing the key factors of the implementation framework and strengthening their competitiveness.

Finally, this study is limited to an initial BIM implementation framework for SME contractors and has not categorized the SME firms so as a future research proposal a more detailed investigation on the BIM implementation framework for different types of construction firms via real cases can be conducted.

Acknowledgment

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Image-based 3D Building Reconstruction Using A-KAZE Feature Extraction Algorithm

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Abstract

The development of 3D reconstruction from 2D building images enables cost-effective and accurate acquisition of spatial data. Feature extraction is a fundamental technique for 3D reconstruction method. However, buildings mostly consist of planar surfaces whose entities are feature-less. This study presents 3D building reconstruction using A-KAZE feature extraction algorithm. Because A-KAZE algorithm does not use Gaussian blurring like SIFT and SURF, A-KAZE algorithm has potential to extract correct visual features for feature matching and 3D reconstruction. The proposed method was tested on actual building scenes acquired from a high-resolution camera. The experimental results showed that the A-KAZE algorithm can detect the sufficient number of features with low computation time. It is expected that the proposed method can be implemented in comprehensive 3D reconstruction of civil infrastructures.

Keywords –

3D reconstruction; feature extraction; A-KAZE; binary descriptor; structure from motion; photogrammetry

1 Introduction

The demand for 3-dimensioanl (3D) reconstruction of a building is increased over the last decade in the field of the Architecture, Engineering, Construction and Facilities Management (AEC&FM), with the purpose of collecting as-built spatial data. As-built spatial data can be used for a variety of applications including inspection of defects [1], building performance assessment [2], and document updates [3]. Traditional approaches of collecting spatial data like manual measurement with visual inspection and total station survey are not only labor-intensive and time-consuming, but also inaccurate because such measurements become highly dependent on the skill, experience, and expertise of the workforce. A potential alternative to these conventional approaches, therefore, is a laser scanning technology, which can generate 3D point cloud data of a structure promptly with a high level of accuracy. However, in spite of the distinctive advantage of this remote sensing technology, its use is limited by its expensive cost and requirement of highly skilled operators. To overcome this challenge, image-based 3D reconstruction has drawn attention because of its ease of use, inexpensive cost, and higher accessibility with the development of computer vision-based techniques.

Structure from Motion (SfM) is a photogrammetric method that generate 3D point cloud data using multiple images acquired from different view angles [4], which is an equivalent principle to a human's ability to perceive a 3D structure from 2D projection. To estimate the intrinsic and extrinsic parameters of camera and to reconstruct a 3D geometry, SfM method uses a process of finding corresponding features from the images. So far, numerous feature extraction algorithms have been proposed in the field of computer vision and image processing since extracting and matching such pairwise features among images are the key steps of SfM method [5]. However, using only visual features to reconstruct a 3D scene is a challenging task. Recently, many researchers have used different types of geometric entities as visual features to estimate the parameters of camera. The most commonly used visual feature is the point-based feature, also known as interest-point or keypoint. Since point-based methods have significantly high time complexity, lines and planes are also used as high-level visual features [6]. These visual features can be found on building scenes, whose objects are mostly consisting of planar surfaces. However, high-level visual features are commonly variant to changes in orientation of scenes and illumination information [7].

Recently, retrieval algorithms with localized keypoint are widely used in 3D reconstruction techniques. The keypoint is mostly detected on regions with significant variation in edges and keypoint descriptors are invariant to orientation changes of images acquired through different angle-view. In computer vision, several 3D reconstruction commercial software packages have emerged to gain robustness and enhance efficiency of extracting features from images.

During recent decades, Scale-Invariant Feature Transform (SIFT) [8] algorithm has been perceived as the most common choice for feature detector and descriptor. However, SIFT and Speeded Up Robust Feature (SURF) [9] exploit Gaussian scale space which blurs the details with noises to equivalent extent and does not preserve boundaries of an object [10]. Since buildings have elements with sharp edges like wall and roof, other alternative algorithm is needed rather than SIFT and SURF. Otherwise, manual optimization of miss-matched image pairs is required when using an unreliable feature extraction algorithm. Barazzetti et al [11] presented 3D reconstruction method to obtain accurate point clouds automatically. This study evaluated the performance of SIFT descriptor on different sizes of test images. The evaluation results showed that computation time increased considerably when the size of the image was increased.

This study presents a 3D reconstruction method using A-KAZE feature extraction algorithm for finding pairwise features from building images, to generate an accurate 3D points clouds automatically. A-KAZE is a non-linear scale space-based algorithm that has a great potential of preserving sharp boundaries of buildings' elements. In this study, the comparative analysis among SIFT, SURF, and A-KAZE has served to evaluate each algorithm as a feature detector and descriptor. To achieve a practical implementation, a typical building has set to be a target for 3D reconstruction.

2 Methodology

Accelerated-KAZE (A-KAZE) feature detector and descriptor, which is proposed by Alcantarilla et al. [12], uses nonlinear scale spaces to extract corresponding features of images. This algorithm is developed from KAZE algorithm [13] by embedding mathematical Fast Explicit Diffusion (FED) in pyramidal structure to speed up the nonlinear scale space computation. In comparison to Gaussian scale space of SIFT and SURF, nonlinear scale space can extract corresponding features of images while maintaining details and reducing noises by means of nonlinear diffusion filtering. Moreover, the computational complexity $O(n^2)$ (where n is the number of input images) of A-KAZE is lower than that of SIFT and SURF [14].

A-KAZE is mainly comprised of three steps: a nonlinear scale space building with FED, feature detection, and feature description. The first step is to define a set of evolution times for building the nonlinear scale space. Then A-KAZE detects the feature points that are the local maxima of the determinant of the Hessian matrix using nonlinear scale space. Finally, given feature points are represented by Modified-Local Difference Binary (M-LDB).

In the first step, A-KAZE builds pyramidal structure of nonlinear scale space. The scale space is discretized into a series of octaves (O) and sub-levels (S). The set of octaves and sub-levels are identified by discrete octave (o) and a sub-level (s) and they are mapped to their corresponding scale (σ) as shown in equation (1).

$$\sigma_i(o,s) = 2^{o+s/S},\ o \in [0...O-1],\ s \in [0...S-1],\ i \in [0...M] \quad (1)$$

Where M is the total number of filtered images. Then the set of discrete scale levels in pixel units is transformed into σi time units because nonlinear diffusion filtering is defined in time term as shown in equation (2).

$$t_i = \frac{1}{2}\sigma_i^2,\ i = \{0...M\} \quad (2)$$

Moreover, the input image can be convolved with a Gaussian blurring of standard deviation σ to reduce noise and possible artefacts. From the filtered input image, the contrast factor (λ) is computed in an automatic way as the 70 % of the gradient histogram. To overcome the main drawback of KAZE which is its high computational cost, FED scheme is embedded into the pyramidal structure.

In the second step, feature points which are local maxima are detected from the filtered images (Li), by computing the determinant of the Hessian matrix in the nonlinear scale space. Hessian matrix of the images is computed by a normalized scale factor as shown in equation (3),

$$L^i_{Hessian} = \sigma^2_{i,norm}(L^i_{xx}L^i_{yy} - L^i_{xy}L^i_{xy}) \quad (3)$$

Then the determinant of the given Hessian Matrix is computed to find local maxima points at each evolution level. The pre-defined threshold for potential local maxima points is set to be a window of 3×3 pixels. The computation is implemented efficiently by discarding non-local maxima points. These candidate points are recalculated to determine whether the points are maxima by comparing each point form i+1 and i-1 evolution level. Finally, the given maxima points are assigned to be feature points.

A Modified-Local Difference Binary (M-LDB) is employed as a feature descriptor in A-KAZE. The M-LBD descriptor follows the principle of a LDB descriptor [15] that computes binary strings for image patches using gradient and intensity information from non-linear scale space. In the LDB descriptor, each image patch is divided into various sizes of n×n grid cells and those partitions are efficient to compute average intensity. However, the LDB descriptor is sensitive to rotation of image patches that requires high computational cost. Thus, A-KAZE achieves a scale and rotation invariance by scale-dependent sampling and estimating the main orientation information. The M-LDB uses horizontal and vertical derivatives from detected features to construct the descriptor.

In this study, a brute-force method is employed for efficient feature matching. The brute-force approach finds corresponding features from multiple images in different angle. The process mainly consists of three steps: comparing binary descriptors and testing ratio, using estimators to compute fundamental matrixes, and using epipolar constraint for eliminating outlier matches. Then, only inlier matches are exploited for homography estimation by using random sample consensus (RANSAC) method.

3 Experimental Results

To demonstrate that A-KAZE algorithm is an optimal feature extraction algorithm for building scenes as a feature detector and descriptor, a comparative analysis has presented. OpenCV library is used for implementation of feature extraction and matching algorithms, with the default parameters. The test images of building's wall surface are captured by a Zenmuse Z3 camera equipped in a Quadcopter DJI Matrice 100 (see Figure 1). Resolution of the images are ultra-high-definition of 4000×2250 pixels (4K). Since the size of the building is incompatible to any other objects, 3D reconstruction is needed to be facilitated by using images of high resolution to provide a 3D model with valuable and practical information for building operators.

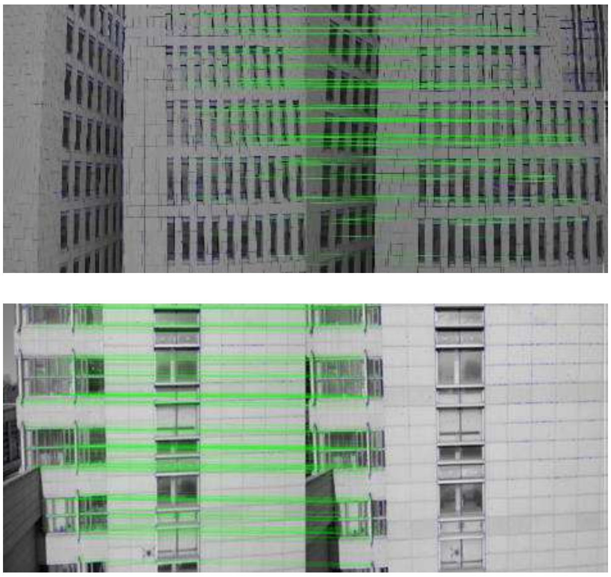

Figure 1. Exemplar images of feature extraction results of building scenes

Table 1. The results of feature extraction and matching of building scenes. The highest values are indicated in bold.

	Detected keypoints	**Matching score**	**Computation time (sec,)**
SIFT	2051	26.09	6.88
SURF	**16603**	16.26	11.06
A-KAZE	3317	**32.47**	**5.91**

As shown in Figure 1, keypoints are sufficiently detected and matched. The results also imply that A-KAZE algorithm reliably extracted corresponding keypoints from building scenes whose objects had poor-textured surface. Table 1 presents the matching results of Figure 1 using SIFT, SURF, and A-KAZE. As presented in Table 1, the matching results indicate that SURF algorithm detected the highest number of keypoints from the images and for the matched features. However, SURF algorithm showed the lowest matching score among algorithms. Although SIFT algorithm showed compatible matching score result, the number of detected keypoints and matched features are relatively lower than other algorithms. A-KAZE algorithm achieved a stable performance in detecting keypoints with the highest matching score.

Since feature extraction and matching are repetitive processes on many multiple images in 3D reconstruction procedure, computation time is a critical determinant. The time complexity for computing A-KAZE algorithm is presented as the lowest among the three algorithms, as shown in Table 1. These results potentially imply that A-KAZE is an optimal algorithm for extracting and matching correct features from building images.

Figure 2 is a result of 3D building reconstruction of which surface is poor-textured. The 3D reconstruction model is generated by 43 sequential images of 4K resolution using A-KAZE algorithm. The result presents a similar scene to its source images. This potentially imply that A-KAZE is an optimal algorithm for extracting and matching correct features from building images.

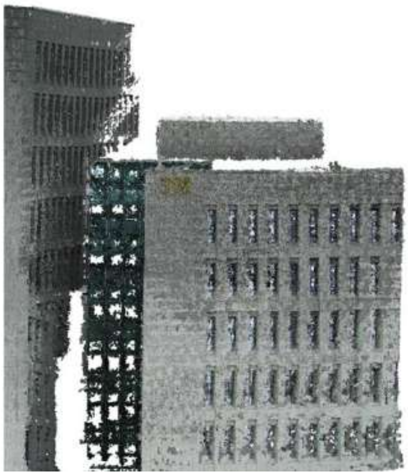

Figure 2. Exemplar images of 3D reconstruction of building

4 Conclusion

This study presented a 3D reconstruction method using A-KAZE feature extraction algorithm to detect correct corresponding keypoints and to reconstruct accurate 3D point clouds of buildings automatically. Because buildings mostly consist of texture-less elements with planar surfaces, conventional feature extraction algorithms encountered challenges. To solve this problem, A-KAZE feature extraction algorithm was employed in this study. To assess the performance of A-KAZE algorithm as feature detector and descriptor, analysis of detecting and matching results has conducted. The results presented that A-KAZE algorithm reliably and efficiently detected corresponding features from high-resolution building images which were acquired in different view angles. This study, thus far, contributes to establishing a comprehensive 3D reconstruction method for buildings.

Acknowledgements

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Integrating parametric design with robotic additive manufacturing for 3D clay printing: An experimental study

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Abstract –
This paper presents an ongoing work in relation to the development of a parametric design algorithm and an automated system for additive manufacturing that aims to be implemented in 3D clay printing tasks. The purpose of this experimental study is to establish a first insight and provide information as well as guidelines for a comprehensive and robust additive manufacturing methodology that can be implemented in the area of 3D clay printing, aiming to be widely available and open for use in the relevant construction industry. Specifically, this paper emphasizes on the installation of an industrial extruder for 3D clay printing mounted on a robot, on toolpath planning process using a parametric design environment and on robotic execution of selected case studies. Based on existing 3D printing technology principles and on available rapid prototyping mechanisms, this process suggests an algorithm for system's control as well as for robotic toolpath development applied in additive manufacturing of small to medium objects. The algorithm is developed in a parametric associative environment allowing its flexible use and execution in a number of case studies, aiming to tentatively test the effectiveness of the suggested robotic additive manufacturing workflow and their future implementation in large scale examples.

Keywords –
Parametric design; Robotic additive manufacturing; Robotic control; Toolpath planning; 3D clay extruder

1 Introduction

The term Additive Manufacturing (AM), also commonly known as three-dimensional (3D) printing, is used to describe the process of material deposition in layers, leading to solidified products. The technology of AM has gained considerable attention the last few decades and today has succeeded to be a rapidly growing field worldwide with a number of technologies available for public use. This direction of investigation has been thoroughly explored and various methods have been introduced and discussed [1]. To name a few, these might include Fused Deposition Modeling (FDM), Selective Laser Sintering (SLS), Inkjet Powder Printing, etc. [2, 3]. A number of advantages have led the manufacturing industry to introduce such technologies into daily production, which include the freedom to create any morphology without the application of molds [1], the minimization of material waste, etc.

Today, we have reached a stage where AM technologies are available for industrial and household applications in reasonable prices or even are available for reproduction through open source platforms and mechanisms [4]. Nevertheless, any selection of specific technology and its application contains particular limitations and constrains. These might include limitations in regard to the size of working area, leading to print results in small scales, constrains in regard to the type of material used, the type of mechanisms as well as the methods applied.

When tasks refer to the 3D printing of small to medium scale objects, these can be largely solved with available industrial technology. However, an area that faces limitations in large extend in terms of AM implementation is the construction industry, where the necessity for manufacturing building parts or even complete structures in actual scale, demands more thorough and comprehensive procedures that take into account actual construction parameters. In addition, due to the multiple and complex tasks involved during the construction of a building, including the need for specific technique and materials implementation [1], the introduction of open source and custom platforms for additive manufacturing is more than a necessity in order to allow direct and flexible intervention of automated mechanisms according to the large scale objective under investigation.

Large scale AM and particularly its application in construction industry is an area that is rapidly growing with many examples attempting to introduce techniques derived from 3D printing principles for the production of houses in full scale, for instance the 3D Print Canal House in Netherlands [3]. Towards this direction several attempts to provide such technologies have been conducted, especially in the area of concrete printing. Such works date back to the well-known Contour Crafting (CC) technique [5] and later to the introduction of other techniques, for instance D-Shape [6], Concrete Printing [7], Additive manufacturing of concrete [8], CONPrint3D [9], and so on. Although, similarities can be found in the abovementioned technologies in regard to their objectives, differences can also be observed, mostly it terms of material deposition and control automation processes. The techniques of Concrete Crafting and Concrete Printing as well as similar directions of investigation are based on the layer-by-layer deposition of concrete materials with the application of gantry and mounted nozzles [5, 8, 10], while technics like D-Shape follow principals similar to the Inject Powder Printing [6]. Beyond the obvious opportunities that innovations in large scale AM can bring to the construction industry, numerous advantages might be offered, which include reduction of construction cost and time, minimization of errors during construction, etc. [11]. Also, might allow issues related to the local and ecological aspect of material use to come to the fore [12, 13, 14], an area that lies within the broader field of sustainable construction, currently under consideration. This direction, together with the introduction of digital fabrication, for instance 3D printing in large scale, can reduce the environmental impact of structures [15].

In addition, recent attempts towards the introduction of advanced technology in Architecture, Engineering and Construction (AEC) industry, for instance, the use of digital design and modelling tools including Building Information Modelling (BIM) and parametric associative design or the application of robots and automation mechanisms in fabrication process, open new opportunities for integrating design to production processes. This might allow a more thorough and complete investigation, both in terms of the selected designs to be realized due to the ability of BIM and parametric tools to allow their real time control and modification prior to their actual construction according to a number of criteria (environmental performances, constructability, etc.). Also, this might include a more flexible and customized processes for controlling output data for construction of non-standard morphologies and later on their physical execution using automated and robotic construction systems [16, 17, 18]. In addition, advanced tools and mechanisms allow a more productive and open source approaches [19], which can be applicable to the construction industry, advantages that are necessary to be acquired during an AM process in actual scale.

However, in order to complete a fully operable system for 3D printing, knowledge in regard to the software and hardware installation are necessary, an area that is not always accessible by the majority of architects or constructors. In this paper, an attempt to overcome such limitations is conducted by introducing a robotized method for hardware installation and toolpath planning process that can be easily available and can be adopted by people involved in similar research directions. Further prospects are, by using similar principles, to extend the scale of additive construction, aiming at their implementation in various scales with emphasis on large scale manufacturing, an area that currently is in the forefront of the research conducted in our laboratory for sustainable robotic construction [12].

Within this framework, and by following similar principals [16], this paper presents a methodology for integrating parametric design and robotic additive manufacturing, aiming to be applied in, both small/ medium and large scale 3D clay printing tasks [13, 14]. The process aspires to promote the sustainable aspect of the material evolved but also to stress the advantages carried out in the design and construction industry by integrating parametric tools with automated construction technics.

The structure of the paper is as follows; in the next section the methodological framework is briefly explained; then, analytical descriptions in regard to the installation process of the industrial 3D clay extruder and the robotic calibration are given; afterwards, the toolpath planning development process, the robotic control and finally the robotic execution are demonstrated by testing a number of case studies; and finally, conclusion is drawn.

2 Methodological framework

As it has been mentioned, the aim of this ongoing study is to develop a robust and reliable methodology that will allow the integration of parametric design with robotic additive manufacturing mechanisms for 3D clay printing. This, in combination with the application of clay material, which promotes the ecological aspect of the suggested methodology, aspires to provide a sustainable and custom/open source platform that can be applied in different case studies. Such cases might include printable objects range from small/medium to large ones, using them as individual building elements in the construction industry.

Analytically, the proposed methodological framework considers all necessary actions required to embed the selected automated mechanisms for 3D clay printing in the overall automated construction system. Also, is designed to include all necessary steps required for a complete workflow procedure from design to production with emphasis on toolpath planning process and robotic control.

Initially, the installation of an industrial 3D clay extruder, and specifically the Clay Kit with LDM Wasp Extruder by WASP [20, 21] is embedded in the construction system and particularly is mounded at the end of an industrial robot ABB 600-20/1.65 with IRC5 controller. The industrial extruder consists of two main parts, the clay pump that extrudes the material and the 3D clay extruder that is responsible for the deposition of material in layers. The installation of the mechanisms as well as the robotic system calibration are necessary parts for an accurate and effective 3D clay printing procedure. This, in combination with the need for an inseparable workflow that achieve the parametric development of the objects to be built, the toolpath planning generation and subsequently the robotic control for robotic execution, consists all necessary steps towards a complete and integrated methodology.

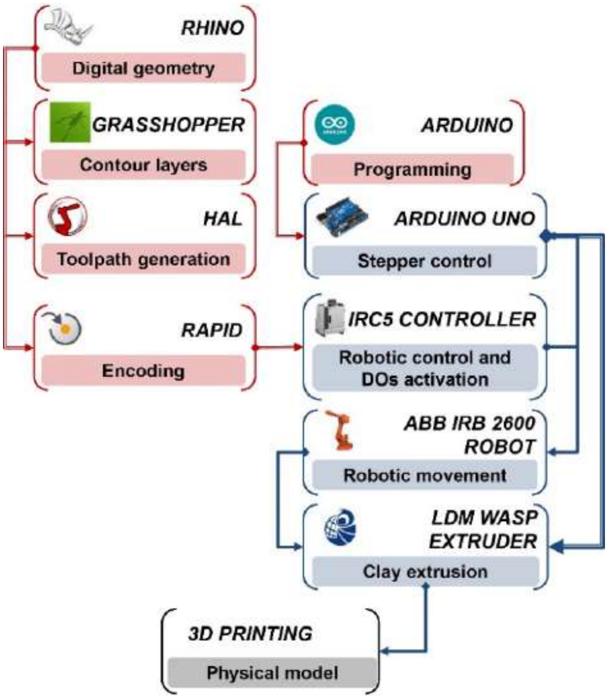


Figure 1. Methodological framework in the form of diagram for the 3D clay extrusion system development

In regard to the installation of the industrial 3D clay extruder, a number of sub-components consisting the overall system are studied and carefully mounted on the robotic arm. These include the clay pump that is responsible for continuous clay material feed to the clay extruder (nozzle) and the 3D clay extruder with nozzle that is responsible for extruding clay material and for layer deposing according to predefined width and height. As regards the toolpath planning process, similarities with other conventional [22] or advanced parametric tools and platforms [23] used for toolpath planning, which are introduced in additive manufacturing can be found. In this case, due to the parametric nature of the customized/open source platform that is introduced, the implementation is achieved in the parametric design environment of Grasshopper software [24] (plug-in for Rhino [25]). This enables the development of various morphologies in digital form that can be easily modified and parametrically control, offering large number of design possibilities. After the digital geometry is developed in the parametric environment, this is sliced based on contour-layer development algorithm, leading to the toolpath generation. Simultaneously, 3D print parameters are embedded to the digital geometry related to the width and height of each contour (filament) and according to the clay material mixture applied. Then, the HAL software [26], a robotic control plug-in for Rhino, is used to produce all necessary data in RAPID code and in turn to be executed by the ABB robotic arm. The following sections describe, in detail, the main steps of the suggested workflow procedure (Figure 1).

3 Installation of 3D extruder and robotic system calibration

3.1 Overview of the automated construction system

The robotic system consists of four main parts, where its synchronization aims at creating a process that will allow 3D clay printing of various complex and non-standard shapes. The system consists of the following parts:

1. The cylindrical tank for clay feed connected with the industrial clay extruder.
2. The industrial clay extruder that consists of one stepper driver that rotates an auger in the form of a rotating helical screw inside a cylindrical chamber, extruding the clay through 1mm nozzle.
3. The on-off switch and flow rate control board for the industrial 3D extruder that is run through an Arduino board, which controls a stepper motor driver.
4. The industrial robotic arm ABB 600-20/1.65 with IRC5 controller.

As it has been mentioned, the automated system is run in the parametric environment of Grasshopper in conjunction with HAL, which allows parallel control of robotic arm movement and activation of the industrial 3D clay extruder. As a result, clay is fed to the extruder at the edge of the robotic arm through the provided clay tank. Important aspect towards a seamless printing process is the accurate/functional design and programming of the automated clay printing control system.

3.2 Design and installation of 3D clay extruder system

Initially, an acrylic base functioning as the supportive system of the industrial 3D extruder is designed, fabricated and finally mounted at the end of the robotic arm. The suggested design solution allows undisturbed ventilation of the stepper motor, easy connection with the industrial clay extruder system, and simple assembly and disassembly of the mechanism for maintenance purposes. The acrylic base is attached to the robotic arm through a supportive steel blade with four screws, which also encloses the industrial 3D extruder fixed with two screws. Figure 2 shows the tool adjusted on the robot.

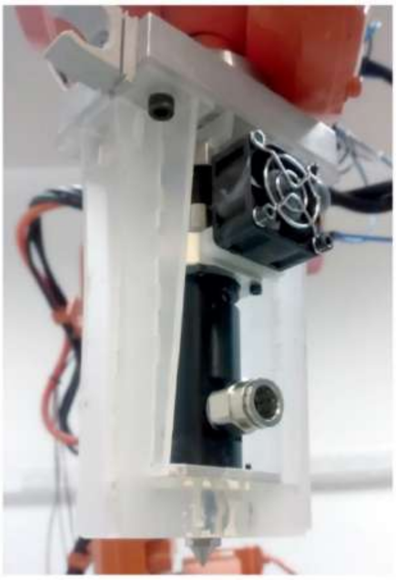


Figure 2. The industrial extruder with the supportive system mounded on the robotic arm

In order to feed with material the extruder at the end of the robotic arm, the cylindrical tank is filled with clay that is provided by the manufacturer [27]. By pushing air pressure into the tank, the piston is activated and pours the clay that is inside. The clay is passed to the cylindrical chamber of the industrial 3D extruder through a plastic pipe. In order to activate the industrial 3D clay extruder through its stepper motor, a stepper controller is used for rotation movement. The programming of stepper controller (CNC Single Axis 4A TB6600 2/4 Phase Hybrid Stepper Motor Drivers Controller) is achieved in Arduino environment using an Arduino UNO board. The programming allows pulse rate control in order to adjust the rotational direction and speed of the stepper motor. For powering the Arduino UNO board and the stepper driver, an external power supply is used. With the use of a Siple Pole Double Throw Toggle Switch (SPDT), it is possible to activate the Arduino UNO directly from the power supply or through a relay connected to the power supply and controlled by the IRC5 robotic controller. The use of switch allows manual preparation of the system for printing and automatic control through the control of robotic arm. Finally, the board for system's control is placed on the robotic arm (Figure 3).

Figure 3. The 3D clay printing control system mounted on the industrial robot

3.3 Robotic system calibration

In order to achieve accurate and automated 3D clay printing process, the control of material flow from the pneumatic piston to the nozzle is important to be examined. The Arduino UNO board is programmed to control the rotation of the stepper motor at a constant and continuous rotational speed, which achieve the movement of clay material into the chamber and then its exit from the nozzle. As it has been mentioned, the Arduino board is powered by an external electrical source that is connected to a relay on the robotic arm controller. By activating the relay, the Arduino operates and controls the flow of clay. When the relay is switched off, the clay funneling stops. The on/off control of relay occurs in real time using the HAL plug-in. The activation or deactivation of nozzle funneling is based on the generated toolpath that is derived according to the digital shape under investigation.

A significant aspect in the printing process is the calibration of the robotic arm movement with the clay extrusion speed. This is done by observing the results derived from initial case studies, where several changes in robotic movement speed occurred. During the case studies execution, the robotic movement is controlled using the Teach Pendant, allowing determination of its right speed. Figure 4 shows results of calibration: under extrusion print (A) using 15 mm/s speed; over extrusion print (B) with TCP velocity of 5mm/s, and calibrated extrusion print (C) with a robotic movement speed of 9 mm/s.

Figure 4. Results of 3D printing speed calibration. A. Under extrusion speed, B. Over extrusion speed, C. Calibrated extrusion speed

Finally, for the correct deposition of material on the base of working area, the height calibration of the nozzle in relation to the base is required. This is done by placing the nozzle perpendicularly to the corner of the base with an approximate distance of 0-0.2mm. For the correct positioning of nozzle, this is repeated three times, as many as the rest of base's corners. Using the HAL plug-in, the point of nozzle placement is recorder, updating the point in the parametric environment and then associating this with the base. In addition, for the right deposition of material, two initial layers of the geometry are added to the base with 5mm offset from the perimeter in accordance with the first layer of the shape. The form is printed on a solid layer, providing results of uniform clay layers.

4 Toolpath planning, robotic control and execution

4.1 Parametric design and control

In a 3D printing process, important parameters determining the end result are the layer height that defines the distance between the sections in the contour process, the line width that is influenced by the filament width of the extruded materials and the wall thickness that determines the number of polylines per layer, calculated based on the width of extruded materials. These parameters are introduced into the Grasshopper parametric environment in order to identify the robotic toolpath.

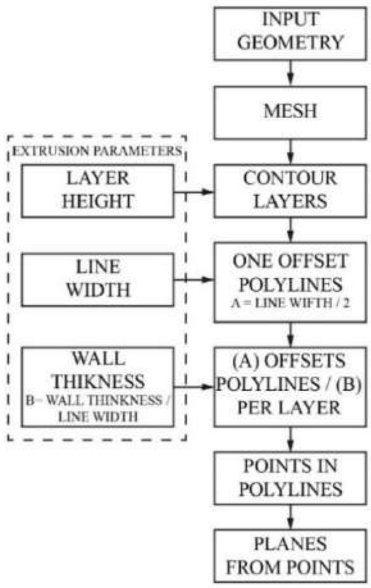


Figure 5. Flowchart of the contour geometrical configuration algorithm

The purpose of the parametric algorithm is to receive and process any digital geometry (BREP), by converting this into mesh object. Then, it generates contour layers in the form of consecutive polylines. The users can determine the print precision by varying the layer height up to 2mm. In this phase of experimentation and for case study purposes, the layers are defined with a height of up to 1mm. Subsequently, the sequential sections of layers are offset with inward direction and with value 0.5mm that is determined by the line width, which represents the filament of the extruder material (in this case 1mm/0.5). Moreover, the wall thickness is defined by the user, by specifying an integer number of required offsets in order for the extruder to print the expected width. The integer number is described by the roundness reduction of the thickness/line width relationship and also it calculates the group of polyline assigned in every layer height. Finally, polylines are divided into successive points, which create the toolpath of the robotic arm (Figure 5).

4.2 Toolpath planning

The development of toolpath for robotic motion behavior is based on the successive points of contour polylines generated in the parametric environment. Also, in the same algorithm the digital output (DO) activation control connected to the relay is used to activate the Arduino board, resulting in the rotation of stepper motor, and hence in the extrusion of clay material.

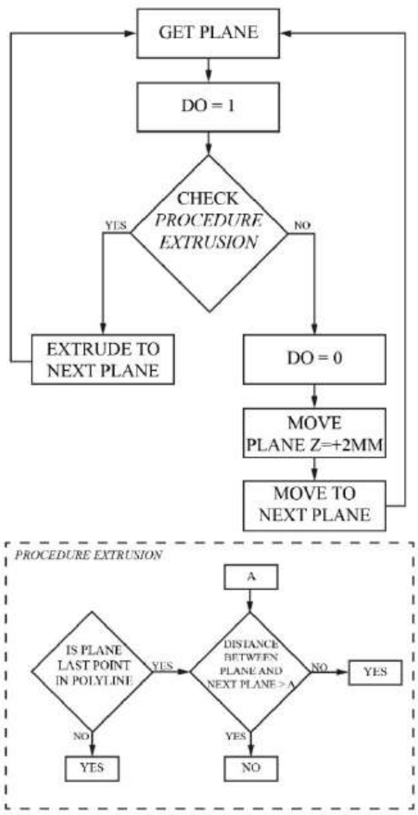


Figure 6 Flowchart of the toolpath development process

The robotic movement commences at the starting point of toolpath that is assigned outside the geometry at the corner of the base, and at the same time the clay extruder is actuated. Then, the deposition of filaments on the two thick layers of material on the base are executed. This process is based on the geometry of the initial contour layer (polyline), whereas the contour is offset 5mm and it is filled with radial lines from the center of the polygon in outwards direction. After the two layers on the base of the object are generated, the process of toolpath development is taken place.

The toolpath development process (for material extrusion) is based on the point-to-point motion driven by each contour layer, geometrically defined as polyline. The algorithm compares the distance between previous polyline's end point and next polyline's start point. If the line being created does not belong to the previous polyline, then the extruder is deactivated. In off state, the nozzle is disabled and is raised 2mm from the printed layer (from previous polyline's end point to the next polyline's start point) at a height of 2mm.

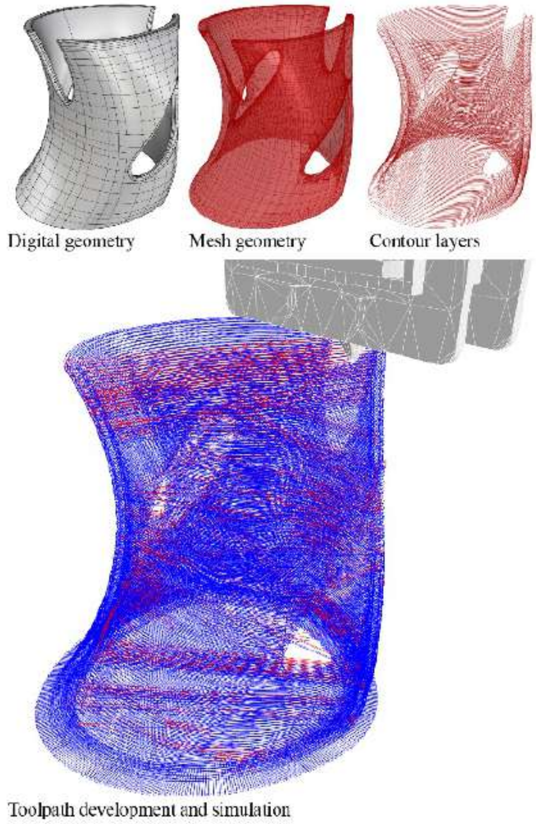


Figure 7. Toolpath development results. Blue colour shows the DO activation and red colour shows the DO deactivation

Subsequently, the nozzle approaches the next polyline's start point and the clay extrusion is activated. By turning off the nozzle at a height of 2mm ensures that the object is properly printed, as the movement of the nozzle does not touch or collide with the printed structure or does not deposit material in undesirable areas of the geometry. Finally, the toolpath development process is repeated in each sequential group of polylines for each contour layer in order to develop the overall toolpath. This is sent to the robotic controller for printing execution. Figure 6 shows the flowchart that describes the toolpath development process and figure 7 the toolpath generation in the parametric environment. Several case studies have been conducted, as shown in figure 8, in order to investigate results and draw useful conclusion for evolving printing process and for improving the functionality of the integrated platform.

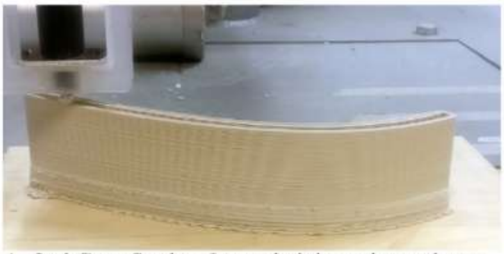
In the first case study, a compact geometry is used to investigate the toolpath for clay extrusion. In this case, clay material waste is observed because there is no interruption and removal as well as deactivation of the extrusion process. Also, the layer height range is investigated, resulting in 1mm being the ideal one. Figure 8 (A) shows the second case study, where the appropriate layer height is defined and the speed of the robotic arm relative to the extrusion speed is investigated. In this case, as mentioned above, the speed of the robotic machine (TCP velocity), relative to the rotation of the stepper motor, is set at 9 mm/s. Finally, in the third case study (Figure 8B) a more complex form that consist of openings is tested, and specifically the ability of the methodology applied to automatically activate/deactivate and remove the nozzle in cases of open hole patterns is explored. Also, results in terms of the quality of printing (smooth surface resolution, etc.) are derived, which are influenced from the layer width and height.

Although, the experimental case studies introduced in this paper are in small scale, our attempt is to apply the suggested methodology in medium scale printing, but most importantly, in large scale tasks that can be revealed in construction industry. An experimentation in all scale levels with the parallel examination of appropriate clay material mixtures [27] will allow thorough and comprehensive results to be derived, evaluating in parallel the feasibility of the suggested platform to be introduced in construction industry in a future stage.

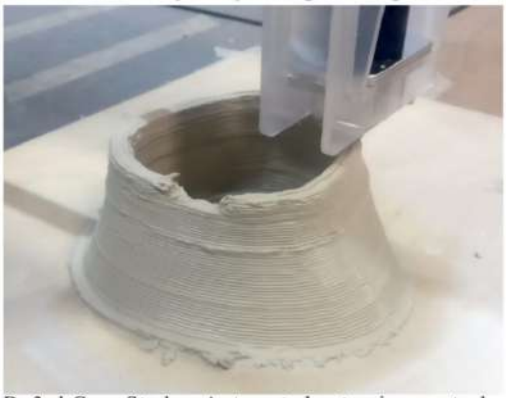
5 Conclusion

Currently, there is a tendency towards parametric design incorporated within platforms for performance evaluation of buildings, offering opportunities for design optimization and selection of the best results that can be realized in actual scale. Also, there is an increased interest among educational establishments towards automated construction processes, mainly by using industrial robotic arms for the manufacturing of complex and non-standard morphologies. However, little work has been observed in regard to the coherent and robust integration of such advanced digital design tools with automated construction processes. In this paper, the methodological framework and the initial results of experimentation in regard to the integration of a parametric design environment with a robotic additive process is presented. The aim is to develop an open source/customized platform that offers an alternative and ease solution for 3D clay printing in robotic construction tasks.

The methodological framework includes all important steps for a complete and effective integration that can achieve a smooth and seamless workflow from digital parametric design investigation to robotic production. The main pillars of this investigation include; the installation of industrial 3D clay extruder and robotic system calibration; the toolpath planning and the robotic control process, incorporated into the parametric environment; and finally the robotic execution, initially through small scale 3D clay printing studies. Within this framework, results in term of automated construction system calibration including extruder's stepper motor and robotic speed are obtained. Also, results in terms of toolpath planning process including layers' width and height of filament are obtained, offering all necessary data required for robotic execution in actual scale.



A. 2nd Case Study - Layer height and speed test



B. 3rd Case Study - Automated extrusion control

Figure 8. Two case study experiments using the 3D cay extruder mounted on the robot

In conclusion, this investigation has demonstrated a first attempt to integrate design and manufacturing tools within an open source platform. This allows an ease and effective development of robotic-driven automated system for 3D clay printing that can be potentially available for further implementation and use. Although, the first results are quite promising, further studies are required in order to test the feasibility of suggested methodology, together with a more thorough examination in regard to the use of clay mixtures and their application in different scales. Simultaneously, further studies in robotic AM need to move beyond experimental stage towards application in real construction scenarios taking into consideration sustainability criteria.

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A Study AR Based Smart Device for Work Management at Plant Construction Sites

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Abstract

One of the difficulties encountered at a plant construction site is frequent changes to design, which causes work overload. This can lead to increased construction costs, delayed progress, inferior work quality and poor productivity due to redundant work among project participants or omission of work.

In this study, we propose a work management system that uses smart devices based on augmented reality technology, which provides real-time information on plant construction so that site workers and managers can reduce wastes and errors, as well as check maintenance information more easily.

Keywords –

Augmented Reality; Smart-Device; Pipe-assembly; DBS(Device Breakdown Structure)

1 Introduction

1.1 Research Background and Purpose

A plant construction project is large in scale than general construction site, and involves complicated planning and processes. At a plant construction site, work data are generated for different stages of work, including architectural work, pipe installation, electricity and other facilities. During construction, massive amounts of data are generated, and management of this data is challenging. Thus, plant construction projects are harder to implement compared to other construction projects.

Various research has been undertaken for efficient management of plant construction, including studies on MIS using QR codes, barcodes, RFID and cloud systems.

However, these technologies entail the problem of redundant work due to delayed processing of real-time data and duplicated systems. As a result, construction time is stretched, and the same work is repeated unnecessarily. Productivity also declines in the maintenance and management stage, as a delay in the resolution of troubled tasks spreads to other related tasks.

In this study, we gather construction site managers' opinions to identify work processes that need improvement and design a plant site information management system accordingly, which can be useful for site workers and managers. At a plant site, a manager often works inefficiently due to poor processing of real-time data and lack of communication between the company and the site office. Moreover, construction workers have difficulty communicating with a manager due to complicated plant design. To address these issues, we apply an AR (augmented reality)-based smart device for pipe installation and construction management, which account for the largest part of a plant project (43%), to identify how to effectively install pipes and manage object data.

1.2 The Scope and Methods of Research

As mentioned above, we propose a management system for plant construction workers and managers that uses an AR-based smart device. At a plant site, workers install pipes based on drawings generated prior to the implementation. However, there is a wide discrepancy between drawings and the actual site, which makes it hard to install pipes. Thus, it is important to establish an information-sharing system between workers and managers to deliver accurate information on the site situation when installing pipes. To this end, we propose using an AR-based smart device.

The method and process of this research is:

(1) Preceding Research Analysis
- Existing review of literature
- Analysis of management characteristic of plant construction and process

(2) Requirement Analysis and Function Derivation
- Figuring out smart device applicability in the

plant field
- Requirement analysis to solve problems

(3) Establishing DBS (Device Breakdown Structure) for optimal plant construction
- Process Analysis at Plant Site
- Analysis of maintenance Work at Plant Site
- DBS Proposal by Different Work Processes

(4) AR Technology at Plant Construction Site

2 Research Trend

2.1 Literature Review

Since the mid-2000s, active research has been undertaken to identify how to use various IT technologies to improve plant construction, specifically, to shorten construction time, reduce costs, ensure flawless construction, engage in accident-proof planning, enhance work predictability, eliminate wastes, improve productivity, and reduce maintenance costs.

Most studies on plant construction and management have been limited to proposing conceptual methodologies or solving logistics issues (e.g. delivery of materials). There are few studies on how to generate and utilize real-time information on pipe work or how to discover errors.

Table 1 Existing research

Area of management	Research subjects
Construction	Ontology-based BIM modeling; AR-based system framework 4D tools for greater efficiency in site management
Site condition	Use of smart phone to improve management process; visualization of project information using real-time data sharing and management, wireless communication; and augmented reality
Safety	New 4D safety management and monitoring system 'C-RTICS2' for more efficient construction and communication among work partners Behavior-based preventive safety system, visualized management with VCS (Virtual Construction Simulation System)
	Note
Construction	Marker-based AR: Research on identification of objects, selection of marker type, marker detection, and marker-less AR technology
Site condition	Wearable device for real-time work coordination Wearable device; Cloud system for massive data management
Safety	Set apart in terms of device and visualization method, while similar in technology for communication between office and construction site Partly applicable to safety management in terms of carrying out preventive safety management in visualized form

2.2 Plant Construction Management

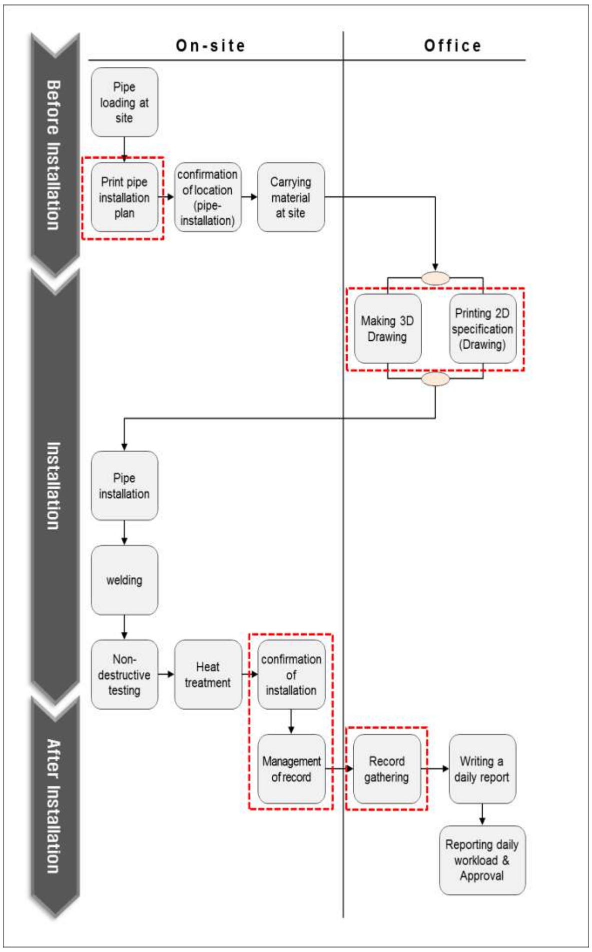

Figure 1. Pipe construction process

At a plant construction site, pipe installation can be divided into three stages: pre-installation, installation and post-installation.

In the first stage, materials are delivered and detailed 2D drawings are produced, based on which the site is surveyed, and 3D drawings are produced.

In the installation stage, workers install pipes based on the drawings. In the after-installation stage, managers and workers carry out maintenance work.

In this process, workers and managers do not fully share information, and it is hard for a manager to accurately explain the installation process to workers based on drawings. To resolve this difficulty, we propose a new process and system.

3 Analysis of plant workers' needs

Moon [16] conducted an interview with and surveyed the project sites of S company, one of the country's leading construction companies, and found out that workers needed smart applications for construction assistance, data confirmation and checks and guidelines, particularly for communication support and progress management (Figure 2.).

He showed that, at plant construction sites, workers need to have a smart device system to share information during the design and implementation processes.

Table 2 Applicable work territories

Direction	Contents
1	Construction Assistance App.
2	Data confirmation and check App.
3	Data input App.
4	Guideline App.
5	Communication support App.
6	Progress management App.

At a plant site, workers need drawings and related data to handle materials and make necessary installations.

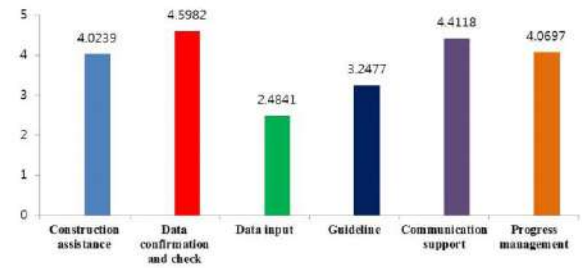

Figure 2. Overall result

These data are generated in different forms and communicated to workers in visualized forms. The alteration of certain data affects other data and generates new information. Using smart devices and applications could support this process

4 Establishing DBS(Device Breakdown Structure) for optimal plant construction

4.1 Process Analysis at Plant Site

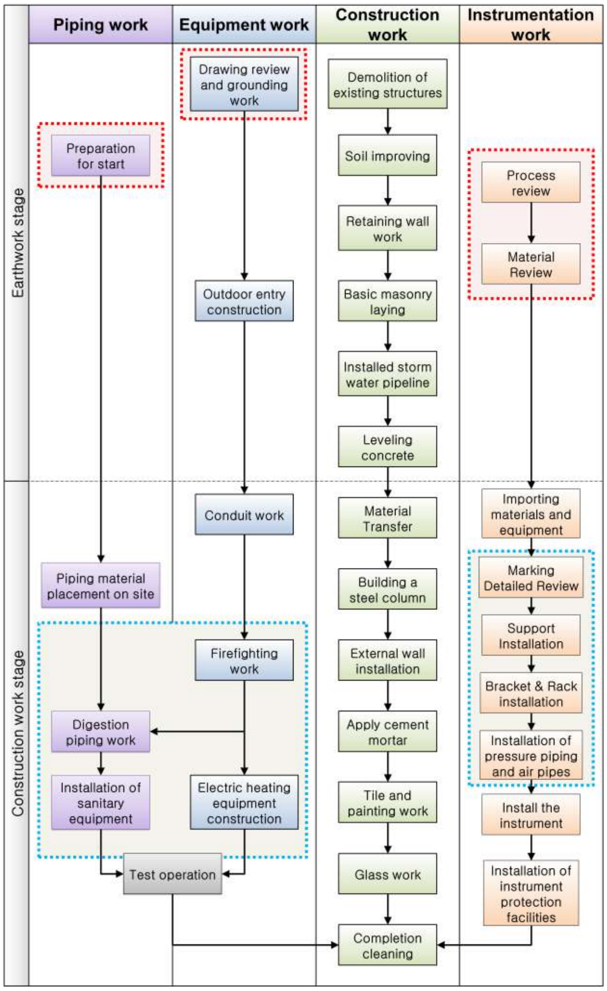

Figure 3. Construction work process of plant site

We analyzed the construction process at a plant site to identify areas of work in which the use of a smart device can be applied. The analysis was done for earth work and architectural work, specifically for processes such as architectural work and electricity, pipe and facility installation.

The analysis results showed that, for earth work, it is important to convert materials data and drawings into a 3D model to help workers' understanding of the process. For architectural work, it is important to produce information on materials and processes that are in progress or completed, and to provide a 3D model based on augmented reality for review.

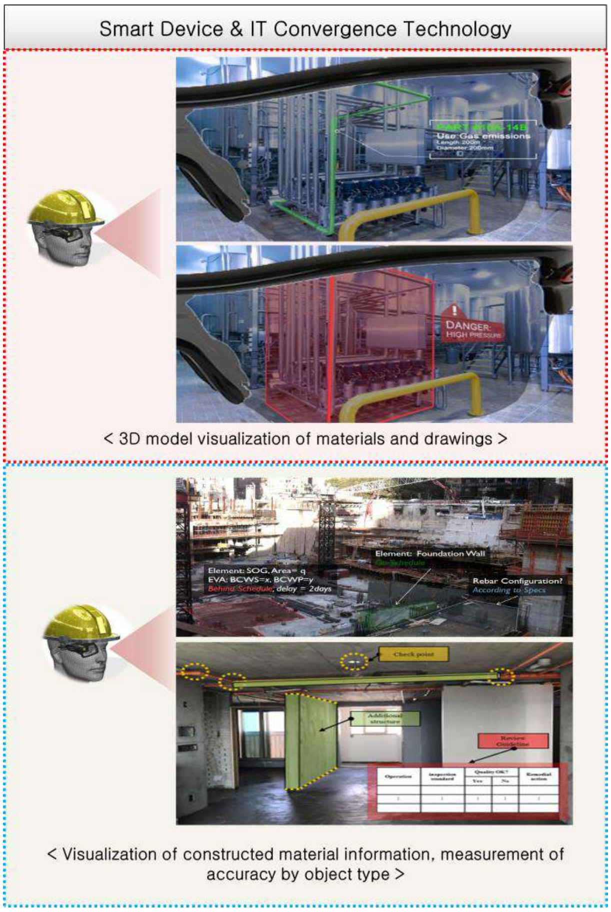

Figure 4. Smart device & IT convergence technology in plant site

4.2 Analysis of maintenance Work at Plant Site

The analysis results showed that facilities management companies, inspectors and facilities managers need a maintenance system that uses an AR-based smart device to inspect, maintain and repair plant facilities.

More specifically, tasks that could use an AR-based smart device included planning and review of facilities maintenance, updating drawings/records for the facilities management company, managing records and site locations confirming maintenance results for inspectors and conducting site check and maintenance work for facilities managers. Smart devices can be used to track records of materials and visualize related information.

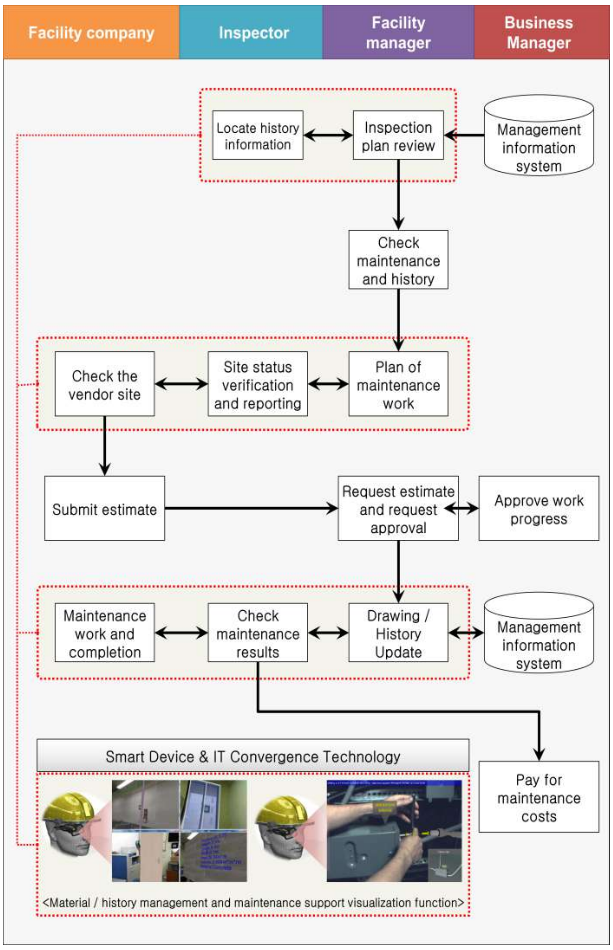

Figure 5. Maintenance process of plant site

4.3 DBS by Different Work Processes

Based on interviews and analysis of plant processes, we identified smart devices suitable for various participants of a plant construction project, that is, plant constructors, architectural workers, facilities supervisors and facilities managers. Then we examined various functions of smart wearable devices that can be used to process data generated by site workers.

Our investigation showed that watch-type, band-type, and glass-type devices are suitable for a plant construction project. As for device sensors, bio information, GPS/NFC, accelerometer, visual information and Bluetooth are applicable to plant construction. We matched site workers' needs with different types and functions of smart devices so that the workers could choose an efficient device.

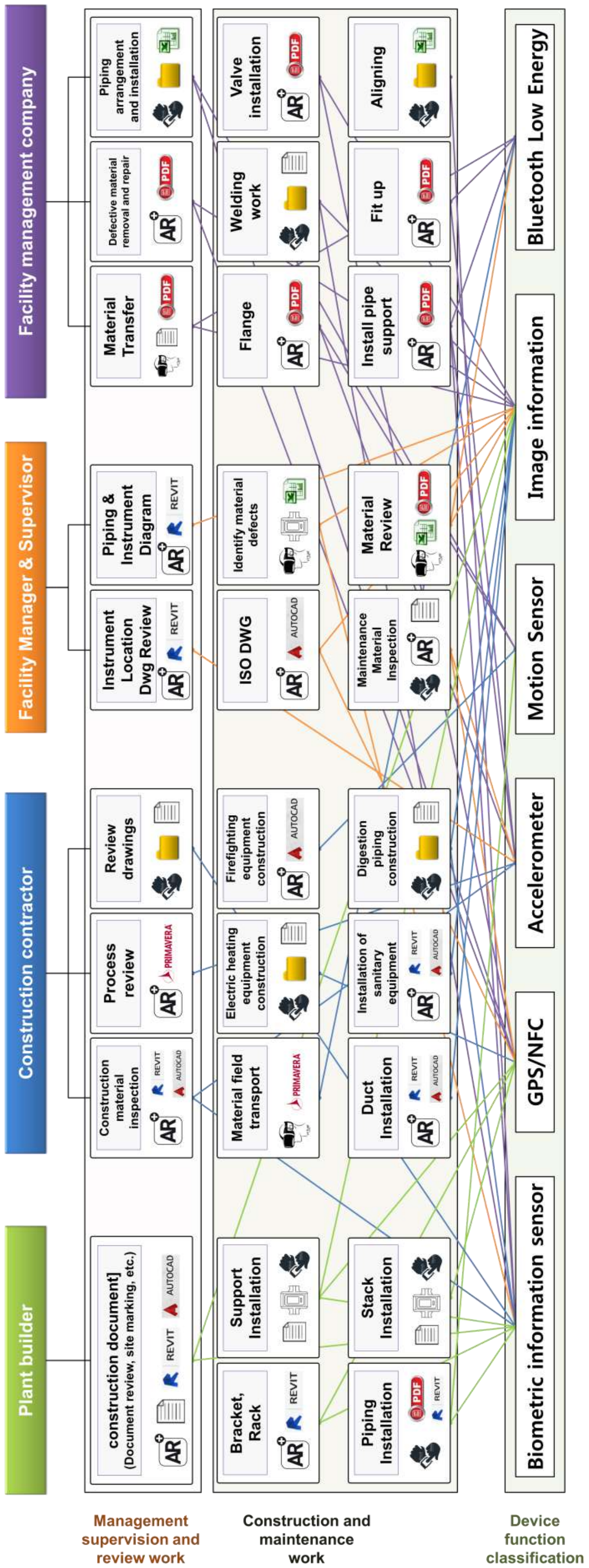

Figure 6. Device breakdown structure

5 AR Technology at Plant Construction Site

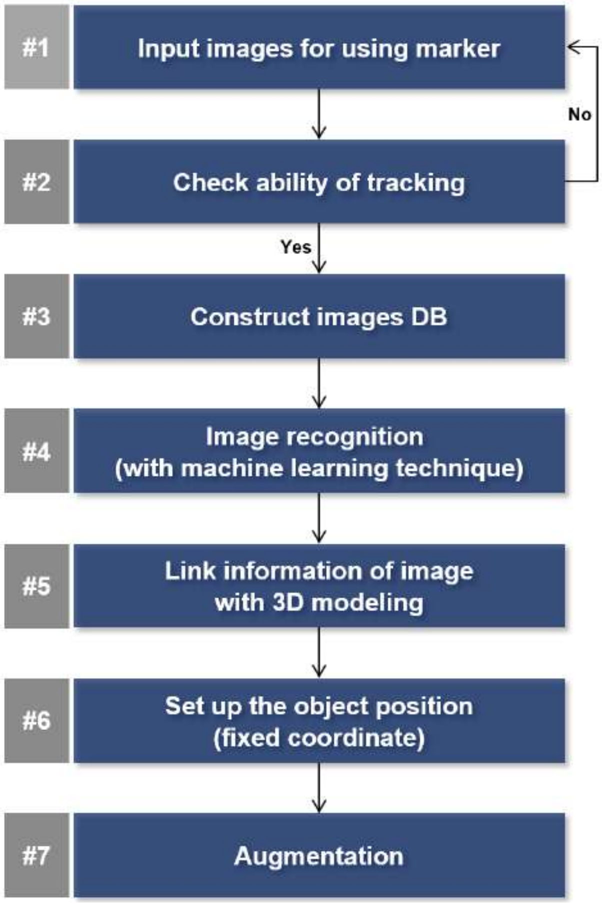

Figure 7. Augmented Reality System Diagram

To apply AR technology at a plant construction site, we conducted an experiment (See Figure 7). First, image input was made to use marker. Second, to check that images were recognized as markers by the smart device. If the image was recognized as a marker, save it in DB. or if not, input the image again. Third, image data of useful information were collected to generate an AR marker file. Fourth, the stored image data is used to improve the object recognition rate through machine learning techniques. Fifth, the marker was linked with 3D modelling/images, and sixth, the position of the object was set on a smart device display. Lastly, AR data were generated accordingly for use at a plant site

Through this process, the worker uses the camera of the smart device at the plant construction site to recognize objects from various angles as markers, and links objects and 3D modeling information.

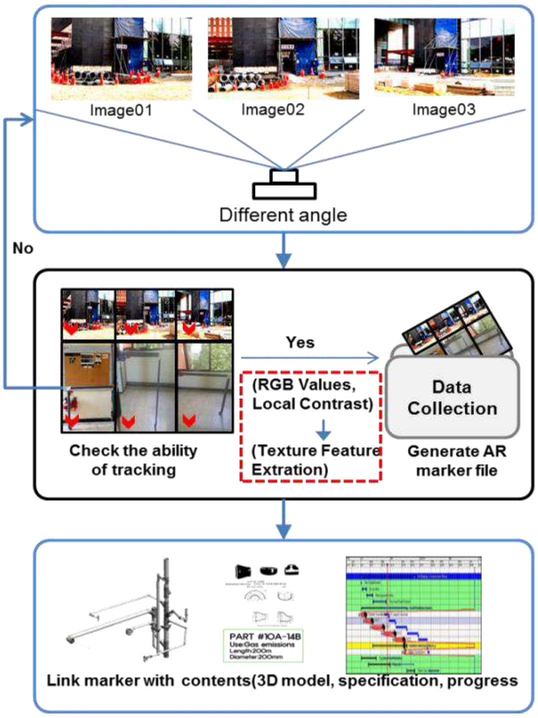

Figure 8. Images for using marker

6 Conclusions

In this study, we analyzed traditional processes of plant construction, conducted interviews to identify difficulties and problems at plant construction sites, and explored the applicability of smart device at plant sites. To this end, we analyzed work processes at plant sites, examined maintenance work, established DBS (Device Breakdown Structure) for various participants of a plant construction project and examined how to apply AR technology.

Regarding work processes at a plant site, we examined different stages of a construction project and identified technological elements that can be applied to earth work and architectural work. For analysis of maintenance work, we identified areas of work that need visualized information. Additionally, we established DBS for site participants and examined how to adopt marker-based AR technology at a plant construction site.

Based on the analysis of plant construction processes and maintenance work, smart devices can be adopted at a plant construction site according to DBS of different work areas, and AR data can be generated through marker-based image links. Using these data, workers can check information and acquire better understanding of the work process. Moreover, a Cloud system may be introduced for real-time information sharing. Based on these findings, we plan to conduct further research on marker-less image tracking using deep-learning technology.

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The new tradition - Dialogues on production in architecture

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Abstract –

Tools of digitalisation and automation are changing the labour market and human's interaction with production material in general. In architectural processes, this change involves the stage of production but also, and more interestingly, the design one. Architecture has a social role, which includes many processes. Each process requires different times, challenges, and tools. Consequently, the impact of innovation is not the same for these processes. Many manufactories require innovative design and advanced researches. These manufactories have different relationships with digitalisation and innovation, and not all factories have advanced technology; the lack of updates is due to financial or cultural reasons.

This paper aims at investigating the production of structural wood components of the architectural process. The analysis of the impact of innovation in the architectural process cannot be limited to robot or other digital tools, but it is necessary to consider the social and cultural context as well (1). The study is divided in two sections: (2) the role of architecture at the margin of numerous processes (between design and production), but also between innovation and tradition. The investigation needs to include many factors in order to best describe how innovation affects the design and the production. (3) The methodology is structured in three dialogues: with research, design, and manufacturing. Each one of these has specific limits and tools. The collected data describes the role of innovation and tradition in the specific sector of structural wood components of the architectural process.

Keywords –
Cultural change; Dialogue; Architecture; Manufacturing.

1 Introduction

Technical evolution has always been considered within its social conditions: the cultural and geographical backgrounds influence technological innovation and its impact on people.

Three important truths emerge from this close relationship: the rapid development of digital tools, the gap between different work sectors, and the 'fear' of machines and automation. These conditions are closely related, and each one determines the others.

The rapid development of digital tools improves day by day: the possibility of working from different countries or of sending digital information to line production are only two of many examples.

These digital tools interact with humans in various ways every day, consequently absorbing innovation in different ways as well: the lack of updates can be a discriminating factor, and it can increase the distance between the different work sectors. This is a dangerous gap because it can compromise the entire process, like the complex one of architecture for instance.

The third emerging reality is that of 'fear', deriving from the gap between those who use digitalisation and those who do not. There is a misunderstanding of digital evolution, as it is not considered in accordance with the context in which it develops. Consequently, this fear fuels the rejection of digital change, of evolution, and of the introduction of new work tools. In the course of history, many technical revolutions have evolved the labour market and human's social condition. However, actual technical evolution is different: it is very fast and it influences many aspects of human life (especially work related), its identity, and its cultural tradition.

Therefore, the three emerging truths – rapidity, work gap, fear - concern every work process, and could compromise its actual quality, even in architecture.

This paper aims at investigating the impact of digital innovation on architecture, how new tools are integrated in its processes, especially in the component production one. Although the paper focuses the research on this specific process, evaluating the development of other architectural processes is also necessary in order to better understand the development of digital and automation tools. Considerations on a single process cannot be made separately from the others.

The paper is organised in two parts: the first one reconstructs the processes of architecture and it describes the impact of innovation on them. These processes are very different, because each one has its own times and tools. For this reason, communication between these different processes is not simple and the involved factors often encounter difficulties. An architect must be capable of coordinating the numerous factors that move along the margins of the various processes. In this scenario, digital tools could simplify this complex communication and could help to solve some difficulties between the many architectural factors. This section focuses on the interaction between design and production because there is a gap between them that is rapidly expanding. One of the reasons for this is the close relationship between manufactories and their local tradition. In order to investigate the relationship between innovation and tradition, we chose one specific productive process: the structural wood components of the architectural process, because it represents one of the best contexts in which tradition meets innovation. In the architectural context, there are numerous digital tools for design processes on the one side, and many manufactories connected to their traditional tools for wood modelling on the other. The evolution in the design and the production processes necessarily have different speeds: each process involves different kinds of factors and materials. This difference can generate the abovementioned work gap and human fear: in architecture, these correspond to solutions that are less and less adaptable to the social needs. Moreover, productive actions today are not only human or mechanic, but also automated and robotic. The actual processes of modelling and assembly can be expanded beyond human capabilities and its traditional tools. These new limits redefine architectural processes and their relationship with tradition, local materials, and cultural context. The aim of the research is to analyse this specific gap.

The second section of the paper describes the methodology used to investigate main architectural processes: design, research, production, and their levels of innovation. This methodology was structured for the PhD research in progress at Università Iuav di Venezia. The research deals with the impact of automation on the design of structural wood components, starting from industrial applications, experiments, and failed attempts, up to discovering the new limits that are created by automation and new intelligences.

This requires different investigation strategies, although the challenge is the same: defining the level of innovation and its impact on the building sector.

The analysis allows reconstructing the role of automation in each architectural process and evaluating their interaction. This last aspect is in fact fundamental in order to develop architectural quality, in accordance with the social and functional needs described by Virginia Gangemi [1]: in this case, automation can contribute to the development of an appropriate technological and architectural design.

To understand the appropriation of technology, it is necessary to investigate on more levels. A specific methodology that uses several research tools, in accordance with the different processes and actors, has been developed precisely for this reason. Final data collection helps to compare the role of innovation in each single process: for example, comparing the advanced university research with the manufacturing production, and the innovative automation with the traditional tools. Thanks to these comparisons, it is possible to evaluate how the architectural production process is changing, and consequently how the architectural design process is as well. This research is structured in three dialogues that deal with some of the most important factors of the architectural process: the researches, the designers, and the manufactories. The final comparison can help describe the appropriateness of automation in architecture and in its cultural context.

Figure 1. The human action in the processing of a wooden component.

2 On the margin

Invisible technology, as Nicola Sinopoli describes it [2], deals with the complexity of the architectural process and the numerous operators who are involved in it. Digital innovation has a specific type of impact on each process, with important consequences on the communication between the factors involved. In fact, digitalisation and automation allow many operators to communicate in shared digital dimensions through shared languages of informatics. On the other side, the tools of digitalisation and information can amplify the gap between the various architectural processes, like between design and production. Therefore, the interaction between these invisible technologies (in accordance with the integration of digitalisation) can either be very efficient and productive, or bring to architectural and social failure.

The architect is the administrator of these invisible processes, although the complexity of the architectural discipline has grown century-by-century in history: today, there are numerous specialisations in the field, and the architect is required to hold and balance most of them. It is like a sort of 'borderline', a common ground where several professions meet, each with its own challenges, times, tools, and approaches to automation and digitalisation. Today's digitalisation and automation are changing every profession and every profession's processes. The capability of these processes to update themselves weighs in on the balance of the architectural production as a whole. Therefore, the misunderstanding of the digital evolution and the lack of updates could compromise the architectural quality and its construction. The proposed analysis aims to understand the main reasons behind this deficiency: these reasons could be financial or even cultural, where tradition holds an important role.

By investigating along the margins of innovative and traditional production, the paper aims to understand the impact of digital tools on architectural quality, in order to explore and redefine the relationship between men and their architectural means [3], both human and robotic. As according to Stephen Kieran and James Timberlake [4], an architect cannot embody all qualities of a master builder, but thanks to digital tools he can integrate the numerous processes that are involved in the construction project and can coordinate the architectural design in every process and detail. This refers to several architectural aspects and on several scales: the design and the manufacture processes are closely linked and cannot be considered separately from one another. The architect, like an artisan, has the capability of transforming ideas into manufactured matter, modelling it through its intrinsic proprieties. Material production and its tools has a long history, one that has revolutionised the architectural process in time. The same is happening today: digitalisation and automation influence architectural design and creativity.

The interaction between idea and material matter through digitalisation can contribute to "rebuild" the figure of the manufacturer. As Guido Nardi says [5]: "The choice of materials and the use of particular techniques […] are strongly conditioned by social, family, and religious traditions, which are the cultural element that is usually internalised, operating in a subconscious dimension. In material civilisations, the manufacturer was the holder of this complex but uniform knowledge. They converge both technical abilities and scientific and social knowing in their manufactured product". Therefore, the architect is a figure that stands on the margin of design and production, but also of tradition and innovation. Today's "contemporary master builder" could resume this care for detail and its production.

The research methodology elaborated for this investigation aims to describe the interaction between architectural processes, as well as how this same interaction can improve the architectural design. The methodology is based on an important definition of innovation and its role. The level of innovation cannot be measured according to one specific technique. Innovation deals with technology, which is the application of a technique in a specific context that holds specific social and cultural needs. Innovation represents a change in a cultural process. Therefore, innovative technology is considered as a cultural process and not as a mere tool. Only a multidisciplinary investigation can make it possible to evaluate how new technologies will be innovative and appropriate for the people, their culture, and their tradition.

3 Investigation methodology and factors

Methodologies deal with an array of operators and factors, which interact with automation in many different ways. Therefore, the proposed methodology is based on several tools in order to investigate in different contexts, some more innovative and others more traditional. As said earlier, the sector of the production of structural wood components represents one of the best cases of interaction between traditional and innovative tools.

The architectural process in wood component design and production involves numerous factors and operators, distinguishing three categories:

- researches (from university and companies);
- designers (architects and engineers);
- manufactories (carpentries and joineries).

These factors are respectively associated to three architectural processes: advanced research, architectural design, and production. The investigation aims at describing the role of automation and digitalisation in each process, outlining three investigation phases:

- the limits of the survey;
- the construction of investigative tools;
- the data collection.

The three investigation categories (Researches, Designers, Manufactories) are described below and are considered as 'Dialogues': dialogue represents one of the first and most important tools of knowledge, like the ancient example of *Platonic Dialogues* (IV-III cen. BC); this research also underlines the importance of dialogue in creating an interaction with several realities, like academic research and manufactories. However, there are some useful considerations that must be made in order to devise proper investigation tools: the expected results will be both theoretical and practical, so their comparison could seem difficult, but it presents many common points. The second consideration is the geographic location of the object of the investigation: the cultural context and the financial status contribute (or not) to the development of automation technology.

3.1 Dialogue 1 - Researches

Advanced research in automation in architectural processes covers an extensive field that is, however, increasing accessible. Many different figures work on architectural automation, therefore a more selective investigation is necessary.

The specific limits of the survey were structured on the following conditions:

- research unit (both universities and companies);
- research unit with at least 5 years of activity;
- research on structural components, both modelling and assembly;
- research unit in Europe.

In this investigation, wood is not a restricting parameter: a general investigation on automation and structure was preferred to a specific investigation on wood structures. It allows to better understand the interaction between different research fields and their developments. 30 research units were identified in Europe, but only 9 units follow the said parameters. These are generally specialised in specific sectors of architecture or tools: for example, robot or additive manufacturing, solid material modelling or component movement.

The research units were analysed on the basis of progressed researches, which contribute to the definition of a profile for each research unit. The bibliography and the interview were the main tools of investigation in this category.

3.2 Dialogue 2 - Designers

The second dialogue is with designers, aiming to form a database of best practices. The selection of architects and engineers began with the identification of case studies. In this category, the limits of the research field refer to buildings (not designers). Each case study had to follow specific parameters:

- it must present an existing building, with environmental and security parameters;
- the building must present a wooden structure;
- it must be localised in Europe;
- its construction must have been completed in the last 10 years;
- the wood component production must have had a significant role in the design process.

The case studies represent the best examples of interaction between design and production. The dialogue between operators is the most important tool that allows the development of the architecture. Digital tools contribute to simplify communication, reducing the margin of error. This communication concerns human and machines, redefining the invisible technology of the architectural processes.

Each case study had to follow specific parameters, with the aim of reconstructing the timeline of the design, production, and assembly processes. Another important parameter was the kind of machine that was used for the wood component production. Thanks to this data, it was possible to identify the most popular machines for architectural production.

3.3 Dialogue 3 - Manufactories

The third dialogue deals with manufactories, presenting several complexities according to their variability and their availability to dialogue with research. Analysing this category is important in order to describe the impact of innovation on local economy. In fact, new digital tools can help develop new architectural design processes, on one side, but also redefine the work processes and the role of human workers on the other. Initially, this dialogue aims to evaluate the innovation in the wood production process through the quantity of the machines and robots that are used. The final goal was to create a "map of innovation"; however, many manufactories would necessarily be excluded from this map because of their lack of machines and automation.

Figure 2. Traditional tools in a Venetian joinery.

As mentioned previously, technological innovation is a process and is not only the result of digital or automated tools: innovation is also conditioned by the social and financial context. Therefore, the geographical location of these manufactories is determinant for their innovation. The investigation became the main tool in discovering the state of the art of manufactories, their variability, and their innovative levels. The analysis was developed in the geographical area of North-East Italy, known as Triveneto, which is composed by three regions: Veneto, Friuli Venezia Giulia, and Trentino Alto Adige. The Triveneto represents one of the most productive areas of Europe and it is characterised by the presences of small and medium businesses with a historical tradition. The parameters for the category were:

- The geographical area (North-East Italy);
- The specific business product, according to the Italian Business Register. Each product was required to have a specific code: *ATECO*; this research used two ATECO: 16.10 *Cutting and planing of wood*, 16.23.2 *Manufacture of other wood carpentry products and carpentry for construction*;
- The manufactory had to be an active business.

Through these parameters, 3.112 businesses were selected, of which 770 carpentries and 2342 joineries. This business database was then ordered according to the specific geography, number of employees, and start year of the business.

A questionnaire was elaborated in order to collect data from the selected businesses, following several levels of investigation. According to the number of participants, thanks to this questionnaire it will be possible to describe the role of automation in wood manufacturing and the role of automation in production.

The questions deal with the presence or absence of digital and automation tools, their use or disuse, and consequently the main reasons behind several production choices. Following this first step, a second step addresses the type of machines and their use for architectural components or material.

In the dialogue with manufactories, the impact of innovation is obviously considered, but the other important common point that is considered is the manufactories' relationship with tradition, their tools, and their materials.

4 Conclusion

The research on automated machines and robots in architectural processes needs to consider many various aspects: the languages of communication, the kind of activity, the level of innovation, the update and upgrade status, and the relation with social context. The paper aims at investigating the impact of digitalisation on architecture, starting with the definition of the methodology of research.

A multidisciplinary approach was necessary to investigate the complex issue, not only for the nature of the processes and their main tools, but also for their integration with innovation and automation.

Starting from the definition of three emerging truths – rapidity, work gap, fear – the investigation on the role of automation in architecture is necessary to describe how innovation can actually contribute to architectural and social quality as a whole. There is a direct connection between architectural design and production: the research aims to identify a strategic point of view on the issue, in order to develop a knowledge and understanding of technological improvement in architecture. It is possible to set up an investigation at the margins of architectural processes, analysing each one and comparing them.

The research focuses on the production of structural wood components, because this sector represents one of the best interactions between tradition and innovation, since it involves advanced design and research in local manufactories. The manufactories that are considered are joineries and carpentries presenting different levels of innovation. The comparison between the architectural factors and the description of their innovative role is the main tool for a better understating of the appropriation of automation and digitalisation in architecture.

The research identifies three process categories: the research, the design, and the manufacturing. Each one of these processes includes factors with which it dialogues. Therefore, the research methodology is structured and adapted in order to investigate different processes with different research limits.

The research methodology is based on three forms of dialogue: Researches, Designers, and Manufactories. The comparison between these processes concerns the impact of innovation in social culture. Innovation is more than a simple technique: it is a process and a cultural change. The interaction between these three sectors represents a cross-disciplinary description, which is useful to understand if an innovative technology can be appropriate. Although this paper investigates a specific context (structural wood components), the research methodology can be applied to several sectors, which can differ in their architectural and geographical qualities. The aim of the research is the dialogue between many aspects of the architectural process: design and production, human and machine, tradition and innovation. Therefore, dialogue becomes the main investigation tool, able to involve and compare many factors. It can contribute to contrast the human fear toward digital innovation and its rapid evolution. It can help define the role of innovation not only in architecture, but also in society and in the labour market. 'Dialogue' holds the capability of comparing the innovation levels between many processes and their contexts. It is where research and designers come into contact and where (and how) man redefines a new tradition. Comparing research and manufactories, designers and production is necessary to understand the role of automation and digitalisation in architecture. Architecture must be capable of answering social needs and offer a better quality of life. Therefore, dialogue is not an answer but a tool for the analysis of the appropriation of innovation in our society. Innovation is not automation but how we use it. Luca De Biase wrote [6]: "Distinguishing between what is important and what is only interesting, and making the umpteenth cultural leap. Everyone, together. Because even if computers go faster, humans can go farther". Human capability is fundamental in developing new tools and in recognising the cultural change to which they contribute. The research on automated machines and robots in architectural process cannot be made separately from the cultural context, the human workforce and its traditions. Man must continue updating his capabilities and his territorial knowledge: thanks to these, he can use innovative tools like automation and digitalisation to increase his potential and his culture. He can redefine tradition: he can build a new tradition, a new relationship with materials through new tools. If not, if technique remains the main point of innovation, man will inevitably become and remain only a spectator.

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Automating Analysis of Construction Workers' Viewing Patterns for Personalized Safety Training and Management

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Abstract –

Unrecognized hazards increase the likelihood of workplace fatalities and injuries substantially. However, recent research has demonstrated that a large proportion of hazards remain unrecognized in dynamic construction environments. Recent studies have suggested a strong correlation between viewing patterns of workers and their hazard recognition performance. Hence, it is important to study and analyze the viewing patterns of workers to gain a better understanding of their hazard recognition performance. The objective of this exploratory research is to explore hazard recognition as a visual search process to identifying various visual search factors that affect the process of hazard recognition. Further, the study also proposes a framework to develop a vision based tool capable of recording and analyzing viewing patterns of construction workers and generate feedback for personalized training and proactive safety management.

Keywords –

Hazard Recognition, Construction Safety, Computer vision, Eye tracking

1 Introduction

Every day about 6.5 million workers work on more than 200,000 construction sites across the United States [1]. However, with 900 fatal and over 200,000 non-fatal injuries a year [1], construction workers are more likely to be injured than their counterparts in other industries. Over the years, researchers have attempted to understand the underlying precursors of accidents in construction [2,3]. Among others, hazard recognition has received significant attention [4–6]. Recognizing hazards is one of the first steps in effective safety management; however, studies across the world have shown that 30% to 50% of hazards remain unrecognized in construction environments [6–10].

To improve hazard recognition skill of workers, several training programs have been developed and implemented within the construction industry. However, research has shown that construction workers fail to recognize a significant portion of hazards despite having received training [11,12]. Research in human factors and visual search [13] has revealed several contributing factors that influence person's detection and recognition performance while they scan their environment for hazards. For example. a recent study [14] argues that one of the reasons for unrecognized hazards is that workers often pay attention to the primary task alone and ignore the surrounding areas. The same study also suggests that workers often selectively pay attention to a particular type of hazards while ignoring others types, which result in poor hazard recognition levels.

To recognize hazards in their workplaces, workers need to first detect the hazardous object or condition and identify it correctly, to associate a level of risk to it. This is essentially a visual search process and the outcome of any such process is affected by the viewing pattern and attention distribution of the person conducting the search [15]. Therefore, it is important to design training interventions that aim to improve workers' visual search and enable them to detect hazard better. The first step towards developing such training interventions is to understand what constitutes a good visual search.

Hence, there is a need to explore hazard recognition from a visual search perspective to identify and evaluate various metrics that define the viewing patterns of workers and affect their hazard recognition performance. In order to gain an intrusive understanding of workers' viewing behavior, it is important to study their viewing patterns while they engage in their regular work in real construction environments. However, examining the viewing patterns of workers manually would not only require a lot of time and repetitive effort but will also be prone to human errors causing inaccurate assessment and inefficient feedback. Therefore, the objective of this study is 1) to identify the visual search metrics that affect hazard recognition and 2) automate the capture and analysis of visual search data collected from workers in real construction sites.

More specifically, the study provides a framework for a computer-vision based system that can be used to generate personalized feedback for workers and safety managers for training purposes and generate data that will potentially assist in proactive safety management.

2 Background

2.1 Visual Search

Visual search is a task of scanning the environment to find particular visual stimuli or features (the targets) among other visual stimuli or features (the distractors) [16]. Hazard recognition can essentially be viewed as a "multiple target visual search process" where hazards are the targets while other objects and features in the environment serve as the distractors.

The visual search is influenced by several factors, such as age differences [17], professional experience [18], the similarity in targets and distractors [19], and the type of search being conducted [16]. Therefore, studying visual search allows us to examine attentional abilities, cognition and perception.

Eye-tracking provides an objective measure of stimuli that received attention during visual search activities by analyzing eye movement data and has found application in aviation, medicine, transportation, and education [20,21]. The Eye tracking device records the corneal reflection of infrared lighting to track pupil position, mapping the subject's focus of attention on his field of view (gaze) [22].

2.2 Computer Vision in Construction

Computer vision seeks to enable computer systems to automate the tasks that the human visual system do [23–28]. Computer vision techniques include image reconstruction, object detection and tracking, feature extraction, pose estimation, image restoration etc. One of the most popular applications is perhaps the face detection in our cell phone cameras.

Computer vision is widely used in robotics[23], medicine [24], surveillance [25], transportation [26] and others. In construction, computer vision is gaining popularity due to its applications in progress monitoring[29–31], productivity analysis[27,32], structural health monitoring, 3D reconstruction [33,34] and automated documentation [35,36]. Although computer vision has not been leveraged to its full potential, it has several applications in replacing or augmenting the conventional field-based safety monitoring tools [37].

3 Objectives

The objectives of this research were:

1) to identify the visual search metrics that affect hazard recognition performance of workers and

2) to provide a framework for developing an automated vision-based system that records the gaze behavior of workers in a construction site and computes the visual search metrics identified above.

Objective 1 helps us understand the process of hazard recognition from a visual search perspective and Objective 2 enables us to collect and analyze that information automatically for a large-scale personalized safety monitoring and training. Achieving these two goals will enable interventions and proactive safety management while maintaining a high manager-to-worker ratio that is economically inevitable.

4 Research Method

The study was completed in two phases (fig 1). Phase 1 consisted of identifying the visual search metrics that affect hazard recognition performance. Phase 2 consisted of developing a computer vision based tool to capture and analyze eye-tracking data in order to compute the identified metrics automatically and on a large scale.'

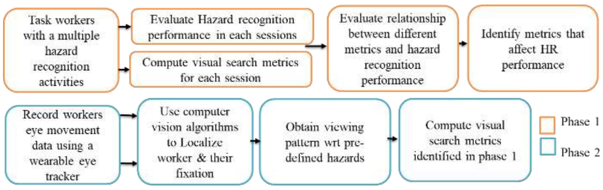

Fig 1. Method Overview

4.1 Phase 1

This phase was completed in two steps as detailed below

4.1.1 Data Collection

Twenty-four construction workers representing diverse speciality trades were selected. The experience of workers varied from 2 years to 28 years (Mean: 10.05) and their ages ranged from 19 years to 51 Years (Mean: 32.5). After gathering worker demographic information, the participants were placed 30 cm from a computer screen with the centre of the screen in line with participant's eyes. An Eye tracking device (Eyetech VT-2) with the sampling rate of 60 Hz placed at the top of the screen was calibrated for each worker.

The workers were then tasked with identifying hazards in 12 pre-selected construction case images that were randomly selected from a set of 24 case images captured from real projects. The images were displayed on a computer screen with a resolution of 1920 X 1080. As the workers identified hazards verbally from each case image, the researchers catalogued the information and their eye movements were captured and recorded by the eye tracker.

The hazards in each case image were pre-identified by an expert panel of three safety professionals with the cumulative experience of 62 years. The hazard recognition performance of workers was measured in terms of hazard recognition index:

$$HRI = \frac{Hazards\ identified\ by\ subject}{Total\ Preidentified\ Hazards\ in\ that\ image}$$

The eye movement data captured during the experiment was used to calculate following visual search metrics:

Search Duration (SD)

Search duration is the time (in seconds) for which the participant views a scene before terminating the search. The search duration consists of fixations (when participants focus on a particular point) and saccades (rapid eye movements between fixations)

Fixation Count (FC)

The fixation count is the number of discrete points in a visual field, where participant fixates or focuses their attention. The number of fixations is indicative of the importance or "noticeability" of objects/ areas to a user [38].

Fixation Time (FT)

Fixation time is the time spent by each participant in fixating on different objects or areas. It is calculated by taking the sum of durations of all fixations. Fixation time reflects the amount of attention paid by the participant to each photograph.

$$T = \sum_{i=1}^{n} (E(f_i) - S(f_i))$$

Where E and S are the end time and start time for i^th fixation (f_i)

Mean Fixation Duration (MFD)

The mean fixation duration (MFD), also known as average fixation duration [39], is the sum of the durations of all fixations divided by the number of fixations[40]. It is computed using equation [37]

$$MFD = \frac{FT}{FC}$$

This metric indicates the time spent by the participants focusing on individual objects. Longer fixation durations indicate that subjects spent more time and effort in evaluating and extracting information from the stimulus [41]. Longer fixations are also indicative of more visual effort and "substantial increase in demand for attentiveness [42]

Ratio of On-Target: All-target Fixation Time (ROAFT)

Each hazard in the case images was defined as the area of Interest (AOI), which is an area that fully encloses the hazard. The Ratio of "On-Target" to "all target" fixation time or ROAFT [43] is the sum of durations of fixation on AOI, divided by the total duration of all fixations for the entire case image (Area of Glance or AOG). It is computed using equation [43]

$$ROAFT = \frac{\sum_{i=1}^{n}\big(E(f_i) - S(f_i)\big) in\ AOI}{\sum_{j=1}^{n}\big(E(f_j) - S(f_j)\big)\ in\ AOG}$$

Where E and S are the end time and start time for i^th fixation (f_i) in AOI and j^th Fixation in AOG in numerator and denominator respectively.

This metric is a good indicator of the amount of visual attention devoted to hazards relative to the total time spent on the case image.

Fixation Rate (FR)

Fixation rate is the ratio of the number of fixation in AOI to the total number of fixation in the entire case image (that is Area of Glance or AOG).

$$FR = \frac{f_n}{f_N}$$

Where f_n = the number of fixations in AOI

f_N= Total number of fixations in AOG

The fixation rate is indicative of search efficiency, with smaller ratio suggesting that participants spend more effort in finding the pertinent objects, thereby indicating lower search efficiency [38].

4.1.2 Data analysis

After collecting the data, the correlation analysis was carried out for each worker to measure the correlation between each of the metrics listed above and hazard recognition performance.

For each worker, average HRI index was calculated using equation:

$$AV\_HRI_j = \frac{\sum_{i=1}^{n} HRI_{ji}}{n}$$

Where AV_HRI_j =average hazard recognition performance for j^th worker

HRI_{ji} = Hazard recognition index for jth worker in ith photograph

n=number of photographs = 12

Similarly, for each visual search metric described above, the average value was computed for each worker. Finally, Pearson's correlation coefficients were calculated for each metrics to obtain each of degree of correlation with hazard recognition performance.

4.2 Phase 2

Once relevant metrics are identified in phase 1, this phase focused on developing the framework for an automated vision based system that captures eye-tracking data from workers while they engage in their regular work and compute these identified metrics.

The framework of the system can be demonstrated in two sub phases- Pre-processing phase and test phase as shown in the figure 2 below.

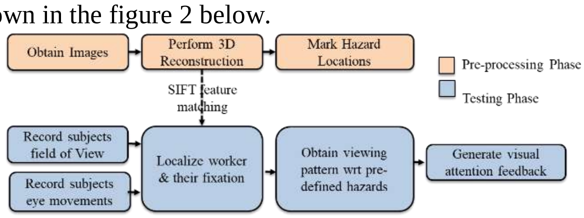

Figure 2. Method overview for Phase 2

4.2.1 Pre-processing phase

This phase focuses on building the pre-processing data. It is completed in two steps as detailed below

4.2.1.1 Obtaining initial reference images

Multiple images of a construction site are obtained using a monocular camera. The easiest way to obtain such images is to record a walkthrough video of construction site while following different trajectories. This ensures that objects are captured from different angles and distances. The frames are then extracted from this video, which serve as reference images to be used in subsequent steps.

4.2.1.2 Annotating AOIs

In this step, a panel of safety experts pre-identifies the hazards in the work site by watching the walkthrough video and conducting open discussions. The locations of these AOIs are marked on an initial set of images as AOIs. This can be semi-automated using homography matrices and affine transformation (discussed later in the case study). The hazards are annotated on preprocessing images as rectangular bounding boxes. The bounding boxes are defined by Xmin, Ymin & Xmax, Ymax, which correspond to the upper left corner and lower right corner of the bounding box respectively.

4.2.2 Testing Phase

This phase focuses on computing various visual search metrics for individual workers as they move in a real world construction site. This involves localizing the participant and their gaze positions at regular time intervals. This helps in defining participants' attention distribution and in turn compute various visual search metrics. The steps involved in testing phase are as follows:

4.2.2.1 Obtain test images

As participants move around the construction site, a wearable eye tracker equipped with an HD video camera can simultaneously record their gaze position & direction, and their field of view as first-person view (FPV). The image frames are then extracted from the recorded video, which serve as test images to be used in subsequent sections.

4.2.2.2 Localizing workers

In this step, the position of a worker at different intervals is obtained. The test images are appended to the point cloud, developed in pre-processing phase, and each test image is feature matched with the pre-processing images, to find the best match for each test image. Scale Invariant Feature Transform (SIFT) algorithm [44] is used to conduct pairwise matching. These matches (or correspondences) are stored in an array for future use discussed in step 2.4). The best match for a particular test image is the pre-processing image that has maximum matched features with it. The known camera location of the preprocessing image gives us the location of the participant for its best-matched test image. This enables us to track the trajectory of worker throughout the construction site.

4.2.2.3 Obtain gaze location for each frame

The goal of this step is to obtain the fixation point (gaze location) of the subject in each testing image. The wearable eye tracker records, the data stream that contains gaze position of the subject at every 1/100th second. Using the timestamps, the data is synced with the frame rate of the FPV to extract a gaze positions such that they represent each frame of the FPV. Since each frame represents a test image, we have a gaze position for every test image.

4.2.2.4 Transforming gaze positions using Homography matrices

After the 4.2.2.3, we now have a fixation point (gaze position) for each test image and from step 4.2.2.2; we have a corresponding preprocessing image for each test image. Hence, the objective of this step is to transform the fixation point location from test images to the matched preprocessing image. After this, the system checks whether the gaze location is within any of the AOIs or not. If it is, we count the fixation for that AOI and measure the duration of fixation using the timestamps.

To transform the location of fixation point from testing image to its corresponding pre-processing image, we compute the homography matrix for each match [45] using the correspondences obtained in step 4.2.2.2. The homography (H) matrix is calculated using the following equation 1 [45]

$$\boldsymbol{x_i'} = \boldsymbol{H x_i} \qquad \textit{Eq. (1)}$$

Where $x_i = [x_i\ y_i\ w_i]^T$ and $x'_i = [x'_i\ y'_i\ w'_i]^T$ are the point correspondences that are obtained through pairwise SIFT feature matching.

4.2.2.5 Obtaining viewing pattern with respect to pre-identified hazards

The following condition is checked for test image with x' y' being the transformed gaze position calculated above

$$X` > X_{min}\ \boldsymbol{AND}\ x` < X_{max}\ \boldsymbol{AND}\ y` > Y_{min}\ \boldsymbol{AND}\ y` < Y_{max}$$

Where X_{min}, Y_{min} and X_{max}, Y_{max} are the lower left and upper right corners of bounding box defining the particular AOI.

If the condition is met, it indicates that the fixation point is within the AOI. In this case, the fixation is counted for the particular AOI, if the condition remains true for at least 240ms (average fixation duration in a visual search process). The duration of fixation is obtained by calculating the difference between the timestamp when the condition was met and the last timestamp before the check fails.

4.2.2.6 Analyzing the data and computing metrics

Finally, the visual attention distribution for each subject is generated. Specifically, the output provides information about the areas subjects paid attention to and areas they did not. This information is used to calculate various visual search metrics identified in phase 1.

5 Results

5.1 Phase 1

The results of correlation analysis are shown below.

Table 1. Results of Phase 1

Metric	Pearson's Correlation Coef	p-value	N
SD	0.563**	0.005	23
FT	0.635**	0.001	23
FC	0.649**	0.001	23
MFD	0.393*	0.064	23
ROAFT	-0.093	0.673	23
FR	-0.132	0.548	23

** Significant at $\alpha = 0.05$, * Significant at $\alpha = 0.07$.

The results indicate that hazard recognition performance is strongly and positively correlated with search duration, fixation counts, and fixation time. MFD shows a weak correlation, which is also significant at $\alpha = 0.07$. This implies that searching for longer durations, focusing visual attention on more number of objects and areas, and fixating for longer durations can improve hazard recognition performance.

The results do not provide enough evidence to suggest that a relationship between hazard recognition and remaining two visual search metrics exist (at $\alpha<0.05$).

5.2 Phase 2

5.2.1 Case study Set up

The framework for automated capture and analysis of eye tracking data presented in this study was validated in a live construction site in Raleigh, North Carolina. The objective was to automatically record and analyze attention distribution of a subject while they move around the construction site wearing a wearable eye-tracking device and validate the accuracy of output by comparing it with manually computed results. Five hazards were pre-identified by a panel of safety experts in the portion of the construction site that was to be used for this case study. These hazards are shown in figure 3

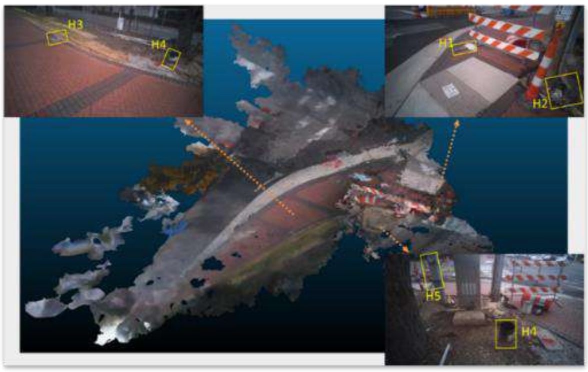

Figure 3. Predefined Hazards. H1: Trip Hazard; H2= Live Electrical Wires; H3: Protruding Rod; H4: Chemical Hazard; H5: Electric Junction Box

The methodology described in 4.2 was followed as explained below.

5.2.1.1 Pre-processing Phase

A walk through video of the selected portion of the site was recorded using Tobii glasses 2 front mounted HD camera with the 10p resolution. A one-minute and 42-second video captured the test area from multiple angles and 2512 frames were extracted that served as pre-processing images.

The features were extracted from these images using SIFT algorithm and these features were used to perform 3D reconstruction of the test area using Structure for Motion or SFM [46]. After this, the pre-identified hazards were annotated on the pre-processing images as AOIs. The AOIs were manually annotated in few images and using the homography between the images, the locations of AOIs were computed automatically on other images using homography matrices.

5.2.1.2 Test Phase:

The subject was tasked to move in the test area while his eye movement data and his field of view were recorded using Tobii glasses 2. It recorded the gaze position and gaze direction, which was used to compute the fixation point location (gaze location) of the subject. This data was recorded at 100Hz and the video was recorded at 25 FPS that captured subject's field of view.

The video recorded by Tobii glasses was exported and 362 frames were extracted from it, which served as test images. The eye tracking data was also exported and the data rows containing the gaze position were extracted. The localization of subject and his gaze position was carried out as explained in the method section (4.2.2.2). Finally, the number of fixations on each AOI and fixation durations were computed as described in step 4.2.2.5. The process was repeated for all test images to obtain the visual attention distribution for the subject while he was in the test area and compute all metrics described in 2.1

5.2.2 Case Study Results

The visual attention distribution for the subject was computed in terms of distribution of dwell times (total fixation duration on an AOI) among five pre-identified AOIs. The other visual search metrics were computed as described in section 4.1. Table 2 & 3 shows the results obtained from the proposed system.

Table 2. Visual Attention distribution of subject

DT_1 (ms)	**DT_2 (ms)**	**DT_3 (ms)**	**DT_4 (ms)**	**DT_5 (ms)**
900	235	257	1148	1270

Table 3. Visual search metrics computed by system

SD (ms)	**FC**	**FT (ms)**	**MFD**
18250	33	8212.5	248.86

As shown in Table 2, participant spent 18 seconds in the test area and fixated on 33 different objects/areas. The Dwell times are shown in table 1 DT1 to DT5 give the distribution of attention over different AOS, which indicate that the participant focused mainly on hazard 4 and 5 paid little attention to hazards 2 and 3. The total fixation time (FT) was 8.21 sec, meaning subject spent only 45% of the time in obtaining information from the scene; remaining 7.52 sec or 55% of the time was spent in searching with no acquisition of visual information.

6 Validation of Accuracy of Localization

To validate the accuracy of localization of fixation points, the dwell times obtained from the system were compared with the swell times computed manually using fixation overlay video obtained from Tobii's recording software. The fixation count for each AOI was obtained by manually counting the number of sets where fixation was within AOI for six consecutive frames. This was multiplied by the mean fixation duration to get the dwell time for each AOI. The results of validation show an accuracy is 88% on average.

Table 4. Validation Results

AOI	**H1**	**H2**	**H3**	**H4**	**H5**
DT1 System	900	235	257	1148	1270
DT2 Manual	744	248	248	992	992
Variation (ms)	156	13	9	156	278
Accuracy %	**83%**	**94%**	**96%**	**86%**	**78%**

7 Discussion & Conclusions

The results of this study advance the theoretical knowledge in the area of construction safety and assist researchers and practitioners develop effective training programs and hazard control strategies. This study represents one of the first research efforts towards understanding hazard recognition from a visual search perspective and evaluating the key parameters that impact hazard search. The contributions and the implications of this study are discussed below.

First, the study identifies and examines various visual search metrics that are closely related to hazard recognition performance. This paves the way for further studies aimed at identifying and studying the effects of various factors that influence workers ability to detect and recognize hazards in construction environments.

Second, the results suggest a strong correlation between the duration of search and the number of hazards recognized by a worker. The current practice does not require workers to spend a specific amount of time in searching for hazards. Instead, workers arbitrarily (or based on experience) examine the work environment, hoping to detect all hazards. Hence, sessions that involve hazard recognition in the field (such as Job Hazard Analysis) should be designed as such to require workers spend a set minimum amount of time to search for hazards in their work environment. Similarly, the training programs can focus on the importance of spending sufficient time in searching hazards as well.

Third, the second phase of the study demonstrates the use of computer vision techniques to automate the process of analyzing eye movement data. It presents a novel framework for developing a system that is capable of analyzing eye-tracking data with dynamic subjects in real environments, which is an active problem in eye tracking research. It helps in automated analyses of viewing behavior and visual attention distribution of construction workers on a large scale. This data can be used to provide focused and personalized process feedback to workers, which will help subject understand their viewing behavior and identify specific deficiencies in their hazard search.

Moreover, the system enables us to collect and analyze visual attention data on a much larger scale. This large data will help researchers better understand the relationship between viewing patterns and hazard recognition performance. The data can also provide insights about common viewing patterns among workers and help safety managers identify hazards that are more likely to remain unrecognized in construction sites.

Finally, the framework would be beneficial to eye tracking researchers in other areas as well, that require analysis of eye tracking data when subjects are moving in real-world environments.

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Electrical Appliance Control for Smart Buildings Using Real-time Location Tracking and Virtual Environments

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Abstract

Building automation is becoming increasingly popular due to the growing use of the Internet of Things (IoT) framework in the built environment. While there has been a spurt of mobile applications that control electronics in buildings, most of these utilize complex user-interfaces that require multiple interactions to realize user-intent which negatively impacts their adoption. In this paper, we present a framework that provides an intuitive and effective user interface to control electrical devices and fixtures in the connected home of the future. The framework utilizes a handheld point-and-click device that can be used to turn appliances on and off by pointing at them. This functionality is enabled by tracking the location of the device in real time within a virtual building model to determine the user's context and intent.

The position and orientation of the device is used to project a ray in the virtual world to determine the appliance of interest to the user, which is then controlled through the IoT infrastructure. The system is proposed to be implemented using ultra-wideband (UWB) and inertial measurement units (IMU). This research proposes a novel and necessary interface between users and "things" in the IoT paradigm for the built environment that does not require extensive modifications to the appliances itself. Future research will be performed to determine means of incorporating our framework into existing automation efforts such as motion-controlled devices and for defining presets for multiple devices through an extension of the presented framework. Additionally the virtual model also provides a means for tracking and accounting for the electricity usage of the home per device. This utility of the prototype enables sustainable maintenance and operations to optimize the energy-usage of buildings.

Keywords –

Smart homes, Internet of things, Appliance Control, Real-time tracking

1 Introduction

Over the past two decades, significant improvements in sensing and telecommunications has led to the emergence of smart environments [1]. This trend has resulted in the idea of smart homes take root in society, and we are starting to see isolated implementations of increasingly sophisticated tools, devices and systems for home automation. Examples of these innovations include automatic systems for temperature regulation, illumination control, and waste disposal.

The definition of what constitutes a smart/automated home has changed over time due to the rapid development of networking frameworks. Specifically, the growth of Internet of Things (IoT) applications in built environments has led to the increase of inter-connected platforms within the smart home.

According to Mendes et al. [2], a smart home is "A concentrator and disseminator of information and services to cover the totality of a home's functional areas in order to improve the levels of comfort and quality but also to provide a gateway or interface to the exterior by the means of an interaction with other paradigms". De Silva et al. [3] describes the smart home as a "home-like environment that possesses ambient intelligence and automatic control capable of reaction to the behavior of residents and to offer various accommodations (to them)".

It is observed that true home automation is only achieved when an established intelligent space improves overall user experience by simplifying and expediting the process of indoor environmental interaction. Creating an efficiently working intelligent area requires novel ways for humans to be able to communicate with it. An example of such an innovation is the context-aware system infrastructure for indoor location tracking. These technologies improve current smart house frameworks by providing an automated area in which the human location, orientation and gestures can be used to regulate and control appliances in the home.

Current methods of appliance control have improved the ability to exploit the functionality and utility of smart houses. However, these control devices are often expensive, with extensive hardware infrastructure, and inefficient interface operation. Given all of the above, it is the goal of this paper to present an appliance control prototype that fills in efficiency gaps discovered in others by providing an intuitive interface, cost-effective overall design and aesthetically pleasing architecture.

2 Literature Review

Research efforts in the creation of appliance control systems have culminated in mobile and fixed applications that utilize complex procedures that require multiple interactions and the recollection of numerous commands to realize user-intent. Moreover, many current state-of-the art automation systems have the disadvantage of being expensive due to the need for large amounts of physical components for these systems to work for both wired and wireless systems. This section highlights some of the issues with currently available solutions for home automation control.

2.1 Inefficient Interface Design

Based on literature review conducted by the authors, there are three main interface designs used for smart home control devices. These include graphical user interfaces, gesture driven interface, and command line interface. Identified products and prototypes have adequately been able to achieve some level of effective home automation. However certain limitations of these systems have been recognized. Details of these findings are provided in this section.

2.1.1 Graphical User Interface (GUI)

This interface type allows the user to interact with target appliances through graphical icons displayed on a control device. One method used to create GUI interfaces for controllers is with a top-down layout. The design works by providing echelonically arranged icons that allow specific actions to be reached the when the user progresses through the necessary hierarchical levels. When used for home-automation, top-down interfaced controllers typically have display screens that show the different areas of the building which contains all of the appliances or implements that the user could possibly interact with. These zones are made up of several tiers or layers that the user has to go through in order to locate the specific item they would like to communicate with. There are several examples of researchers employing this interface layout to successfully create remote controllers to communicate with appliances.

Vikram et al. [4] in 2017 designed a Wi-Fi based, low-cost automation system that had a similar GUI arrangement. The interface utilized an Android application and allowed the individual to exercise desired control over the lighting, air regulation and other electronics systems within their vicinity. Prototypes like the one created by Kumar and Sharma [5] also used a top-down interface design when creating a smart home platform that was controlled with both a computer and smartphone. The framework was fabricated to allow a remote user, control and monitor the on/off status of connected appliances within an interior intelligent space.

Despite the adequate functionality of the systems discussed above, their GUI top-down layout has an innate problem. Specifically, these kinds of interfaces excessively prolong actualization of an action in a target by requiring the refining of a user`s intentions before producing results. This procedure ends up defeating the entire purpose of home automation by making it more cumbersome than some traditional manual methods of appliance control. For example, an individual using a home automation device with a top-down interface in a small-sized room may have to go through several menu-screens just to turn off a light fixture. In this situation, flicking a wall switch (which is supposed to be the slower manual method) ends up being the faster way of realizing the user’s desires. Additionally, using top-down design approach creates difficulties when the interface has to be programmatically constructed. When a change has to be made to a menu screen, it is difficult making sure that the alteration is in the right hierarchal position in the top-down arrangement [6]. As a result, moving items across different graphical layers becomes overly convoluted.

To resolve the issues related to top-down interface layouts, different methods to GUI design have been proposed by different entities. One of these approaches suggested by Gamba et al. [6] utilized a reverse approach to the top-down methodology. They suggested a bottom-up strategy to create a different and more simplistic procedure of executing home automation. The goal of the researchers was to start from the thought of the user to affect a target in a zone.

Ultimately they ended up with a three-tier interface layout for reaching target areas. Even though the bottom-up approach is an improvement, it still requires multiple steps before a target appliance can be turned on or off. Moreover, for more complex appliance systems, the categorization of labels is required before the correct device can be chosen. This labeling process further complicates the construction of the system. Also developers have to always worry about arranging labels on a functionality basis. If this is done incorrectly, the system will revert to a top-down platform thereby defeating the overall goal of the proposed three tiered approach.

2.1.2 Gesture and Voice Driven Interfaces (GDI)

Gesture driven interfaces have also been increasing used for indoor intelligent spaces. The interface relies on specific physical gestures done by the user to create an automated response. Devices like the gesture pendant allow the wearer to control elements in the house via hand gestures [7]. Within the home, the pendant was used to regulate entertainment systems and room lighting with movement of the pendant wearers arm. Similar to this device, a smart class room was created by Shi et al. [8].The goal was to improve teaching within a school setting by utilizing video to recognize specific motions that can be used to display information and visuals needed to aid in student learning. Within workplace settings, systems like the Monica project employ gestural identifiers to retrieve and present needed information to employees within an office [9]. Ultimately, this helped streamline work processes by speeding up information recovery. More recently, electronic home-assistants such as Google Echo and Amazon Alexa are enabled with the functionality of control devices in the home using voice commands.

All of the examples listed above work well enough within their respective indoor smart environments. However, there is a fundamental issue with reliability when it comes to gesture and voice-driven systems. Most dependability problems stem from accidental activations. A user may be performing day to day tasks and set-off an automated response by unknowingly gesturing a signal. Contrastingly, in some situations, the user may actually intend to issue a specific command and the system may not respond due to the slightest inaccuracies in the individual's gesture or accent. Since there are not any templates in most of these systems to provide real-time direction on gesture accuracy, the user might have to try (without guidance) slightly changing their input multiple times before performing the right command. Consequently, this situation leads to frustration when the system is in use.

Additionally, a frequent user of the system may experience fatigue when using gesture driven interfaces. Particularly for hand-based gesture driven interfaces, having to do different motions constantly becomes an exhaustive process. This is especially true since most of these motions are not ergonomic, thereby causing muscle fatigue and user discomfort when done for a period. In the case of voice-based interface, the user is expected to verbally describe their intent, which would require them to suitably label each appliance in their home and recollect that label while issue verbal command.

2.1.3 Command Line Interface (CLI)

Even though considered dated, command line interfaces are still being used by some home automation developers. These interface frameworks work by allowing the user to provide commands in the form of lines of text. These texts then activate a response in target devices. Some mobile telephony technologies utilize command line interfaces to allow human interaction with a smart environment. By definition, mobile telephony refers to the connecting telephones to provide communication over distances. In 2008, Shahriya et al, [10] developed a procedure that utilized mobile telephony to communicate with appliances. This prototype used Short Message Service (SMS) capable mobile phones to provide attention commands that allowed communication with certain appliances within a home. One unique feature of the system is that it only supports Java enabled phones. This may prove to be a problem over the course of the decade due to the decline of manufactured Java enabled phones [11].

A similar telephone based design was proposed by Baig et al. [12] .Their prototype was created to help regulate appliances remotely by using a mobile application that required voice commands. The commands were then converted to line texts that were then transferred to a GSM network. Command line interfaces like the examples listed above have been tested and proven to work. However the major downside of these interface platforms is that they require the recollection of several different commands. Memorizing multiple different commands might prove difficult and overall negatively impacts user experience.

2.2 Extensive Hardware Infrastructure

The hardware requirements for extant home automation systems can pose to be hindrances to their adoptions. This section describes the components necessary for wired and wireless home automation frameworks.

2.2.1 Wired Frameworks

The history of home automation efforts begun first with the development of wired networking protocols. Power line communication frameworks were mostly used to achieve this end. These systems require the alteration of already existing communication lines to transfer both data and electrical power [13]. X10 technology is one of the older innovations that led the way in main stream use of powerline technology for home automation. The system allowed control device interact with target electrical units within the home. Even with this advantage, the inherent wired design of X10 created problems with distance restriction, power phase limitations and overall poor performance due to its unreliability. To resolve these issues, technology like A10 have been created to improve upon X-10 signals while other manufacturers have developed their own unique power line protocols (i.e. Universal Powerline Bus).

Despite these improvements in the utility and functionality of powerline frameworks, the fundamental issue of the system (i.e. requiring extensive hardware infrastructure) remains. This issue presents a problem since it leads to the increase in energy expenditure. Additionally, the need for large amounts of hardware limits the ability to scale the system since the implementation of changes will be difficult.

2.2.2 Wireless Frameworks

Wireless frameworks have recently been gaining popularity in the home automation industry as a more permanent solution to the limitations of current wired systems. Platforms like Z-wave help set the standards for wire-free home automation. Zigbee, which is similar to Z-wave, is another technology that provides great home automation service with great network reliability.

However, these wireless systems (and others similar to them) require receivers attached to their target appliances in order to be controlled by the user. The cost of installing individual receivers on each item increases home automation expenditure.

2.3 Goals of Proposed Prototype

After completing literature review and identifying gaps in the current state of the art, the authors present an alternative methodology that aims to accomplish the following goals:

1. Improved User-Device Interaction

Device aims to simplify user interaction with the smart indoor environment to allow a more straightforward means of communicating with target appliances. Utilizing a simple point-and-click device, the system should prevent users from having to navigate through several different graphical displays before being able to trigger a real-world action. This design should also allow minimal back-end modeling when there is a change in the layout of electrical appliances in a room.

2. Lack of Appliance Modification

Another goal set by the researchers is to create a system that does not require any additional modifications to the functionality of the electrical appliances themselves. The only alteration done will be to the power source of each target appliance. Wireless relay switch systems will be employed to this end.

3. Reduced Infrastructure/Cost

The system utilized ultra wide band wireless technology instead of a wired solution. Doing this should reduce the overall cost of the hardware infrastructure thereby curtailing the need for excessive wiring. Moreover, the proposed framework does not require target appliances to have receivers in order to work; further lowering installation costs. The reduction in infrastructure should also allow for a more aesthetically pleasing design without cables and wires strewn about the home.

4. Scalability

The research aims to create a dynamic prototype that is also scalable. The wireless nature of the prototype allows for the easy implementation of changes when the extension or reduction of the network is required. This is in contrast to wired installations, in which cable extensions are a tiresome affair [14].

3 Methodology

This section details the conceptual design of the proposed framework. The appliance control system is comprised of different components that are that are connected by wireless communication technology. The wireless set-up allows interaction between these device components and enables automation based on commands issued by the user.

To actualize these commands, the user requires input hardware. A microcontroller equipped with a position sensor was used to achieve this end. This data is then fed to a created virtual environment that is a model of the real-world indoor location. The virtual environment determines the user's desires through spatial analysis and communicates with a relay to enable or pre-vent the flow of power to the electrical device.

Discussed in the next few sections are details about the major components of the system and specifics on how they work. Figure 1 further highlights the processes involved to enable the prototype operate.

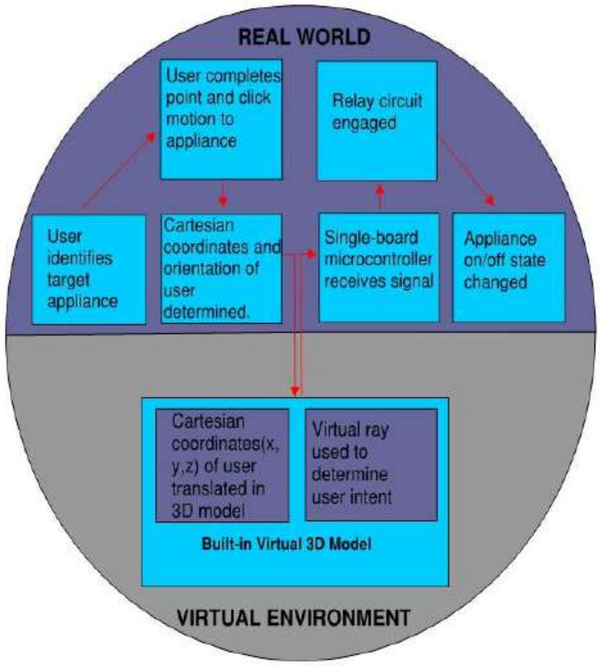

Figure 1. Process Model of Prototype

Figure 2 provides an overview of the components of the entire appliance control system. All physical components of the prototype are displayed with arrows indicating how each of them interacts to produce desired results during use.

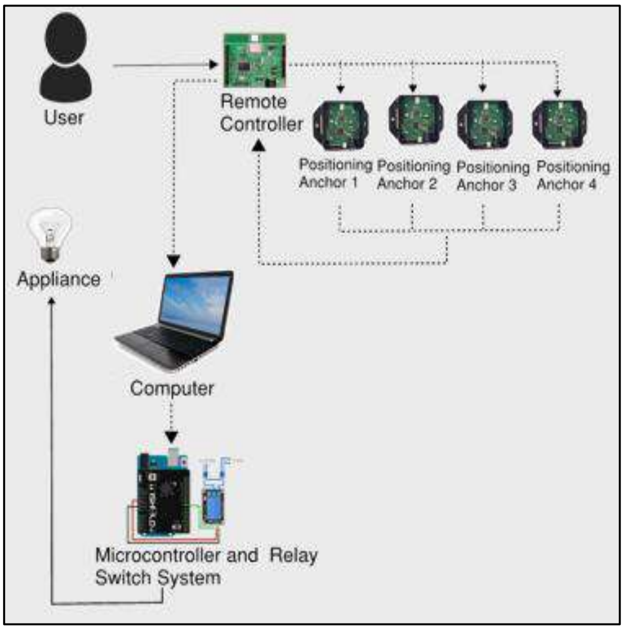

Figure 2. Overview of System Prototype

The systems consists of the following major components:

1. Position and Orientation Tracker

The system uses a position and orientation to provide information of an object or a user within a spatial area. This information is require to determine the user's intent as it will be used to select the appropriate appliance for control.

2. Handheld Remote

The remote device is the medium through the user directly interacts with the electrical appliance control system. The proposed handheld device will be a portable microcontroller with a singular button. This design concept allows for a user-friendly, easy-to-use gadget. This set-up is makes it easier and faster for the individuals to see their desires actualized.

3. Electrical Control System

This hardware component comprises of a microcontroller circuit board with wireless communication capabilities and a relay switch. The relay is necessary to separate the electric current required to power the appliance from that necessary for operating the microcontroller. This component is shown in Figure 4.

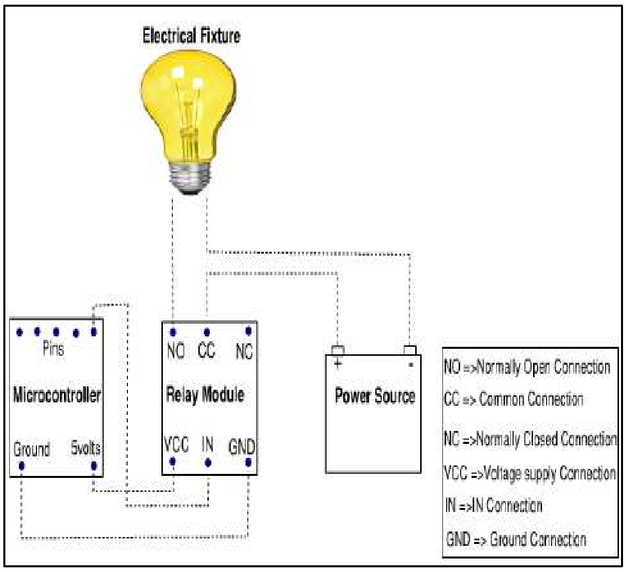

Figure 4. Circuit Diagram of relay/electrical control system.

1. Virtual Environment

A virtual environment was created as part of the main component of the of the appliance control prototype. The virtual environment will act as the medium that translates the user's intentions. The position and orientation of the handheld device is used to project a ray in the 3D environment to determine the appliance of interest to the user, which is then controlled through the IoT infrastructure. The pre-built virtual environment has the benefit of serving as a virtual reflection of the real-world location.

4 Case Study

A case study was performed to test a prototype of the system proposed for appliance selection. This involved selecting a suitable room with multiple electronic fixtures and performing the following steps as described in this section.

4.1 Virtual Environment Creation

After a room was selection, its geometric and spatial dimensions were obtained using a laser measurer. Care was taken to ensure that all measurements were highly accurate and were precise representations of the structural design of the room. Additionally, the spatial location of the light fixtures were determined and recorded. This spatial information was used to create a virtual model of the room.

To create the virtual environment, the research goals demanded a dynamic platform that allowed easy replication of any layout changes that might occur in the real word. Typically for architectural design work, building information modeling tools like Revit are used to graphically depict as-planned and as-built models of building structures. However for the purpose of this research, employing Revit for three dimensional design work would have proved limiting due to the software's long rendering time and lack of interactivity during walkthroughs [15]. To prevent this issue, a game engine, was used to create the virtual environment. Specifically, Unity 3D was the gaming tool utilized. Its programmable interface and cross platform ability made it the ideal tool required for the project [16]. Additionally the ability of the game engine to allow easy alteration to virtual elements means that unexpected changes in the real-world location can readily be replicated in the virtual environment to maintain a high degree of accuracy.

4.2 Positioning Tracking Technology Installation

Monitoring the location of the user required the installation of ultra wideband (UWB) tracking technology and motion sensors. To this end, UWB anchors were utilized to help determine the user's context within the confines of the testing location. This hardware is comprised of four anchor/sensors and a remote device.

To begin the installation procedure the four anchors were placed across the room at exact locations on walls.

To ensure the anchors positioned optimally they were placed at elevated points within the line-of-sight of the user. Care was also taken to ensure that all sensor hardware was spread around the user at different heights per anchor to improve coordination between anchors and boost their ability to deter-mine the 3D spatial location of the user. Additionally, anchors were placed far away from metallic objects to prevent diminished performance of the anchor's antenna.

Next, a tag was configured to enable communication with the anchors. The tag works by determining its location relative to the installed anchors in the room. This location dictating feature is facilitated through the creation of a coordinate system based on the spatial relationships between each anchor. One anchor is selected to be the origin point of the coordinate system. Going off this origin point, two other anchors are then set as the y-axis and x-axis. Once all the axes have been substantiated, manual measurements using a laser was conducted to determine for each anchor, their heights from the ground and their relative location on the created coordinate plane. Results obtained from these measurements represented the x, y and z coordinates of each sensor. Since all of these devices were distributed in a non-linear form around the location, the newly created coordinate system conformed to the rooms shape and orientation.

With the coordinate points set, the microcontroller is initialized by uploading it with code written in C language. The previously measured x, y and z points of each anchor is put into this code and algorithm uses this information to find the relative location and orientation of the handheld remote device.

This relative positioning algorithm works by treating the anchors as reference frames in a three-dimensional space and used these set points to determine the real time coordinates of the user as they move around the room. To read the orientation of the users pointing motion, the code was further expanded to communicate with an embedded gyroscopic and accelerometer sensors in the remote controller. Given the tri-axis nature of these sensors the absolute orientation or rotation of the device can be extracted. To do this, quaternions are utilized. The Quarternions which are represented by 4 parameters provide mathematical notation to represent rotation state of an object. Next, all of this data is communicated to the game engine software thereby allowing the real-world orientation and spatial location of the remote device to be visually replicated in the created 3D environment.

4.3 Relay Installation

For this step in the set-up process, a relay was installed to provide the means of controlling the appliance by leveraging electromagnetic fields to open and close the switches. The researchers performed following procedures to complete the relay-microcontroller framework:

4. Required components were identified and gathered for use. These components included a micro-controller circuit board and a 5V relay module.
5. Next, the connections between the controller circuit board and the relays were set-up. Using wiring, the board is connected to an inlet pin of the relay. Next the power supply pin (5V) and ground pin of the board is linked to the relay module.
6. The third step involves the relay connections to the ac current power source and the chosen light fixtures. The relevant relay terminals required to achieve this end are as follows:
    - Common connection: The central terminal of the relay. It was connected to the power source of the ac current.
    - Normally open: This connection is a switch for the circuit. Like the name suggest it stays open in its initial state. Closing it however allows current to flow to the light bulb, thereby turning it on.
    - Normally Closed: This connection is opposite to the normally open. When opened its interrupting the current flowing through the light bulb thereby turning it off.

Ultimately, the microcontroller was programmed to regulate the on/off state of the relay based on a received wireless signal.

4.4 Prototype Testing

Once all of the requisite components of the prototype had been set up, testing began. The test location was a simple rectangular shaped room in an office building.

A user was then given the point and click device to regulate the on/off state of each light fixture. To ensure that the prototype worked to maximum efficiency, the area of room was divided into 10 equal sized rectangular sectors. Then the tester was placed in each rectangular sector in the room and allowed to press the button that controlled the electrical appliance at different angles. Doing this helped the researchers ascertain the accuracy of the motions sensors in determining the user's context in the chosen location. Additionally selecting different areas of the room to activate the light fixtures, helped in calibrating the orientation-determining feature of the system to maximum efficiency. A distribution schema of 10 was selected to make it easier to obtain a percentage of accuracy for the prototype.

Figure 4 and 5 respectively show the real world use of the hand held controller and its replication in the virtual world.

Figure 4. Real-world testing of handheld point and click device.

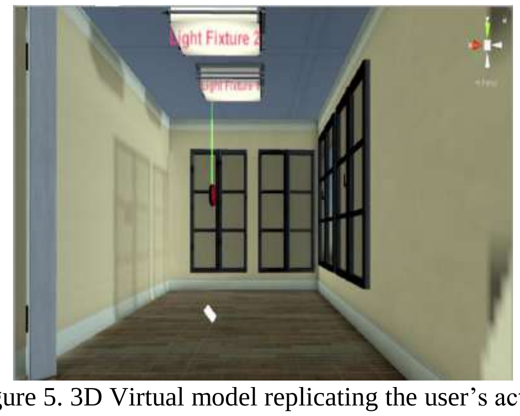

Figure 5. 3D Virtual model replicating the user's action

5 Results and Discussion

As expected, the completed prototype was fully functional for each sector throughout the room. The single button feature of the device created a direct method for the individual to interact with the test area. Also utilizing a simple design provided a shallow learning curve for the user to understand how to operate the device and expedited the process of target appliance response.

The system was created using ultra-wideband technology as the basis for wireless communication therefore curtailing the need for excessive components. This setup makes the prototype less physically extensive than wired systems for home appliance control.

Moreover using multi-connected electricity relay systems and a virtual environment for target identification further reduced the need for additional hardware components traditionally used in popular wireless platforms (i.e. receivers). Consequently this design allows for a more affordable, easily scalable and easily changeable prototype. All of these results and features of the final product meet the goals set by the authors and show the overall benefits of utilizing the proposed system for appliance control.

The concept of indoor-positioning innovations and context aware systems was introduced earlier in the paper to set up a simple positionally aware appliance control device. The proposed prototype was successfully created by integrating microcontroller circuitry, wireless communication, electrical relay switches, and virtual environments. Testing the limits of the created platform revealed its suitability in reaching all performance and design goals set in this research paper.

This research can enables applications within the field of home automation. The use of the prototype can be expanded by integrating an electricity usage monitor to track the power consumption of individual electronic appliances within the home. Doing this will encourage the user to adopt environmentally friendly behavior and aid them in managing their home by providing a means to regulate energy consumption (and thereby utility expenses) of the home.

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A Simulation-based Earthmoving Fleet Optimization Platform (SEFOP) for Truck/Excavator Selection in Rough Grading Project

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Abstract –

Earthmoving operations are complex system where many resources collaborate to carry out tasks. Although considerable efforts have been made in the development of efficient methods and systems for recommending appropriate fleets of equipment, in practice, average production rate method still prevails in favour of its simplicity at the cost of possible inaccuracy in planning and estimating at construction stage. In this paper, a simulation-based fleet selection methodology was introduced. Then, Simulation-based Earthmoving Fleet Optimization Platform (SEFOP), as an intuitive and efficient tool for equipment selection optimization in earthmoving operations, was presented. The proposed methodology and tool were applied on a real-world rough grading project and the outputted results proved that the SEFOP tool is able to provide a decision maker with insightful fleet selection strategy and accurate cost and duration estimates.

Keywords –

Earthmoving; Fleet Selection; Simulation; Optimization

1 Introduction

Due to the lack of specific information such as equipment models, the temporary haul road layout design, and earthworks volume assignment plans, it is unrealistic to come out with resource allocation plans by examining the detailed earthmoving operations at bidding stage. As a result, the industry often applies general deterministic approaches by applying “four to six passes” rule based on average production rates [1]. In particular, the average production rates are derived from RS Means [2] or other company-specific or industry-wide benchmarking database by considering basic factors such as fixed truck and excavator type, bucket size, hauling distance, soil properties, average cycle time, efficiency factor, and etc. This kind of average production rates based deterministic method for fleet selection [3] is widely taught at post-secondary institutions and is the primarily applied method in construction industry. However, once being processed to the construction stage when specific field information become available, average production rates methods may fall short in resource planning and productivity estimating as it only accounts for particular categories of equipment and work conditions. As proofed by Yi and Lu in [4], the method based on average production rates tends to underestimate crew productivity by an average of 30%, compared to detailed operation analysis method, resulting in poorly selected fleet and reduced chances to the successful earthmoving operation.

In order to help obtain the optimum resource allocation in earthmoving operations, a substantial number of researches have been conducted by modelling the earthmoving operations [5][6][7]. Gransberg [8] used a deterministic method of dividing the cycle time by the loading time of the trucks in order to determine the required number of haulers. Shi [9] used neural networks in order to determine the number of haulers required for a particular excavator. Later, heuristic algorithmic innovations have been integrated with simulation modelling to optimize earthmoving operations. Marzouk and Moselhi [10] successfully established an automated system named Earth Moving Simulation Program (EMSP). It will integrate heuristic algorithms into the simulation model to select a near-optimum fleet configuration. Cheng et al. [11] proposed simulation optimization by combining GA with CYCLONE or other simulation techniques. Zhang et al. [12] further proposed an integration of particle swarm optimization (PSO) and a construction simulation so as to determine efficiently the optimal resource combination for a heavy construction operation. Integrating genetic algorithm, linear programming, and geographic information systems (GIS). The simulation model for large-scale earthmoving operations are developed and successfully applied to two numerical examples [13]. Morley et al. [1] applied simulation to optimize truck numbers by allowing for a multiple truck and excavator types to be considered.

Nevertheless, field planners still use average production rates together with their experience by default for fleet selection at construction stage even though specific field information become available, due to the lack of professional simulation modelling and optimization training, and haste planning under time constraint. Based on author's personal research and working experience in construction industry in Alberta, field supervisors/managers are interested in simulation tools, but hesitate to apply due to prohibitive time consumption compared to average production rates method in the fast-paced and profit-chasing construction industry. In this context, it is necessary to devise a scientifically reliable yet easy-to-use tool to tap all the information at construction stage to result in a refined resource plan in guiding workface executions to the purpose of maximizing profit.

2 Haul Job Definition

In site grading project, haul job is the fundamental unit for earthmoving planning, resource allocation, and production estimating. In this paper, a complete haul job is defined by seven attributes: source, destination, earth volume, haul path, resource, duration and cost. Varying by the earth volumes and hauling route between source and destination, the resource allocation (i.e. truck number), cost and duration for completing haul jobs could differ considerably. Generally, a source is defined by a cut area where a destination is defined by a fill area. A haul route corresponds to a pair of source and destination with a pre-planned haul path, through which the trucks pass to haul the material from cut to fill. In this thesis, haul job is further classified into two categories: cut-dominated haul job and fill-dominated haul job.

Mathematically, a haul job is defined as $H_{ij} = \{v_{\mathrm{ij}}, P_{ij}, Res_{ij}, C_{ij}, T_{ij}\}$. v_{i} is the calculated soil volume in bank measure to be excavated in cut area i; v_{j} is the calculated soil volume in bank measure to be dumped in fill area i; v_{ij} is the soil volume to be hauled in current haul job. If $v_{\mathrm{i}} < v_{\mathrm{j}}$, H_{ij} is defined as a cut-dominated haul job; otherwise, if $v_{\mathrm{i}} > v_{\mathrm{j}}$, H_{ij} is defined as a fill-dominated haul job. P_{ij} is the haul path between cut area i and fill area j; Res_{ij} is an integer number starting from 1 to indicate truck numbers allocate to current haul job; C_{ij} *and* T_{ij} are total cost and total duration of current haul job respectively.

In practice, the earthmoving tasks are decomposed to haul jobs to guide workface operation executions. Similarly, in this paper, haul job serves as the fundamental unit in earthmoving fleet optimization.

3 Optimize Truck Number and Excavator/Truck Type

The number of trucks is determined in order to match up with the production rate of the excavator, which is generally assumed to be the governing resource in earthworks estimating. The number of trucks is dependent on the specific excavator being used, the specific truck type being considered, temporary haul road design, and the truck hauling cycle time. The truck selection starts with one truck. The average total haul job duration with one truck being employed will be recorded and corresponding total haul job cost will be calculated, according to Eq.(1):

$$C_{ij} = \frac{T_{avg}}{f}(U_t N_t + U_{ex} + U_{oh}) \quad (1)$$

Where T_{avg} is the average haul job duration from simulation; f is the operations efficiency factor; U_t is unit cost of truck in \$/hour; U_{ex} is unit cost of excavator in \$/hour; U_{oh} is unit cost of field overhead in \$/hour; C_{ij} is the total cost of haul job H_{ij}.

With same method, total haul job cost of employing multiple trucks can be calculated. The truck number selection strategy is illustrated in Figure 1. It is noted that the termination criterion "Cost N+1 > Cost N" means that employing one more truck will lead to total direct cost increase.

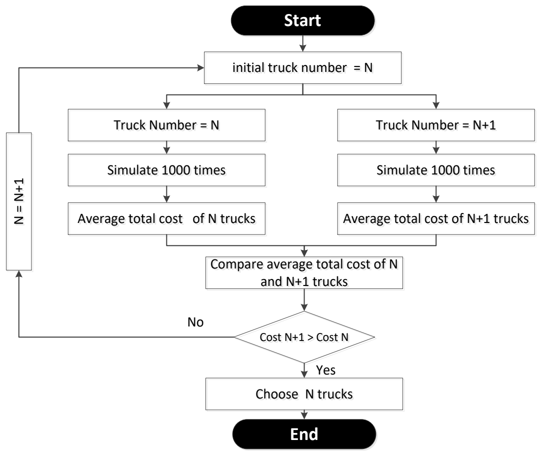


Figure 1. Simulation-based truck number optimization methodology

Having the basis of truck number optimization, truck/excavator type optimization can be made possible by adding one more loop by iterating all the possible truck/excavator combination, as shown in Figure 2. The total project cost (consist of multiple haul jobs) under different truck/excavator combinations will be calculated and compared to result in the optimal truck/excavator selection in terms of minimum total project cost.

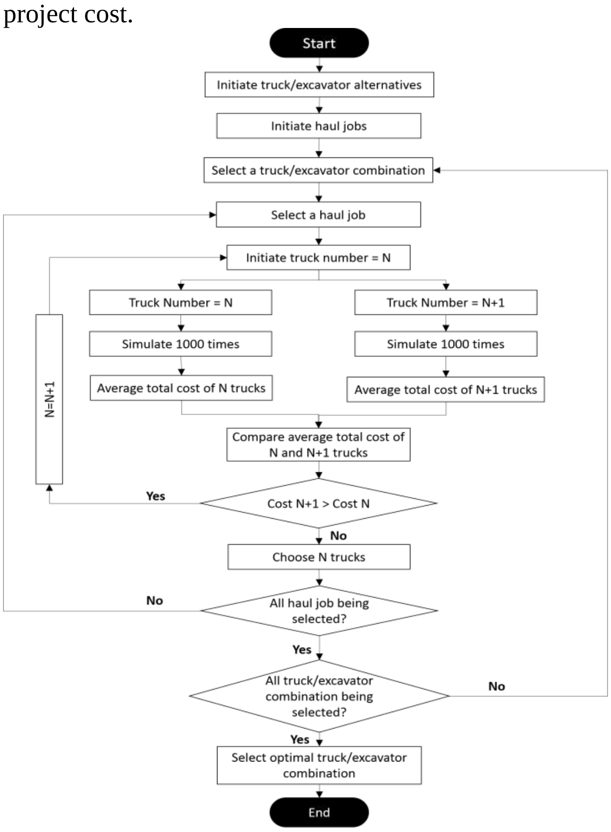


Figure 2. Simulation-based truck/excavator type optimization methodology

4 Simulation-based Earthmoving Fleet Optimization Platform (SEFOP)

For current fleet optimization problem in earthmoving operation, the whole operation process was simulated with discrete event simulation functions in SimPy, providing the foundation for the proposed Simulation-based Earthmoving Fleet Optimization Platform (SEFOP). The excavator was defined as resource in the simulation environment with a default number of 1. Truck loading, hauling, dumping and waiting was encoded with SimPy functions. When loading, the truck needs to call the excavator from resource in the simulation environment. The excavator was simulated to load the truck bucket by bucket when there is no other loading work occupied. When all the earthworks tasks done for current haul job, the program automatically outputs duration and cost, in order to identify optimal truck numbers.

Firstly, to optimize truck numbers, SEFOP will automatically simulate haul job cost and duration under different truck numbers to identify the optimal truck numbers in terms of minimum total haul job cost. Secondly, for equipment type optimizations, SEFOP will automatically simulate different truck/excavator combinations on the basis of truck number optimization program, outputting optimal truck/excavator types together with optimal truck numbers for haul jobs. In addition, SEFOP was programmed to allow optimization for multiple haul jobs.

4.1 SEFOP Main UI Screen

By running the SEFOP application, the below User Interface (UI) will pop up for users to (1) input haul job(s) parameters, and (2) select optimization mode.

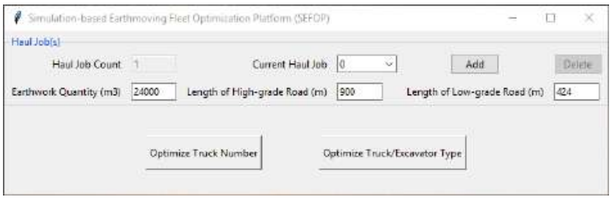


Figure 3. SEFOP User Interface (main)

For each haul job, users need to input "Earthwork Quantity (m3)", "Length of High-grade Road (m)" and "Length of Low-grade Road (m)". The program allows users to input multiple haul jobs by inputting haul job parameters and clicking "Add". Users are also allowed to check each haul job being inputted by choose haul job from a dropdown menu in "Current Haul Job", or delete any haul job by clicking "Delete".

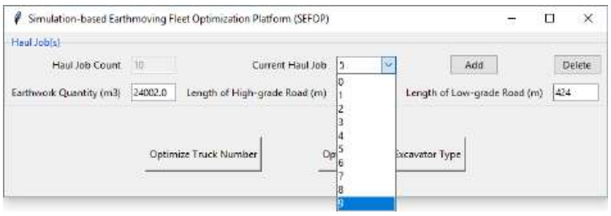


Figure 4. Add Multiple Haul jobs

Once haul job(s) information has been inputted, users can choose either to optimize truck number (when truck and excavator type being selected by field planner or no alternatives exist), or to optimize truck/excavator type (when truck and excavator types not determined and multiple alternatives available), by clicking either "Optimize Truck Number" button or "Optimize Truck/Excavator Type" button on the UI screen.

4.2 Optimize Haul Job Truck Numbers Function

If users choose to optimize truck numbers, the below

UI window will pop up.

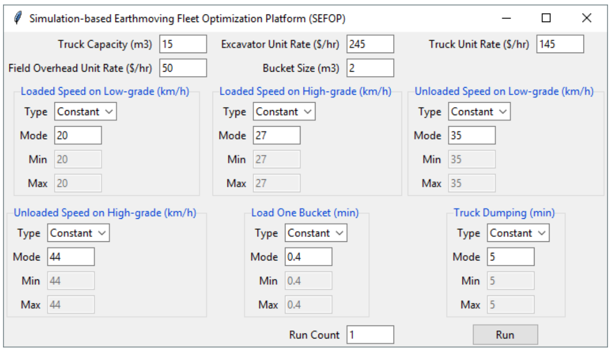
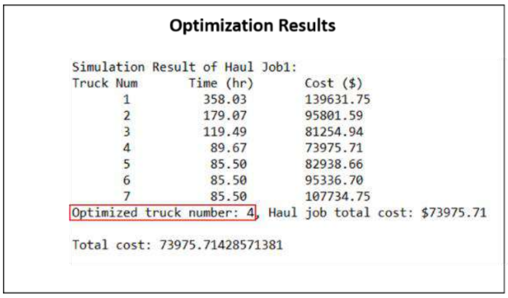


Figure 5. SEFOP User Interface (truck number optimization)

Users need to input "Truck Capacity (m3)", "Bucket Size (m3)", "Excavator Unit Rate ($/hr)", "Truck Unit Rate ($/hr)", "Field Overhead Unit Rate ($/hr)", "Loaded Speed on Low-grade (km/h)", "Loaded Speed on High-grade (km/h)" , "Unloaded Speed on Low-grade (km/h)", "Unloaded Speed on High-grade (km/h)", "Load One Bucket (min)", and "Truck Dumping (min)".

For truck speed and time inputs, users are allowed to input either deterministic value or distributive values by selecting "Constant" or "Distributed" from dropdown menu "Type". For distributive inputs, users are requested to input three values as "Mode", "Min", and "Max". The distribution used in SEFOP is triangular distribution.

The last input requested is "Run Count", to specify how many simulation runs the users expect for the program to iterate. Theoretically, the more run counts, the more accurate the final averaged results are. Once all the requested fields have been inputted, users can click "Run" to obtain the optimized truck numbers for each haul job. A sample output from SEFOP is shown in Figure 6 with optimal truck numbers marked with red box.


Optimization Results

```
Simulation Result of Haul Job1:
Truck Num        Time (hr)        Cost ($)
    1             358.03          139631.75
    2             179.07          95801.59
    3             119.49          81254.94
    4              89.67          73975.71
    5              85.50          82938.66
    6              85.50          95336.70
    7              85.50          107734.75
Optimized truck number: 4, Haul job total cost: $73975.71

Total cost: 73975.71428571381
```

Figure 6. Optimal Truck Numbers Output

4.3 Optimize Truck/Excavator Type Function

SEFOP is also able to optimize truck/excavator types together with optimal truck numbers for each haul job by considering the entire project. In SEFOP, if users choose to optimize truck/excavator type, the below UI window will pop up.

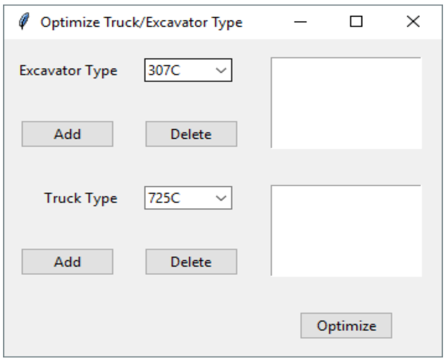
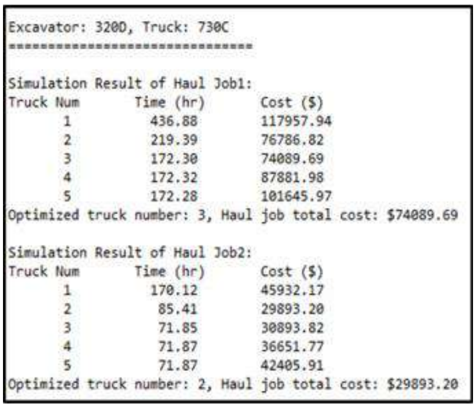
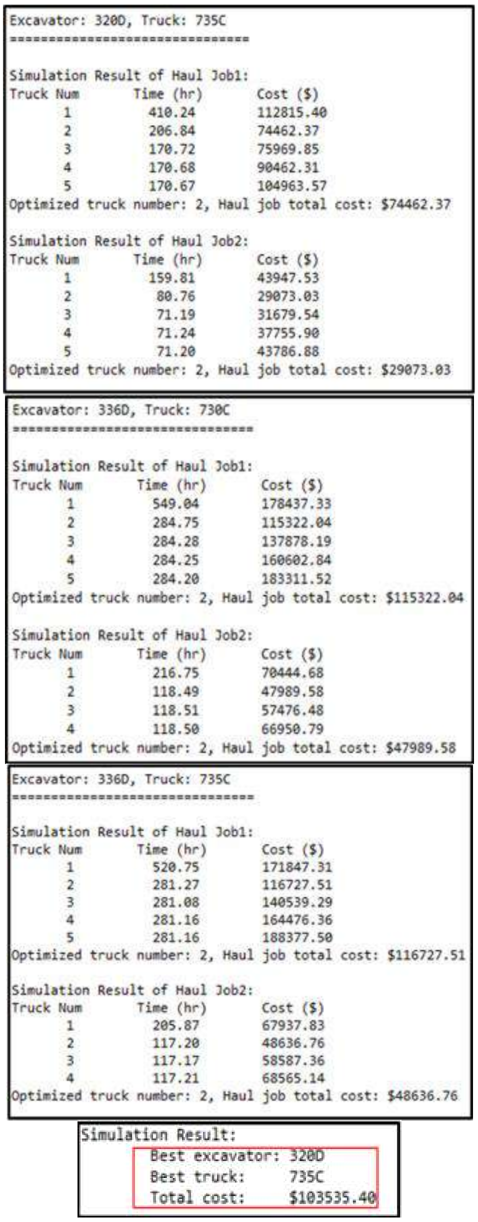


Figure 7. Optimal Truck Numbers Output

The program allows users to input multiple excavator and truck alternatives. Users are also allowed to select excavator type by a dropdown menu including all the common excavator types. Note the SEFOP application only include truck and excavator types from Caterpillar with truck and excavator performance parameters built in the program; the truck and excavator performance parameters can be easily accessed by Caterpillar Handbook [14]. Once excavator type is selected, user need to click "Add" to add the selected excavator type to the excavator pool. Users can delete excavator in the pool by selecting an excavator type in the pool then clicking "Delete". The truck type input functionalities are the same as excavator. Once alternative trucks and excavators are selected and added to the pools, users click "Optimize" to result in optimal excavator/truck type, together with truck numbers of each haul job and project total cost. A sample output from SEFOP is shown in Figure 8 with optimal truck and excavator types marked with red box.


```
Excavator: 320D, Truck: 730C
================================

Simulation Result of Haul Job1:
Truck Num        Time (hr)        Cost ($)
    1             436.88          117957.94
    2             219.39          76786.82
    3             172.30          74089.69
    4             172.32          87881.98
    5             172.28          101645.97
Optimized truck number: 3, Haul job total cost: $74089.69

Simulation Result of Haul Job2:
Truck Num        Time (hr)        Cost ($)
    1             170.12          45932.17
    2              85.41          29893.20
    3              71.85          30893.82
    4              71.87          36651.77
    5              71.87          42405.91
Optimized truck number: 2, Haul job total cost: $29893.20
```

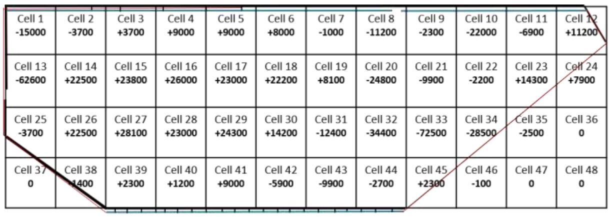


```
Excavator: 320D, Truck: 735C
==============================

Simulation Result of Haul Job1:
Truck Num        Time (hr)        Cost ($)
    1             410.24          112815.40
    2             206.84          74462.37
    3             170.72          75969.85
    4             170.68          90462.31
    5             170.67          104963.57
Optimized truck number: 2, Haul job total cost: $74462.37

Simulation Result of Haul Job2:
Truck Num        Time (hr)        Cost ($)
    1             159.81          43947.53
    2              80.76          29073.03
    3              71.19          31679.54
    4              71.24          37755.90
    5              71.20          43786.88
Optimized truck number: 2, Haul job total cost: $29073.03

Excavator: 336D, Truck: 730C
==============================

Simulation Result of Haul Job1:
Truck Num        Time (hr)        Cost ($)
    1             549.04          178437.33
    2             284.75          115322.04
    3             284.28          137878.19
    4             284.25          160602.84
    5             284.20          183311.52
Optimized truck number: 2, Haul job total cost: $115322.04

Simulation Result of Haul Job2:
Truck Num        Time (hr)        Cost ($)
    1             216.75          70444.68
    2             118.49          47989.58
    3             118.51          57476.48
    4             118.50          66950.79
Optimized truck number: 2, Haul job total cost: $47989.58

Excavator: 336D, Truck: 735C
==============================

Simulation Result of Haul Job1:
Truck Num        Time (hr)        Cost ($)
    1             520.75          171847.31
    2             281.27          116727.51
    3             281.08          140539.29
    4             281.16          164476.36
    5             281.16          188377.50
Optimized truck number: 2, Haul job total cost: $116727.51

Simulation Result of Haul Job2:
Truck Num        Time (hr)        Cost ($)
    1             205.87          67937.83
    2             117.20          48636.76
    3             117.17          58587.36
    4             117.21          68565.14
Optimized truck number: 2, Haul job total cost: $48636.76

Simulation Result:
        Best excavator: 320D
        Best truck:     735C
        Total cost:     $103535.40
```

Figure 8. Optimal excavator/truck type output

5 Case Study

A rough grading project was utilized for evaluating the proposed method. The rough grading project was the preliminary work package of a camp site construction in Fort McMurray, AB. The field was around 120 hectares, divided into 48 cells each being 150 m by 150 m, as shown in Figure 9.



Cell 1 -15000	Cell 2 -3700	Cell 3 +3700	Cell 4 +9000	Cell 5 +9000	Cell 6 +8000	Cell 7 -1000	Cell 8 -11200	Cell 9 -2300	Cell 10 -22000	Cell 11 -6900	Cell 12 +11200
Cell 13 -62600	Cell 14 +22500	Cell 15 +23800	Cell 16 +26000	Cell 17 +23000	Cell 18 +22200	Cell 19 +8100	Cell 20 -24800	Cell 21 -9900	Cell 22 -2200	Cell 23 +14300	Cell 24 +7900
Cell 25 -3700	Cell 26 +22500	Cell 27 +28100	Cell 28 +23000	Cell 29 +24300	Cell 30 +14200	Cell 31 -12400	Cell 32 -34400	Cell 33 -72500	Cell 34 -28500	Cell 35 -2500	Cell 36 0
Cell 37 0	Cell 38 1400	Cell 39 +2300	Cell 40 +1200	Cell 41 +9000	Cell 42 -5900	Cell 43 -9900	Cell 44 -2700	Cell 45 +2300	Cell 46 -100	Cell 47 0	Cell 48 0

Figure 9. Cut and fill cells with earth volumes

A total of 43 earthmoving haul jobs together with temporary haul road designs were obtained by employing the analytical method proposed by Li and Lu (2016) on the current case study project, as shown in Table 1. One fleet will be used to perform the earthworks job with one excavator being the lead resource that governs the production capacity. CAT 320D and CAT 336D excavators are available to this project. CAT 735C and 730C articulated trucks are considered for hauling the earth.

To apply SEFOP tool to optimize equipment selection, the 43 haul jobs in Table 1 were inputted into SEFOP, as shown in Figure 10. Alternative trucks and excavators were inputted as shown in Figure 11.

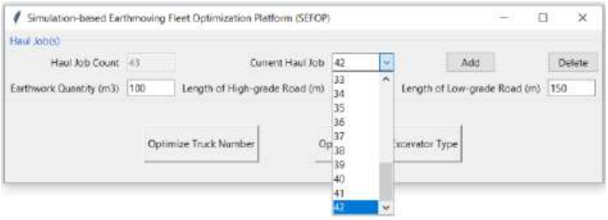


Figure 10. Haul job inputs in SEFOP (start from 0)

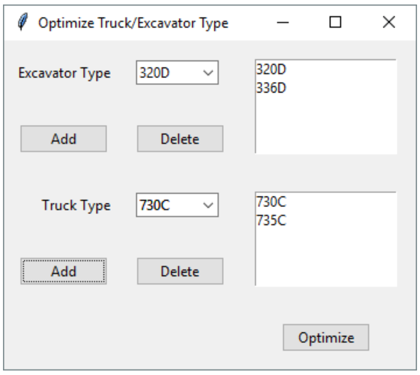


Figure 11. Equipment performance inputs in SEFOP

The simulation run count is set as 1000. By clicking "Run", the cost, duration, and optimal resource for each haul job of each excavator/truck combination were outputted. In this paper, only the results of the optimal excavator/truck combination were shown, in Table 1.

Table1. Optimal excavator/truck combination and cost, duration, and resource for each haul job

Job No	Volume (Bm3)	Haul Distance (m)		No. of Trucks	Duration (hour)	Cost ($)
		d_{gravel}	d_{rough}			
1	20000	1000	0	3	83.07	47764.1
2	15400	150	212	3	60.55	34814.3
3	19700	150	150	3	77.48	44550.7
4	7500	150	0	3	29.54	16984.6
5	15000	0	212	3	58.96	33901.0
6	3700	0	150	3	14.61	8398.7
7	1000	0	150	3	4.02	2311.4
8	4200	450	424	3	18.28	10513.7
9	7000	0	300	4	27.58	15856.0
10	2300	450	574	4	10.66	6126.6
11	7900	0	362	3	31.23	17954.6
12	4300	0	300	3	17.01	9781.2
13	9800	0	212	3	38.56	22173.8
14	6900	0	150	2	27.16	15614.4
15	2200	0	150	3	8.72	5011.7
16	2500	962	150	4	10.99	6319.2
17	15100	1112	0	3	55.36	31830.4
18	8900	662	212	3	33.50	19264.7
19	2300	0	212	3	9.12	5245.9
20	2200	0	212	4	8.81	6034.1
21	100	0	150	2	0.59	274.4
22	3500	812	212	4	15.22	8751.6
23	9000	662	212	4	29.39	16899.4
24	6800	812	0	3	27.32	15707.9
25	100	512	212	3	0.52	301.1
26	3100	450	212	4	12.54	7212.1
27	23000	662	0	3	51.23	29459.0
28	4800	600	0	3	18.95	10895.4
29	22200	512	0	3	48.01	27603.4
30	8700	812	212	3	37.71	21685.0
31	1200	450	424	3	5.31	3051.7
32	16700	600	0	3	39.37	22635.4
33	8100	150	0	2	31.93	18361.2
34	12400	300	0	3	48.77	28043.0
35	20200	600	0	3	79.41	45663.4
36	14200	300	0	3	55.87	32126.7
37	2700	512	424	3	11.93	6862.2
38	2800	300	212	3	11.13	6398.8
39	7100	150	212	3	28.03	16117.1
40	5900	0	150	3	23.25	13369.5
41	1400	0	150	3	5.59	3214.9
42	900	0	362	3	3.66	2103.2
43	2800	0	150	2	11.08	6368.2
		Excavator Type				336 D
		Truck Type				730C

As shown in Table 1, resource allocation, duration, and cost for each given haul job was optimized in terms of minimal operational cost as per methodology in Figure 1. By summing up costs for 43 haul jobs, total earthmoving cost can be obtained. Then, by comparing total earthmoving cost among four fleet combos (320D and 730C, 320D and 735C, 336D and 730C, 336D and 735C), 336D and 730C were selected as optimal solution.

6 Conclusion

A well-designed equipment selection and allocation plan is crucial to the success of earthmoving operations of rough grading projects. In order to help decision makers to select and allocate critical resources, this paper proposed a Simulation-based Earthmoving Fleet Optimization Platform (SEFOP) to automate the fleet selection and allocation process in earthmoving operations in an efficient and user-friendly manner. In specific, this tool provided planner a platform to do "what-if" analysis, providing insight for contractors to select optimal fleet for earthmoving operations. The proposed methodology and SEFOP tool were applied and tested dependent on a real world rough grading projects. It was shown that SEFOP could not only automatically optimize equipment selection and allocate trucks to each haul job consisting of the entire earthmoving job, this intuitive tool could potential improve the business efficiency in resource planning with maximization of profit. Future research will focus on integrating more practical features, such as the nature of soil, the amount of work, the type of earthworks, hydrogeological and other conditions in the simulation process to result in more accurate truck and excavator selection strategy.

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Quantitative Framework for construction Safety Evaluation in Designing Temporary Haul Road Layout on Site Grading Projects

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Abstract –

Temporary haul road layout design is a main factor influencing the cost and safety of haulage in heavy civil construction, especially on large site grading projects which entail mass earthworks. The ideal design of temporary haul road layout is to deliver the project in the lowest construction budget while guaranteeing haulage safety. Previous research endeavours have focused on achieving the lowest earthmoving cost in designing temporary haul road layout but failed to incorporate the equally important safety factors, thus rendering the optimized design to be possibly associated with high safety risks. This paper proposes a framework that aims to quantify haul road design related safety factors in a large site grading project. The feasibility and effectiveness of the proposed methodology is further evaluated by a real world case study. A comparative table with information on safety performance index values and safety indicator values of four alternative layout designs is given to visualize the quantification outcome. In conclusion, the proposed methodology enables construction planners to quantitatively evaluate haul road related safety impact, leading to significant improvements in the safety performance of temporary haul road layout.

Keywords –

Site Grading; Temporary Haul Road; Layout Design; Safety; Evaluation

1 Introduction

Haul roads are most commonly built in mining projects to improve hauling efficiency and ensure hauling safety on mine haul jobs. In the Guidelines for Mine Haul Road Design [1], haul roads are categorized into temporary, semi-permanent and permanent haul road. Unlike the mining project, for site grading and earthmoving operations over a large area, it is not realistic to link a loading area (cut) and a dumpsite area (fill) by permanent or semi-permanent haul roads since the project generally lasts several months. For improving hauling efficiency and safety in large site grading projects, the common practice is to build a limited length of temporary haul roads (e.g. gravel surfaced) along critical truck hauling paths on site. Due to its temporary nature, temporary haul roads are typically built with pit run, limestone or gravel with minimum thickness or even directly laid on rough ground. Generally, the temporary haul road can be simply classified as high grade vs. low grade where high grade haul road can be gravel surfaced while low grade haul road remains rough ground requiring frequent maintenance (by grader) [2].

While haul road design guidelines are available to regulate on various aspects of the haul road on mining projects (e.g. alignment, curvature, surface, and etc.) [1][3], there lacks insightful design specifications for temporary haul roads for heavy civil projects. In trying to establish the guideline, several research endeavors were made recently. Liu [4] proposed a multi-generation compete genetic algorithm (MCGA) to search for the least-cost temporary haul road layout design. Based on Liu's work, Yi and Lu [2] further proposed a more sophisticated mixed-integer linear programming (MILP) method to analytically identify the least-cost design by considering accessibility and connectivity constraints. Though cost-efficiency has been satisfied in the resulting design, the previously proposed methods failed to consider safety factors, thus making the optimized design possibly exposed to potential safety hazards.

As operations safety is highly dependent on well-designed, well-constructed and well-maintained haul roads, insufficient haul road design will have an immediate negative impact on operations safety. Due to the size and weight of earthmoving equipment, when accidents occur, consequences are often severe. According to electronic educational material published by Occupational Safety and Health Administration (OSHA), approximately 75% of struck-by fatalities involve heavy equipment. Also, in the same source it mentioned that one in four "struck-by vehicle" accidents resulting in a fatality involves construction workers, more than any other occupation [5]. The most common causes of heavy construction equipment accidents resulting in fatalities and injuries are categorized by OSHA (2003) [6], namely: (1) being caught in/between; (2) being struck-by equipment/falling objects; (3) falling from vehicle; and (4) equipment rollover. In a typical earthmoving site where large amounts of heavy equipment exist, a well-designed and maintained haul road network will considerably reduce the possibility of encountering safety hazards.

In order to incorporate safety as a design factor in designing temporary haul road layout, the quantification for the underlying safety hazards in a unified measurement is required. Given that there are no safety quantification methods for the earthmoving operations in existing literatures, the objective of this paper is to propose a conceptual framework that can support the quantification of safety by (1) introducing a grid model to represent the earthmoving site and temporary haul road layout design; (2) identifying haul road related safety impact factors in earthmoving operations; and (3) proposing formulating schema for each identified safety impact factor in a consistent unit of measure based on the presented model. The following sections provide a detailed description of how to fulfil the objective step by step with a practical case study.

2 Grid Model, Graph, And Traffic Flows

The grid model of a possible haul road layout design on a rough-grading site was proposed by Liu and Lu, (2015) [4], as demonstrated in Figure 1. For each cell, the centroid is simplified to be the cell's geometric centre; thus, the potential road layout design can be denoted by road links, each connecting the centroids of two adjacent cells with straight-line sections. The road type of each link can be distinguished by a dot line for "rough ground" by default and by a solid line for "gravel surfaced". It should be noted that the "road links" are segments between the centroids of any two adjacent cells, instead of between any two cell centroids; two cells are deemed adjacent only if they are 'immediately adjacent' or 'diagonally adjacent'.

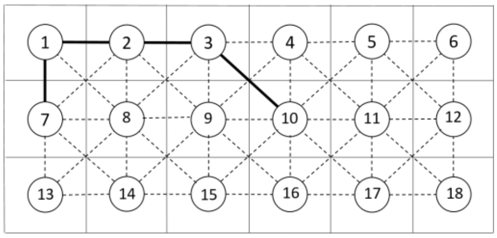


Figure 1. Site partitioning strategy and road links to represent haul road design

Based Graph Theory, an undirected graph is written as $G = (V, E)$, meaning that G consists of node-set V and edge-set E. We use v to represent a node (centroid of a cell) and (i,j) to represent an edge (road link) in the haul road network. Note $\forall$ v $\in$ V, and all $\forall$ (i,j) $\in$ E where i and j are end nodes of edge (i,j). The type of haul road is denoted by a Boolean parameter $x_{(i,j)}$, which equals to "0" given "rough ground" haul road; equals to "1" given "gravel surfaced" haul road (e.g. in Figure 1. $x_{(1,2)} = 0$; $x_{(6,7)} = 1$).

Validated by previous research [4][7], when cut and fill volume data of each cell is given, the optimally allocated traffic volumes on each road link (i.e. traffic flows, in m^3) can be determined by applying linear programming techniques, as shown in Figure 2. The previous research achievements for determining traffic flows on each road link lay a firm foundation for proposing safety index formulating schema described in the subsequent chapter.

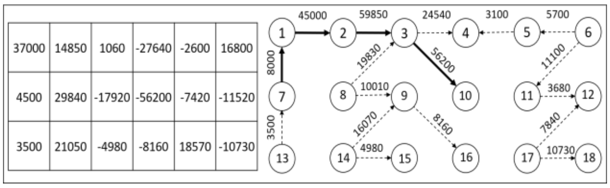


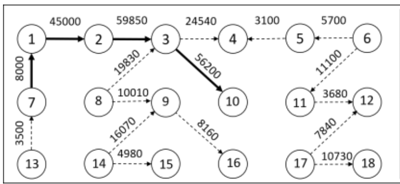
Figure 2. Cell based cut and fill design and optimal earthwork flows

3 Safety Quantification Framework

In trying to quantify hauling safety in earthmoving based on the presented model, a comprehensive literature review [1][3][8] and several field studies were conducted in order to define practical measures that can be taken during the temporary haul road layout design process in evaluation of construction safety. This investigation led to the identification of three major safety measures: (1) proper design of temporary haul road (both geometrically and structurally) to improve the safety at curves and minimize the hazards (e.g. collision, out of control) caused by blocking line of sight; (2) reducing surface hazards such as potholes, rutting, settlement, wash-boarding, and heaving caused by heavy traffic volume; and (3) control of hazardous equipment near labour-intensive onsite facilities.

3.1 Curve Safety Index (CSI)

In current model, a curve is denoted by (i,j,k), which stands for truck hauling from node i to node k, passing node j; i is curve starting node, j is curve centre node; k is curve ending node; note i and k are interchangeable since trucks haul in round trip. In this study, three curve angles are considered, as 45°, 90° and 135° in alignment with the grid model, as illustrated in Figure 3. The dot circles indicate curve centre nodes. Different curves could share the same curve centre node, forming an intersection (e.g. node 3). All the curves are identified based on earthwork flows and cut and fill design, as summarized in Figure 3.



Curve ID	Curve nodes	Curve Degree
1	7_1_2	90°
2	14_9_16	90°
3	2_3_10	45°
4	8_3_4	45°
5	6_11_12	135°

Figure 3. Horizontal curves

From a safety standpoint, haul road must be designed to accommodate the braking capabilities of those vehicles having the least braking potential which will most likely to transverse or directly hit on obstacles (such as wild animals, breakdown trucks, and falling rocks) due to inability to stop in time. This situation is especially severe at horizontal curves. At curves, driver's line of sight is blocked by a hill crest, trees, or an obstacle on the inside of the curve. Insufficient stopping distance can adversely affect the truck hauling safety at a curved section. According to published design regulations [1][3], truck's stopping distance is related to road grades, friction coefficients, rolling resistance, climate condition, and truck sizes. In order to guarantee the safety of truck hauling at curves, contractors are responsible to properly design the temporary haul road layout. To this end, a minimum stopping distance is required to guarantee the hauling safety at curves.

In this paper, the degree of safety at curves is quantified by a performance metric named Curve Safety Index (CSI), scaled from 0% to 100%. This index is formulated in Equation (1):

$$\text{CSI}\ (\%) = \text{Function}\ (\text{R}, \text{SD}, \text{L}, SD_{ijk}^{z}) \qquad (1)$$

R is the minimum allowable radius of a horizontal curve which can be found in AASHTO Green Book, (2001) [9]. In this study, it is assumed that the minimum allowable radius criteria are used by the contractors to design the curve's geometry at the preliminary design phase in that a lot of detailed information on site conditions and crew selections are generally unavailable. With R known, the minimum stopping distance (SD) can be derived from equation in [10]. According to the equation in Department of Labor (1999)[8], the actual stopping distance (L) can be estimated.

With L and SD known at each horizontal curve, a percentile-based measurement indicating the degree of risk in accordance with the SD-L relationship is proposed, namely stopping distance safety indicator (SD_{ijk}). This indicator (SD_{ijk}) classifies the SD-L relationship into four different categories, as (1) L ≥ SD, which represents the occurrence of accidents with SD_{ijk} valued at 100%; (2) 3/4 SD ≤ L < SD, which represents the high risk due to high probability of haulage-related accidents - any minor misbehaviour would cause accidents, SD_{ijk} is valued at 75%; (3) 1/2 SD ≤ L ≤ 3/4 SD, which represents an intermediate level of risk due to low probability of haulage accidents such as driver's absent mindedness and brake failure, SD_{ijk} is valued at 50%; and (4) L ≤ 1/2 SD, and therefore haulage safety is unaffected with SD_{ijk} valued at 0%.

3.2 Surface Hazard Safety Index (SHSI)

According to Thompson and Visser [11], haul road surface condition is related to traffic volume, wearing courses, maintenance management and weather. Failure to establish a good haul road surface will result in increased possibility of encountering surface hazard. Poor haulage surfaces (e.g. potholes rutting, settlement, wash-boarding, frost heaving, and etc.) caused by poor compaction, precipitation/runoff, heavy traffic volume, and inadequate maintenance will severely compromise the ability of a vehicle to safely negotiate the route; or in many instances, drivers may attempt to avoid a certain situation, which could cause serious accidents [12]. According to Mine Safety and Health Administration (MSHA) [8], the surface haulage accidents include: (1) haulage trucks going out-of-control; (2) vehicles/persons being run over by large trucks; and (3) trucks going over dump points. These hazardous situations need to be properly addressed so as to minimize the risk of haulage accidents.

In order to improve safety on construction sites, planners need to comply with MSHA standards and design proper haul road surface condition onsite. The haul road grades should be selected according to truck type, traffic volumes, and maintenance frequency. In the present model, a newly developed performance metric named Surface Hazard Safety Index (SHSI) is proposed to accommodate the quantification of haul road surface hazard. As shown in Equation (2):

$$\text{SHSC}(\%) = \text{Function}\ (f_{ij}^{1}, f_{ij}^{2}, QM_1, QM_2, \text{N}) \qquad (2)$$

f_{ij}^1 is the allocated traffic flows on rough ground haul road while f_{ij}^2 is the allocated traffic flows on gravel-surfaced haul road; N is the total quantity of haul road segments onsite; QM_1 and QM_2 are the "need maintenance" threshold volume of earth being transported on rough ground haul road and on gravel-surfaced haul road, respectively; which means once QM_1 m3 of earth have been transported on rough ground and QM_2 m3 of earth transported on gravel-surfaced haul road, the haul road surface deteriorates to the need - maintenance level. The maintenance frequency, denoted as f_{ij}^1/ QM_1 and f_{ij}^2/ QM_2, will help classify the degree of risk in the present methodology. The higher maintenance frequency, the more likely trucks will encounter surface hazard. The degree of risk can be expressed as 10%*(f_{ij}/QM), subject to $f_{ij}/QM \leq 10$.

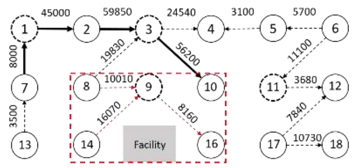
3.3 Travel Routes Safety Index (TRSI)

On site construction facilities such as parking lot and temporary office, where the density of workers peaks among the entire site, is the most sensitive area to safety issues. Frequent truck hauls near the facilities will not only expose the workers to high safety risks (e.g. hit by out-of-control trucks), other harmful effects such as noise, air pollution by dust, and etc., will be produced, potentially influencing workers' health. Therefore, the haul roads need to be properly designed to minimize the safety impact near these facilities. OSHA recommends possible hazards (e.g. fire, explosions, pollution, heavy traffic) shall be located far away from onsite facilities [6].

The present model incorporates a newly developed performance metric named Travel Routes Safety Index (TRSI), as shown in Equation (3). In calculating TRSI, the model allows the user to specify whether a haul road segment within safety impact area (1) has a high level of traffic and close distance to facility, giving rise to high safety risks; or (2) has a low level of traffic and far distance to facility, therefore does not create a significant risk.

$$TRSI(\%) = Function\ (d_{ij-f}, TR_{ij}) \qquad (3)$$

Where d_{ij-f} is the shortest distance between the geometric centre of the facility and the haul road segment; TR_{ij} is a percentile-based measurement indicating the degree of risk in accordance with traffic volume and haul road grade (as shown in Figure 4). In the present model, a safety impact area is defined as a rectangular area within site boundaries that contains the facility area, with 100 meters side-to-side distance (assume all facility areas can be represented by a rectangle). A detailed illustration is given in Figure 4. The red dot line encompassing the onsite facility denotes the safety impact area. The red dot haul road links denote the haul road segments presenting significant safety risks to the facility.



Haul Road Grade	Level of Traffic	Hazard Degree	TR_{ij}
Rough Ground	High	Very High	100%
Gravel-surfaced	High	High	75%
Rough Ground	Low	Medium	50%
Gravel-surfaced	Low	Low	25%
No Road	N/A	No Hazard	0%

Figure 4. Measuring the near-facility hazard on site

3.4 Haul Road Safety Indicator (HRSI)

Therefore, the temporary haul road layout safety is quantified by introducing a safety indicator named Haul Road Safety Indicator (HRSI), which aggregates the three indexes by relative weights, as shown in Equation (4):

$$\mathrm{HRSI} = \mathrm{w1} * \mathrm{CSI} + \mathrm{w2} * \mathrm{TRSI} + \mathrm{w3} * \mathrm{SHCI} \qquad (4)$$

In this formula, the relative weights (w1 to w3) of the three safety indexes can be best obtained from historical safety records of previous projects that classify fatalities and/or injuries into these three major categories. In the absence of such company data, the planner can provide his/her best judgment on their relative weighting by referencing national average figures such as the occupational injuries statistical report published by Bureau of Labor Statistics [13].

4 Case Study

A practical rough grading project is utilized for evaluating the proposed method. The rough grading project was the preliminary work package of a camp site construction in Fort McMurray, AB. The field is divided into 48 cells each being 150 m by 150 m. The project had a total amount of 335,600 m3 of banked earth to be handled from cut and fill. The material considered has no appreciable swell. The cut (-) or fill (+) volume of each cell along with the cell identification number is shown in Figure 5.

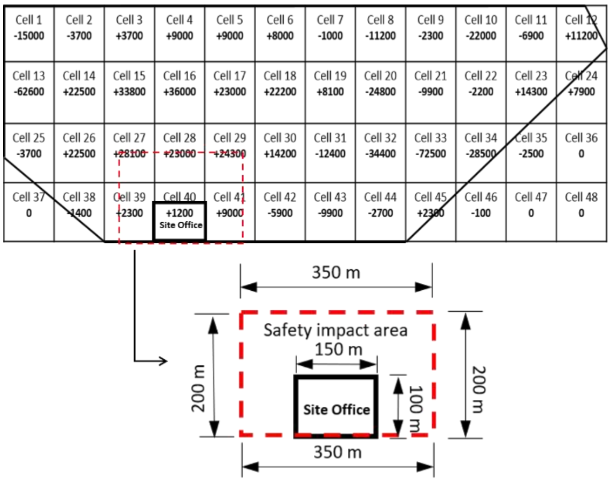


Figure 5. Haul road within safety impact area of onsite facility

The relative weights denoting the three safety indexes were chosen as w1: w2: w3 = 0.4:0.4:0.2. The four layout design options in [4] are selected for evaluation purposes, as shown in Figure 6-9. The proposed approach is coded in Python Version 3.5 [14]. The safety evaluation results of the four layout options are summarized in Table 1.

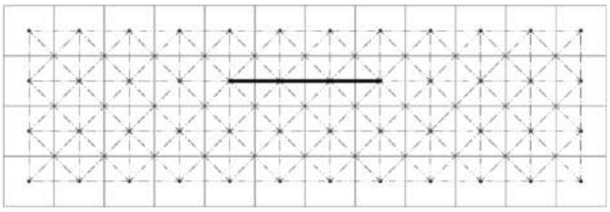


Figure 6. Haul road layout option 1

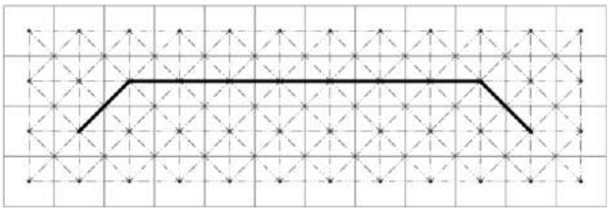


Figure 7. Haul road layout option 2

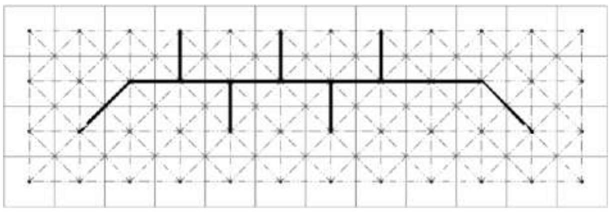


Figure 8. Haul road layout option 3

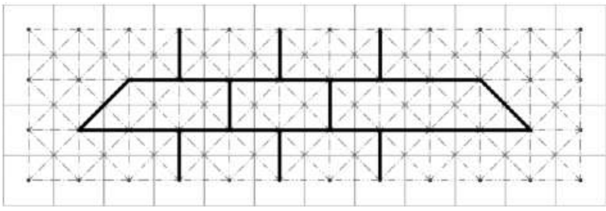


Figure 9. Haul road layout option 4

Table1. Safety evaluations and comparison between the layouts

Layout Option	Road Length (m)	CSI (%)	SHSI (%)	TRSI (%)	HRSI (%)
1	450	65.8	75.3	50.0	66.44
2	1,474	58.5	64.5	57.1	60.62
3	2,224	46.0	55.3	57.1	51.94
4	4,024	34.6	25.7	71.4	38.40

Layout 1 is the riskiest design alternative (HRSI = 66.44) while layout 4 has the least safety risk (HRSI = 38.40). The proposed methodology can lend effective assistance for designers or project manager to evaluate hauling safety, providing insight in designing safer temporary haul road layout.

5 Conclusion

This paper proposes a framework for the quantification of temporary haul road related safety to aid in designing a safer temporary haul road layout in large site grading projects. The quantification approach is developed in four major steps that focus on (1) modelling the earthmoving site and temporary haul road network; (2) identifying potential safety hazards in earthmoving operations in connection with haul road designs; (3) proposing formulating schema for each identified safety hazard in unit measure (0%-100%); and (4) integrating them into a unified safety indicator. A case study with four alternative temporary haul road layout designs is given as a test-bed to evaluate and validate the proposed methodology. The safety evaluating results for respective design alternatives are summarized in a comparative table to intuitively visualize the quantification outcome. In summary, the proposed methodology can be readily implemented in the real world in order to materialize safety impact on temporary haul road layout design. In addition to safety evaluation, the research deliverables could lay a solid basis for immediate future research in developing a robust model that supports multi-objective optimization of temporary haul road layout design in order to realize maximization of safety and minimization of total earthmoving cost simultaneously.

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Exploring Virtual Reality in Construction, Visualization and Building Performance Analysis

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Abstract

In the past two decades, the Architecture, Engineering and Construction (AEC) industry has investigated different approaches to improve communication among project parties, including Virtual reality (VR) however these approaches have not been widely adopted by the industry.

Today, the tremendous advancements in technologies and computer hardware have potentially improved the current approaches and enabled a significant enhancement of user experience of Virtual reality (VR) devices. Based on that the researchers have conducted a review to investigate the global VR applications research in (AEC) community in 2015-2017 to understand the status and the trend of immersive virtual reality (IVR) research in the world using these affordable devices.

This paper also presents a result of an experiment to integrate three different types of AEC digital modeling data and proposed workflows for IVR applications in construction, visualization and building performance analysis. The experiment deals with construction simulation, rapid generation of the VR scene for existing building and airflow visualization. Several workflows investigated game engine and VR tools have been used.

Keywords –

Virtual reality; Laser scanning; Building performance simulation; Visualization

1 Introduction

The Virtual reality (VR) technology has emerged in various domains in the past two decades. It enables the users to immerse themselves in a computer-generated environment which simulates complex, real situations and contexts[1]. The experience of wearing the VR headset has been significantly enhanced due to the tremendous development of computer hardware, central processing unit (CPU), graphics processing units (GPU), data storage et al. Also, these devices have become more affordable. In fact, any business considers computer graphics and 3d modeling will be affected by this technology[2]. The Architecture, Engineering, and Construction (AEC) industry heavily rely on digital modeling, visual communication and simulation[3]. This has attracted the research interests to investigate and applying VR technology to AEC applications.

This paper presented a review of the development of VR technology and their uses in AEC industry through literature review, and conduct an experiment to implement immersive virtual reality (IVR).

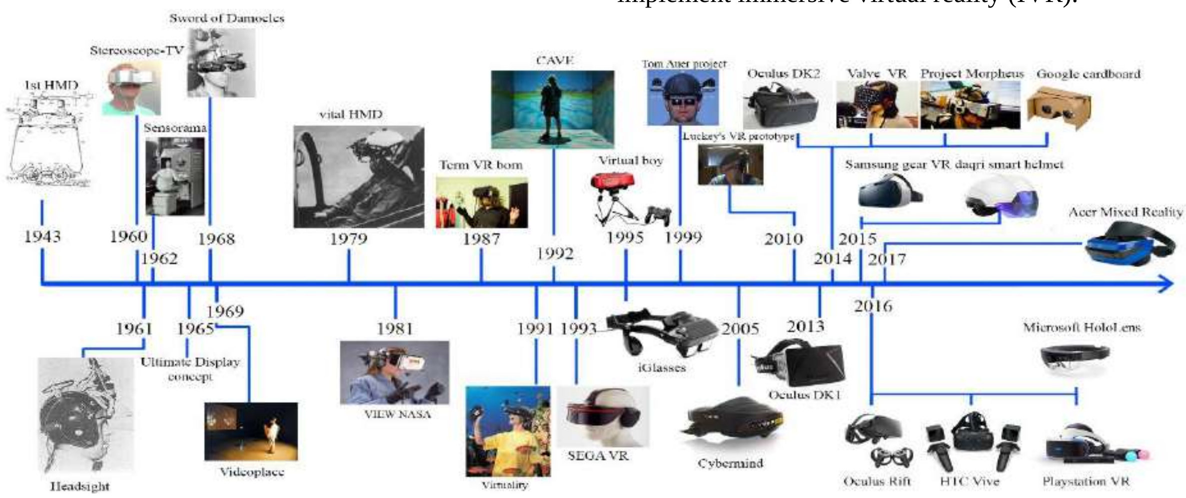

Figure 1. Development of VR headset

2 A review of VR applications in AEC industry

The research compiled the timeline below that demonstrates the development of VR devices Figure 1. The first head mounted display (HMD) was created by McCollum in 1940s. His idea was to display noninteractive films supporting visual display without tracking motion, but there was no integration of computer and image generation. In the late1980s, the term VR was coined by Jaron Lanier. It combines the devices with video imaging and computer graphics[4]. Now, many headsets have been devised which enable human interaction with computers using motion controllers, depth-sensing camera and natural user interfaces.

This review analyzed all articles related to VR applications since 2015 in the Web of Science core collection database. The review centred on architectural design, construction and building technology. A total of 2,790 paper was found. Figure 2 shows the number of research articles published by authors from different regions. Only the regions that have at least 27 publications are listed here. The researchers from the USA (756), England (286), China (224) and Germany (224) have made the most significant contributions in these areas. Also, researchers for the USA have widely collaborated with researchers from other countries (presented as the thickness of the links between the nodes).

Based on an analysis of the keywords of the 2,790 bibliographic, only 89 articles have been identified that are most related to VR applications in the AEC industry. The keywords used in these articles are shown Figure 3.

The keywords were clustered into five groups (shown in different colours in the figure). They are also listed in Table 1.

Table 1 Clusters of keywords used in publications related to VR applications in AEC industry

Group	Keywords
1	Architectural design BIM Design Environment GIS System Visual geographic environment Visualisation
2	Augmented reality Construction Dwelling Education Mixed reality Safety Technology Unity
3	Architecture Cultural heritage Perception Space perception Virtual reality
4	Evacuation Games
5	Construction safety Management

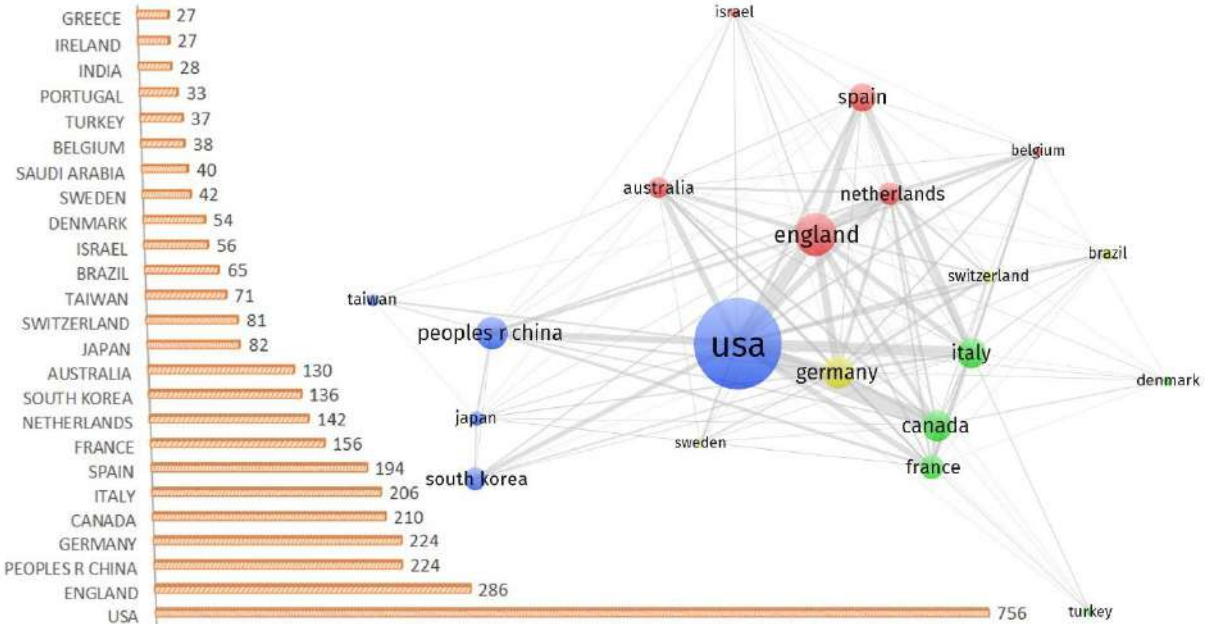

Figure 2 Number of related publications by researchers from different regions

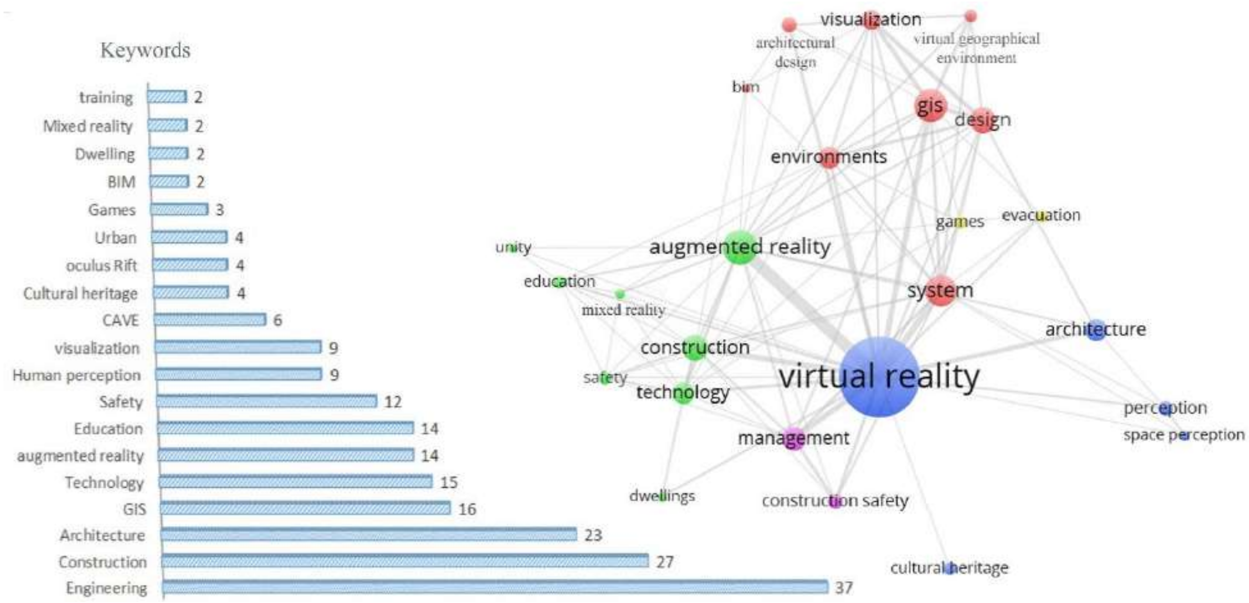

Figure 3. Keywords used in applications of VR in AEC industry

The group 1 shows that BIM-enabled VR has been widely used in architectural design and urban planning (GIS system) for visualization purpose; the group 2 shows that VR together with augmented reality and mixed reality technologies have been widely used for construction safety education; group 3 shows that VR has been used for investigation of space perception in cultural heritage; group 4 shows that VR has been used for education through games; group 5 shows that VR has also been implemented in construction safety management.

Most of the researchers mainly utilised the non-immersive VR devices in their work. These devices mainly provide visualisation capability, while the immersive VR devices enable more advanced human interaction with the computer. Nine research papers [3, 5-12] using immersive VR are shown in Table 2.

3 Experiment for establishing a workflow of IVR applications

The experiment based on three types of data:

1. 4D construction simulation in VR
2. Rapid generation of the VR scene
3. Airflow visualization in VR

Table 2 Research using Immersive VR

Group	Keywords
2017	Diegetic user interfaces for virtual environments with HMDs: a user experience study with oculus rift
2017	vConnect: perceive and interact with real world from CAVE
2016	Design and Evaluation of Data Annotation Workflows for CAVE-like Virtual Environments
2016	A virtual reality integrated design approach to improving occupancy information integrity for closing the building energy performance gap
2016	Construction and Evaluation of an Ultra-Low Latency Frameless Renderer for VR
2015	Neurophysiological correlates of embodiment and motivational factors during the perception of virtual architectural environments
2015	The effect of dangerous goods transporters on hazard perception and evacuation behavior - A virtual reality experiment on tunnel emergencies
2015	Mobile, Low-Cost, and Large-Scale Immersive Data Visualization Environment for Civil Engineering Applications
2015	Immersive virtual environments versus physical built environments: A benchmarking study for building design and user-built environment explorations

3.1 Construction simulation

We prepared the BIM model of the Queen Street Studio (QSS) at the University of Huddersfield using Revit; convert the model data from RVT to FBX file format; then import the FBX file in Unity (a game engine). It was found that the texture of the BIM model was missing in Unity, so the modeller needed to add the texture layers in Unity again.

For the 4D simulation, we used Autodesk navisworks manager to divide the BIM model into parts that represent the construction batches. Then, we defined the construction schedules using timelines, as is shown in Figure 4. The TimeLiner data was exported from naviswork to 3ds max and then the animation data with geometries was exported to Unity. Finally, the immersive VR application was generated from Unity, as is shown in Figure 5.

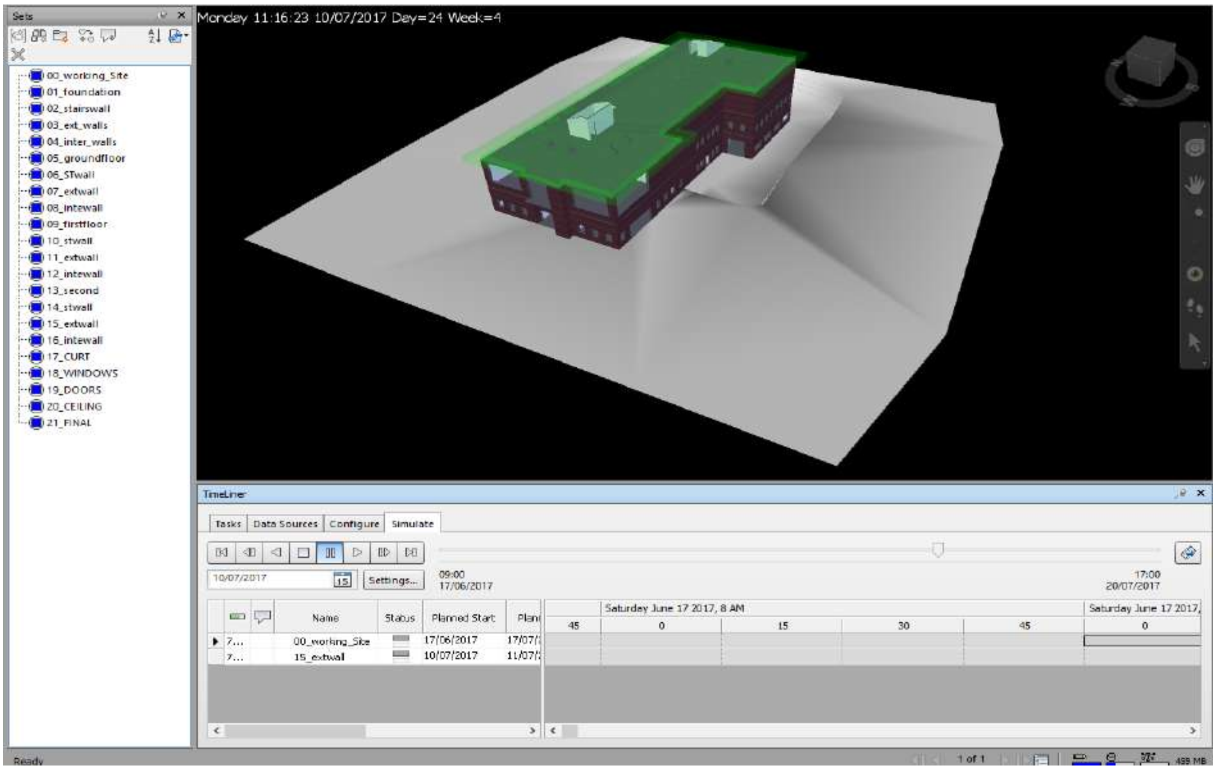

Figure 4. The BIM model and construction sequence of the Queen Street Studio

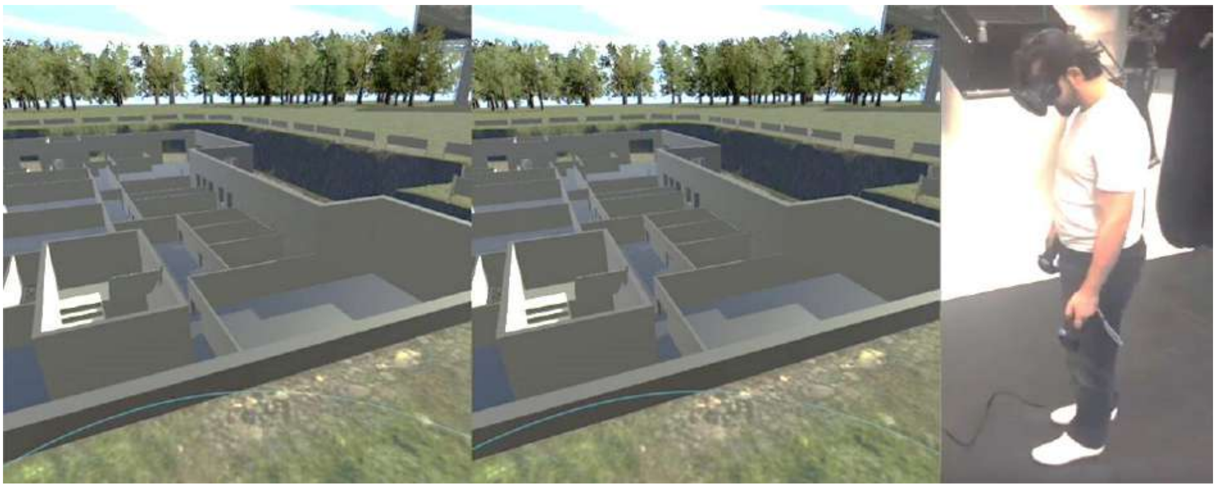

Figure 5. Construction simulation in immersive VR

3.2 Rapid generation of VR scenes

The Terrestrial Laser Scanner is a state-of-the-art survey technology. We used the FARO Focus scanner to capture the 'as-is' state of four rooms in the QSS building, as is shown in Figure 6. The rooms were chosen according to the space area, type of lighting, and the function (shown in Table 3).

Then, we generated the mesh model of the room using the collected point cloud data and then import it to Unity and built the VR application, as is shown in Figure 7. We also import the point cloud directly to Unity and built the VR application as is shown in Figure 8. The mesh model has a better visualization while it requires more process time.

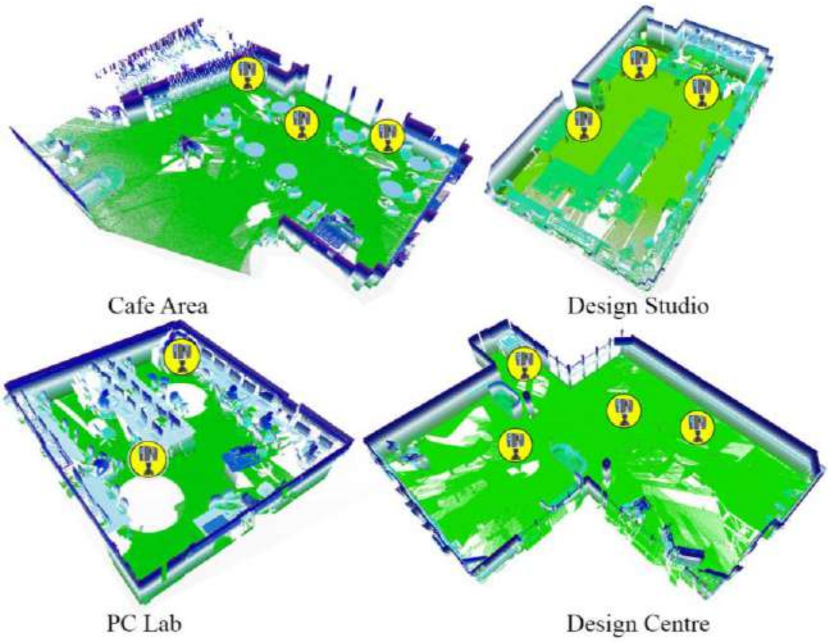

Figure 6. The scanned four rooms in the Queen Street Studio

Table 3. The condition of the rooms chosen for experiments

Space Name	Floor	Type	Area(m2)	Lighting / windows Orientation	Scan stations
Café Area	Ground Floor	Public	62	Daylighting - SE	Three
Design Centre	Ground Floor	Semi public	188	Artificial - S	Four
PC Lab	Basement	Private	58	Artificial - none	Two
Design Studio	First Floor	Private	88	Mixed – SW	Three

Figure 7. Mesh object in Unity

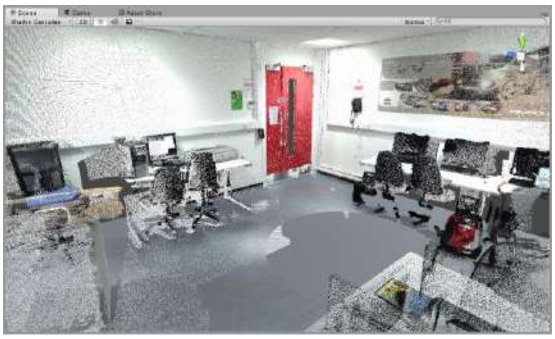

Figure 8. Point cloud data in Unity

3.3 Rapid generation of VR scenes

We used Autodesk CFD to perform CFD simulation of the PC lab at the QSS building. Simulation parameters include: Air Changes per hour is (15) and Supply temperature is (20°C). The results were exported as CSV files which contain the information of velocity, temperature, pressure and density in the simulated space, as is shown in Figure 9.

CFD data was then imported to 3ds Max to generate geometries for visualizing the velocity, temperature, and pressure. There are several representations of CFD data such as splines, planes, arrows, etc.

We set airflow data as splines with temperature colour. The data was then exported as FBX file and imported as a new asset in Unity. Finally, the VR application was built and visualised in the headset, as is shown in Figure 10.

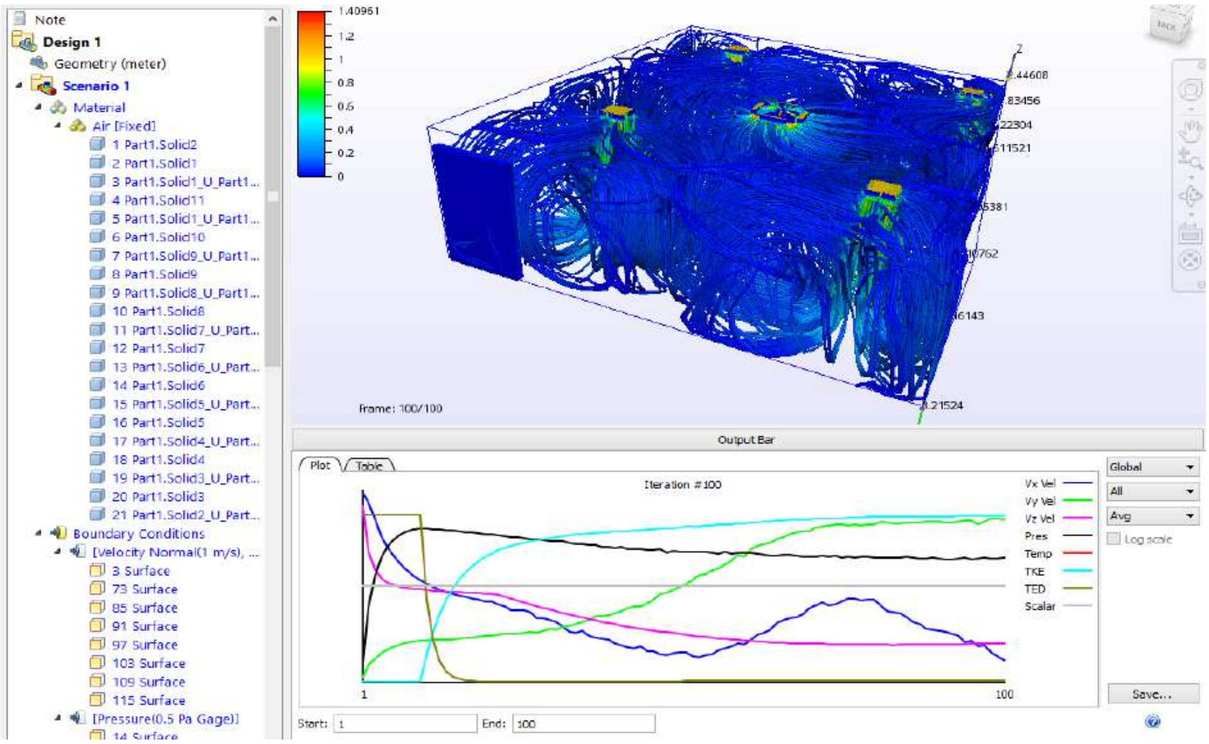

Figure 9. Computational Fluid Dynamics (CFD) simulation of the PC Lab at QSS

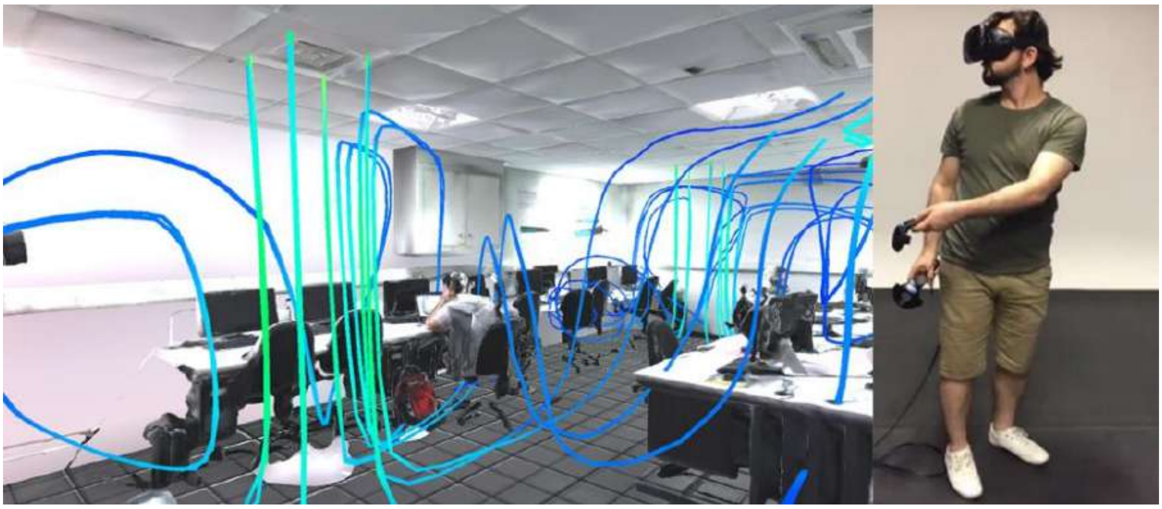

Figure 10. Visualisation of the airflow in immersive VR

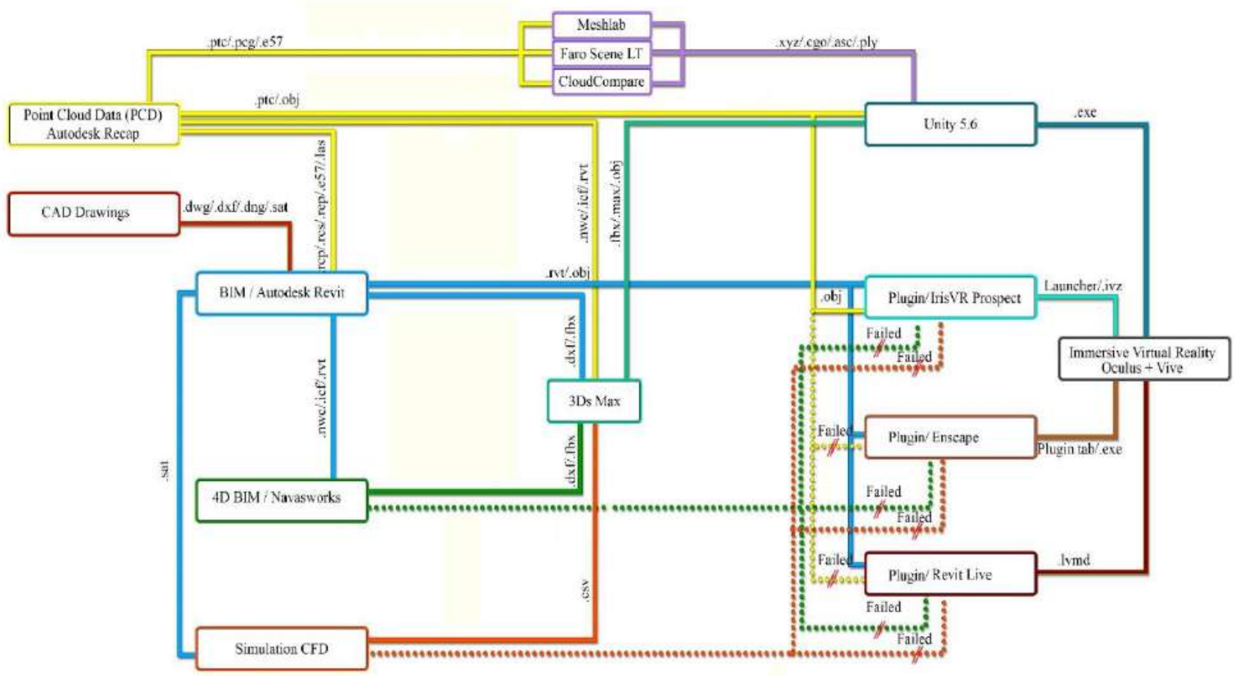

Figure 11. The interoperability of VR applications

4 Summary

This paper reviewed the development of VR devices and literature of VR applications for AEC industry. It also demonstrated three workflows for construction simulation, VR scene generation, and building performance analysis. The literature has shown VR technology was successfully applied in many fields, however, the use of immersive virtual reality (IVR) still not adopted widely, AEC industry is facing many challenges starting from concept design, construction and operation, today VR technology can be a valuable tool to solve some of these challenges.

There are many tools can be used to create VR applications and it is important to understand their usages, functions and interoperability. Figure 11 shows how to exchange data between different tools. This can help others to select the right tools for using VR in their business processes. However, there are few things we need to consider to develop a sophisticated VR experience, 1) knowing the user, the problem, outline the expectation, and the final goal, 2) VR platform (desktop or mobile) and identify the content of creation in reference to VR experience. 3) Integration method and developing time. In addition, the model needs to be created with fewer polygons so that the model will not be too heavy to be loaded into the VR platform and also get rid of unwanted geometries to avoid overload objects. It is highly recommended to give a unique name to each object in the model and group some of them; this helps organize the work through getting the information faster especially in big projects, and make things less complicated if there is a need to change, edit or replace some object.

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A Probabilistic-Based Deterioration Model Using Ground Penetrating Radar

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Abstract – Infrastructure systems are very essential to every aspect of life on Earth. Existing Infrastructure is subjected to degradation while the demands are growing for a better infrastructure system in response to the high standards of safety, health, population growth, and environmental protection. Bridges play a crucial role in urban transportation networks. In addition to that, they are vulnerable to several deterioration agents such as the variable traffic loading, extreme weather conditions, deferred maintenance, etc. The development of Bridge Management Systems (BMSs) has become a fundamental imperative nowadays especially in the large transportation networks due to the huge variance between the need for maintenance actions, and the available funds to perform such actions. Condition assessment is regarded as one of the most critical and vital components of BMSs. Ground Penetrating Radar (GPR) is one of the non-destructive techniques (NDTs) that are used to evaluate the condition of bridge decks which are subjected to the rebar corrosion. This paper presents a corrosiveness index that is capable of evaluating the extent of severity of corrosion in concrete bridge decks. Different clustering algorithms are compared in order to select the most feasible clustering algorithm. A probabilistic deterioration model is constructed in order to model the future condition rating of bridge decks. Anderson darling test is used to select the most feasible probability density function, and the parameters of the probability density functions are obtained using maximum likelihood estimation. Finally, two case studies are presented to illustrate the capabilities of the proposed model.

Keywords –
Bridge Management System; ground Penetrating Radar; bridge decks; corrosion; deterioration model; maximum likelihood estimation

1 Introduction

Bridges are vital links in transportation networks that should be safe, functional and serviceable during their service life to facilitate the mobility of people and transportation of goods which causes sustainable economic development. Concrete bridges are prone to high level of deterioration because of the variable traffic loading, extreme weather conditions, cycles of freeze and thaw, deferred maintenance, etc. More than 40% (700 bridges) of Egyptian bridge inventory out of 1,700 bridges have exceeded their maintenance limit and are at risk of failure.

American Association of State Highway and Transportation Officials (AASHTO) defined Bridge Management System (BMS) as “a system designed to optimize the use of available resources for inspection, maintenance, rehabilitation and replacement of bridges” [1]. AASHTO and Intermodal Surface Transportation Efficiency Act (ISTEA) defined five main components for BMS which are as follows [2]: 1) database for data storage, 2) condition rating model, 3) deterioration model, 4) cost model, and 5) optimization model for running system. The structure of BMS is shown in Figure 1 [2].

The database is the most essential component of the BMS where it is used to store information that is related to every bridge in the network. Bridge condition rating is based on field inspections to evaluate the condition of bridges. Deterioration model is used to predict the condition rating of different bridge elements over time. The cost model is divided into two main types which are: 1) agency costs, and 2) user costs. The agency costs ae based on the expenditure of maintenance, repair and rehabilitation activities (MR&R) to improve the condition rating of the bridges. The user costs are based on the impact of deterioration on road users as a function of the bridge condition [3]. The optimization model is implemented to determine the optimum maintenance, repair and rehabilitation activities for different bridge components. The proposed model focuses on two bridge management components which are: 1) the condition assessment model, and 2) the deterioration model. A corrosion index is developed based on the ground penetrating radar. Also, the weibull distribution is used to model the deterioration of bridge decks. Accurate condition rating and reliable deterioration models help in minimizing the risk of failure of aging infrastructures.

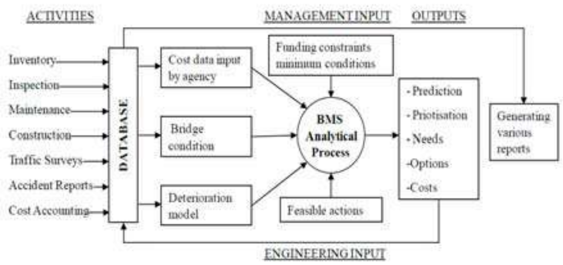

Figure 1: Typical structure of BMS [2]

2 Destructive and Non-Destructive Techniques

The condition assessment model heavily depends on the inspection type. The process of monitoring bridges should be cost effective, efficient, and fit for the purpose [4]. Thus, bridge inspectors should use techniques to assess accurately and effectively the corrosion of the bridge decks. Bridge inspection can be defined as “a process in which the defects on a bridge are identified, recorded to be used for assessing bridge condition”. Inspection techniques are divided into two main categories which are: 1) destructive techniques (DT), and 2) non-destructive techniques (NDT). Destructive Techniques (DT) provide accurate and direct results, but they cause damage to the element under investigation, and they are expensive and time-consuming. Non-Destructive Techniques (NDT) are inexpensive and quick, but they do not provide direct information about the element under inspection. NDTs gain popularity due to their various advantages including; providing a high level of safety for the labor staff, time saving, providing high rates of production in comparison to traditional methods.

Ground penetrating radar (GPR) is one of the non-destructive techniques that are used for field investigation in structural engineering. Ground Penetrating radar can determine the subsurface structure easily and accurately. Moreover, it has the capability of locating metallic and non-metallic objects. GPR transmits pulsed electromagnetic waves from the transmitting antenna which is located on the ground surface and signals are then received by the receiving antenna [5]. The proposed model utilizes GPR in order to evaluate the corrosion of the reinforcement rebars in the concrete bridge decks.

3 Model Development

The utilized GPR system incorporates two ground-coupled antennas which are: 2000 MHZ and 400 MHZ. The 2000 MHZ antenna is utilized because of its high-resolution capability. Thermal drift, electronic instability, cable length differences and variations in antenna airgap can cause ‘jumps’ in the air/ground wavelet first arrival time (usually referred to as the time-zero point). Therefore, traces require the adjusting to a common time-zero position before applying processing methods. This is usually achieved using some particular criteria (e.g., the air wave first break point or first negative peak of the trace) and is often done automatically by the processing software [6, 7, 8].

Several precautions are considered during the operation and processing processes. For the thermal drift, the scanning process was performed at night 2:00 am to overcome the internal heating of the equipment during the operation process. The antenna air gap is removed by moving the profile start time to the asphalt layer. For the dielectric constant of the material (concrete in our case), the wave length of the electromagnetic waves decreases as they encounter higher dielectric material. The utilized GPR is equipped with two antennas. The utilized GPR is equipped with two antennas which are: 2000 and 400 MHZ. Thus, in case the electromagnetic waves fail to reach the desired penetration depth, the lower frequency (400 MHZ) is utilized. The GRED HD software is used to extract the amplitudes of the top reinforcement rebars.

There are two main methods for GPR data analysis which are: 1) numerical amplitude method, and 2) image-based method. Numerical amplitude method depends on the value of amplitude of the reflected waves from the top layer of reinforcement. The higher the amplitude, the better the condition of the bars. This method main limitation is its lack of a clear value for the thresholds that define the different categories of corrosion. For example, the profiles of one bridge deck may have amplitude values from 10 dB to -5 dB, where 10 dB represents the best condition and -5 dB represents the worst for that bridge. Meanwhile, another of Bridges’ profiles may have amplitude values that range from -5 dB to -40 dB, where -5 dB represents the best condition and -40 dB represents the worst condition.

Therefore, a comparison between the clustering algorithms should be performed in order to select the most feasible clustering algorithm. After the selection of the most appropriate clustering algorithm, a corrosion map is developed and consequently a corrosion index is calculated. The second step is to construct a deterioration model. A stochastic model is constructed in order to overcome the vagueness and uncertainties associated with the deterministic models. The most suitable probability density function is defined based on the Anderson Darling statistic. The parameters of the probability density function are defined based on the maximum likelihood estimation algorithm.

3.1 Clustering Algorithms

The proposed model develops a corrosion map that is extensively based on the clustering algorithms. Clustering is the process of partitioning the dataset into a homogenous set of clusters without having any prior information about the clusters where the points within the same cluster share similar features. The selected clustering algorithms incorporate a combination of soft and hard clustering techniques. Hard clustering is the process of the assignment of data points to only one cluster such as K-means. On the other hand, soft clustering is the process of the assignment of data points to the clusters with different membership degrees such as Fuzzy C-means clustering (FCM).

RapidMiner 7.5 and KNIME 3.3.1 softwares [9, 10] are used as platforms to perform the clustering algorithms. The proposed methodology compares between five clustering algorithms which are: K-means, K-medoids, fuzzy C-means, expectation maximization, and X-means. K-means and k-medoids are two similar clustering algorithms. The proposed model assumes that the there are four categories for the condition of the bridge deck which are: "very severe", "severe", "medium", and "good". i.e., three thresholds

3.1.1 K-means algorithm

K-means clustering algorithm is based on minimizing the distance between the average squared Euclidean distance and the clusters' centroids. The output of the clusters' centroids is greatly influenced by the initial selection of the clusters' centroids. The number of clusters in the K-means clustering algorithm must be defined initially. The clusters' centroid is the mean of the data points within the cluster [11]. The output of the K-means is that the similarity between the data points within the same cluster is higher than the similarity between the data points in the different clusters [12]. The main distinct feature between K-means and k-medoids clustering algorithms is that one of the data points represents the centroid of the cluster in the case of k-medoids. K-means algorithm utilizes the mean of the data points.

The steps of K-means clustering are as follows [13]:

1- Select number of desired clusters K.
2- Select K starting points randomly to be used as initial candidates for clusters' centroids.
3- Calculate the distance between data points and cluster centroids.
4- Assign the data point to the cluster centroid which has the minimum distance between the data point and cluster centroids. The distance is simply the Euclidean distance.

$$d(x_i, C_j) = \sqrt{\sum_{d=1}^{n} (x_{id} - c_{id_i})^2} \quad (1)$$

5- Re-compute the new cluster centroids (centroid is the mean point of the cluster).
6- Repeat steps 3, 4, and 5 until convergence (centroid and data points no longer move).

X-means clustering algorithm is introduced in order to overcome a major drawback of the K-means clustering algorithm which is the necessity of knowing the number of clusters (K) before processing. The X-means clustering algorithm tends to search the space to compute the clusters' centroids based on the Bayesian Information Criterion (BIC) or the Akaike Information Criterion (AIC). The expectation maximization clustering algorithm calculates the probabilities of cluster memberships based on one or more probability distribution. The number of the clusters is predetermined in the expectation maximization algorithm. Expectation maximization algorithm is based on maximizing the probability that the data point belongs to the clusters of the model.

3.1.2 Fuzzy C-means Algorithm

Fuzzy C-means (FCM) is an iterative clustering algorithm where each data point is assigned to one cluster or more based on the membership degrees. FCM was developed by Dunn in 1973 and improved by Bezdek in 1981. FCM is based on minimizing the following objective function [14].

$$J_w = \sum_{i=1}^{N} \sum_{j=1}^{C} u_{ij}^m \left\| (X_i - C_j)^2 \right\| \quad (2)$$

Where;
m is a fuzzifier constant that is greater than one. u_{ij} denotes the degree of membership of the X_i in the cluster j and it is between zero and one. X_i is a $i-th$ data point in a d-dimensional space. C_j represents the centroid of the $j-th$ cluster. $||*||$ is a norm distance that represents the similarity between the data point and the centroid of the cluster.

FCM starts by randomly initiating the cluster centroid. The second step is to construct the membership matrix. A membership matrix ($U_{(N\times C)}$) is composed of a group of membership degrees. The degree of membership (u_{ij}) can be calculated using Equation 3. The cluster centroids are then updated and can be calculated using Equation 4. The cluster centroids and the membership degrees are iteratively updated until the convergence criteria are satisfied. The convergence criteria is shown in Equation 5. The de-fuzzification process is performed using Equation 6 where the data point is assigned to the cluster that has the maximum degree of membership.

$$u_{ij} = \frac{1}{\sum_{k=1}^{C}\left(\frac{\|(x_i - c_j)\|}{\|(x_i - c_k)\|}\right)^{\frac{2}{m-1}}} \tag{3}$$

$$C_j = \frac{\sum_{i=1}^{N} u_{ij}^{m} \times x_i}{\sum_{i=1}^{N} u_{ij}^{m}} \tag{4}$$

$$\max_{ij}\{|u_{ij}^{it+1} - u_{ij}^{it}|\} < \zeta \tag{5}$$

$$C_j = \arg_i\{max(u_{ij})\} \tag{6}$$

$$\sum_{j=1}^{c} u_{ij} = 1 \tag{7}$$

Where;

ζ is the termination constant between zero and one. it refers to the number of iteration steps.

3.2 Clustering Validity Indices

Clustering is an un-supervised algorithm. Therefore, evaluating the output of the clustering algorithms is a matter of great importance. Assessing the clustering algorithms is much more difficult than the supervised algorithms because there is no “ground truth”, i.e., there are no-predefined classes for the domain problem. Moreover, it is very difficult to find the appropriate metrics to evaluate the quality of the generated clusters.

The proposed model utilizes two clustering validity approaches to assess the quality of the generated clusters and to identify the optimal partition of clusters which are: 1) Davies-Bouldin index, and 2) Dunn index. The objective of the clustering validity approaches is to select the most feasible thresholds that ensure that the clusters are compact and well-separated, i.e., maximize the inter-cluster distance (distance between the clusters), and minimize the intra-cluster distance (distance between data points within the same cluster) (see Figure 2).

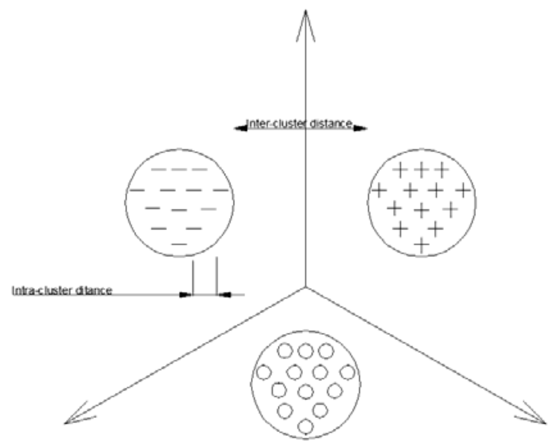

Figure 2: Overview of the clustering process

3.2.1 Davies-Bouldin Index

Davies-Bouldin index is a ratio between the sum of intra-cluster scatter to the inter-cluster separation. The Davies-Bouldin index can be calculated using the following Equation [15].

$$DBI = (\frac{1}{k}\sum_{w,v=1}^{k} \max_{v\neq w}(\frac{D_w + D_v}{d(c_w, c_v)}) \tag{8}$$

Where;

D represents the intra-cluster distance. d represents the inter-cluster distance.

The intra-cluster distance (D), and the inter-cluster distance (d) can be calculated using Equations 9, and 10, respectively based on the Euclidean distance principle. The intra-cluster distance is the average distance between the data points and the cluster centroid. The inter-cluster distance is the distance between the centroid of the two clusters.

$$D = \left(\frac{\sum_{h=1}^{t} ||X_a - C_w||}{N_w}\right) \tag{9}$$

$$d = dist(C_w, C_v) = \sqrt{(C_{w1} - C_{v1})^2 + (C_{w2} - C_{v2})^2 \ldots \left(C_{wq} - C_{vq}\right)^2} \tag{10}$$

Where;

X_a is an arbitrary data point that belongs to a cluster w. C_w, and C_v represent the centroid of clusters w, and v, respectively. N_w represents number of data points in the cluster w. The smaller Davies-Bouldin index denotes that the clusters are compact, and the centers of the clusters are far away from each other (Sahani and Bhuyan 2014). t is the number of the data points in the cluster. q is the number of the dimensions of the model.

3.2.2 Dunn Index

The Dunn index is used to assess the quality of the clusters and it can be calculated using Equation 11 [16].

$$\mathrm{DUI} = \max_{1\le w\le k}\left(\min_{1\le v<K, v\neq w}\left(\min_{i\le K\le K}\left(\frac{\mathrm{d}(x_w,x_v)}{\max(\mathrm{D}(x_k))}\right)\right)\right) \quad (11)$$

Where;

D, and d are defined as above. The larger the Dunn index indicates that the clusters are compact and well-separated.

The clustering index is performed in order to compare between the five clustering algorithms. The clustering index can be calculated using the following equation.

$$CLU = \frac{\mathrm{DUI} - DBI}{2} \quad (12)$$

Where;

DUI represents the Dunn index while DBI represents the Davies-Bouldin index. CLU denotes the clustering index.

Surfer 12 is a plotting and mapping software that is utilized to develop the corrosion map for the concrete bridge decks. Finally, a Corrosion Index (CI) can be calculated as follows.

$$CI = \frac{\sum_{i=1}^{4} Q_i \times W_i}{\sum_{i=1}^{4} Q_i} \quad (13)$$

Where; Q_i represents the quantity of a bridge element in category i. W_i represents the weighting factor for a bridge element in category i. The weighting factors for the "good", "medium", "severe", and "very severe" categories are assumed 100%, 70%, 50%, and 20%, respectively.

4 Deteriroation Models

Deterioration model is the most crucial component of the BMS because it enables the transportation authorities to predict the future bridge condition ratings. Planning of maintenance, repair and rehabilitation activities (MR&R) of bridges is based on calculating accurate future bridge condition ratings. A high-quality deterioration model enables infrastructure managers to optimize MR&R activities and minimize un-planned maintenance activities. The deterioration model constructs a relationship between the facility condition rating and group of explanatory variables such as age, traffic volume, weather conditions, percentage of commercial vehicles, etc.

Goodness of fit is a statistical measure that is used to determine the compatibility of fitting set of data to probability distributions. Goodness of fit is a means to evaluate different probability density functions and to determine discrepancies between observed values and expected values in a certain statistical model. There are several goodness o fit tests such as Kolmogorov-Smirnov test, Anderson Darling and chi-squared test. The proposed model utilizes Anderson Darling statistic.

Anderson Darling test (A^2) is used to compare the fit of an observed cumulative distribution function to an expected cumulative distribution function. Anderson darling provides more weight to the distributions' tail than the Kolmogorov-Smirnov test. Anderson Darling Statistic can be calculated as follows [17].

$$A^2 = -n - \frac{1}{n}\sum_{i=1}^{n}(2\mathrm{i}-1) \times (\ln \mathrm{F}(\mathrm{x_i}) + \ln(1 - \mathrm{F}(\mathrm{X}_{n-i+1}))) \quad (14)$$

There are different methods for parameter estimation of probability density function such as maximum likelihood estimation and least squares, method of moments estimation (MME), and median rank regression (MRR). The proposed model utilizes maximum likelihood estimation (MLE) algorithm as a parameter estimation method. MLE is based on finding the parameters that maximizes the likelihood function where the observations are assumed to be independent. The MLE is characterized by being is asymptotically efficient where larger the sample size the more likely the parameters converge to precise values.

MLE is based on finding the unknown parameter θ that maximizes the $\log \mathrm{L}(\theta/y)$ because it is often easier to maximize the log-likelihood function than the likelihood function itself [18].

$$\log \mathrm{L}(\theta/y) = \sum_{i=1}^{n} \log(f(y_i|\theta)) \quad (15)$$

Where;

$\mathrm{Y_i}$ represents a set of independent variables. $f(y_i|\theta)$ denotes the probability density function of the random variable y_i

5 Model Implementation

There are two case studies to validate the proposed model. The length and the width of the scanned bridge deck of El-Kobba bridge are 20 meters, and 3 meters, respectively. The length and the width of the scanned bridge deck of Torra bridge are 21 meters, and 6 meters. The data collection of El-Kobba bridge deck is shown in Figure 3.

Figure 3: GPR data collection for El-Kobba bridge deck

The grids spacing in both the longitudinal and transversal directions were taken to be 1.0 m. Consequently, the number of scans in the longitudinal and transversal directions in El-Kobba bridge are 3, and 21, respectively. The number of scans in the longitudinal and transversal directions in Torra bridge are 6, and 20, respectively. A plan of the scans of El-Koba bridge deck is shown in Figure 4.

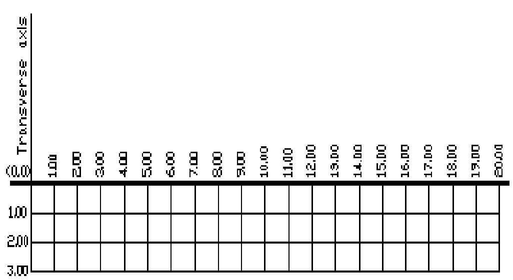

Figure 4: A plan of the scanned paths in El-Kobba bridge deck

After the data collection process, the GPR data profiles are transferred to a PC for processing. The software IDS GRED HD is used to process the B-scans. IDS GRED HD is used to compute the travel time, and the amplitude of each reinforcing rebar. The profile obtained from the GPR is depicted in Figure 5.

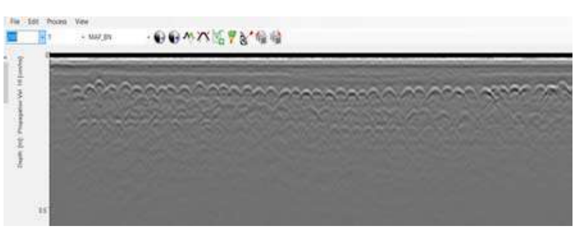

Figure 5: GPR profile of Torra bridge deck

Rebar locations were clear in the raw data as well as obvious areas of deterioration where rebar reflections were weak. Areas of the bridge deck having weak reflection amplitude values are typically indicative of the deterioration. These weaker reflections can be due to several factors, including high chloride content, concrete deterioration or corrosion of the embedded steel rebar, which all attenuate the radar signal.

The RapidMiner software is used in order to perform the K-means clustering, expectation maximization cluster, X-means, and K-medoids. KNIME platform is used in order to perform the fuzzy C-means clustering. The developed clustering model using the RapidMiner platform is shown in Figure 6. The developed clustering model using the KNIME platform is shown in Figure 7.

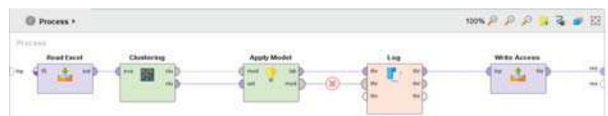

Figure 6: Interface of the RapidMiner platform

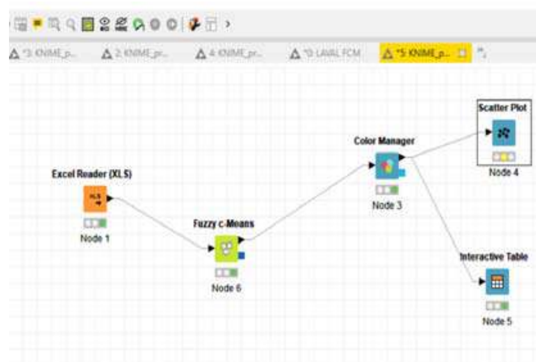

Figure 7: Interface of the KNIME platform

The clustering indices of the five clustering algorithms in Tora and El-Kobba bridges are shown in Table 1. As shown in Table 1, K-medoids has the largest clustering index and therefore K-medoids is the most feasible clustering algorithm. Moreover, K-medoids has the largest clustering algorithm in El-Kobba bridge which means that K-medoids is the most feasible clustering algorithm

Table 1: Clustering indices of the two bridges

Clustering algorithm	Clustering index (EL-Kobba)	Clustering index (Torra)
K-means	1.4118	1.1566
K-medoids	1.8954	2.8291

X-means	1.3948	1.2322
Expectation maximization	1.5585	1.3896
Fuzzy C-means	1.5118	2.3124

The corrosion map for El-Kobba bridge is depicted in Figure 8 where 18.67% of the bridge is a “very severe” condition, 43.98% of the bridge is in a “severe” condition, 30.71% is in a “medium” condition, and 6.64% is in a “good” condition. Based on Equation (13), the Corrosion Index is 70.76% which means that the bridge deck is in the “medium” category. The amplitude thresholds are expressed in volts. The amplitude thresholds are 0.106, 0.202, and 0.325. The corrosion map for Torra bridge is depicted in Figure 9 where 14.8% of the bridge is a “very severe” condition, 22.37% of the bridge is in a “severe” condition, 26.64 is in a “medium” condition, and 36.18% is in a “good” condition. The Corrosion Index is 68.98% which means that the bridge deck is in the “medium” category. The amplitude thresholds are -0.477, -0.3605, and -0.1999.

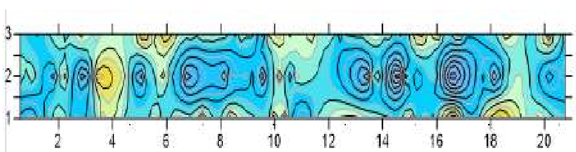

Figure 8: Corrosion map of El-Kobba bridge

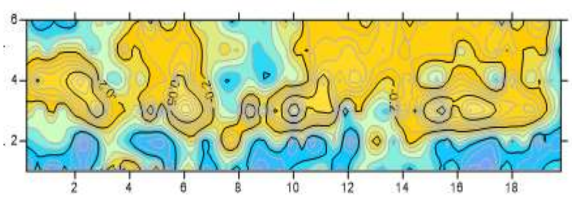

Figure 9: Corrosion map of Torra bridge

The attributes of the bridges are stored in shapefile format for documentation purposes as shown in Figure 10. The shapefile format is a well-known geospatial vector data format for geographic information system (GIS) softwares.

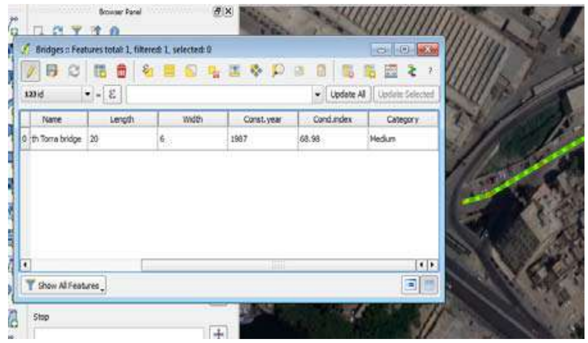

Figure 10: Storing of the bridges’ attributes

Based on the Anderson Darling test, weibull distribution is the best-fit distribution followed by the lognormal distribution, and finally the exponential distribution, whereas the Anderson Darling statistics of the previous distributions are 0.٤٤٨٨, 0.٤٧٠٥, and 0.٦٥٣٩, respectively. The parameters of the weibull distributions are obtained based on the maximum likelihood estimation, whereas the shape factor and scale factor are ١,٩١٧٤, and ٥٠,٩٣٥٤, respectively. The deterioration model based on the weibull distribution is shown in Figure 11.

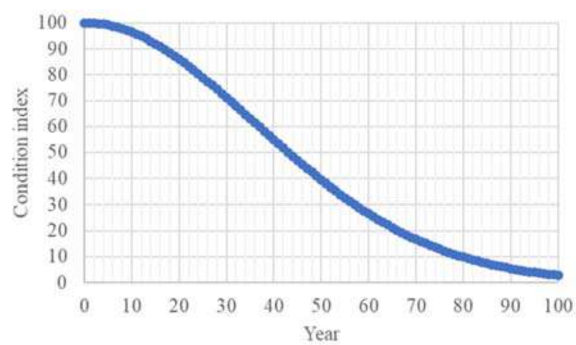

Figure 11: Deterioration model based on weibull distribution

6 Acknowledgment

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Extending IFC for Fire Emergency Real-Time Management Using Sensors and Occupant Information

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Abstract –

The increasing complexity of buildings has brought some difficulties for emergency response. When fires occur in a building, limited perception regarding the disaster area and occupants can increase the probability of injuries and damages. Thus, the availability of comprehensive and timely information may help understand the existing conditions and plan an efficient evacuation. For this purpose, Building Information Modeling (BIM) should be integrated with three sets of information: (1) occupancy that defines the type of space usage; (2) occupants' information; and (3) sensory data. The Industry Foundation Classes (IFC), as a standard of BIM, has the definitions for all areas, volumes, and elements of a building. IFC also has the basic definitions of sensor and occupant entities. However, these entities do not provide enough dynamic and accurate information for supporting emergency management systems. This paper aims to extend IFC for fire emergency real-time management using sensors and occupants' information. The specific objectives of this paper are: (1) extending IfcSensor entity for occupant's sensors; (2) adding new attributes to IfcOccupant to support emergency response operations and defining a new entity for occupancy; and (3) defining the relationships between sensors, occupants, occupancy, time series, and building components in the context of building evacuation. The feasibility of the proposed method is discussed using a case study.

Keywords –

BIM, IFC, Sensory Data, Sensor, Occupant, Occupancy, Fire.

1 Introduction

Statistics show 1,345,500 fires reported in the United States in 2015; out of which, 37.27% are structure fire that have caused 2,685 civilian deaths, 13,000 civilian injuries, and $10.3 billion in property damage [1]. During a fire evacuation, the lack of comprehensive information affects the success and efficiency of emergency management and results in increasing the number of casualties [2].

Wei-Guo et al. [3] stated that the availability of core information about buildings and infrastructure systems improves the effectiveness of managing disasters. Moreover, Tsai et al. [4] emphasized the need of critical building information, such as building evacuation plans and electrical and mechanical equipment. Walder and Bernoulli [5] emphasized the need for critical spatial information and semantic information related to the structure and equipment, as well as the disaster. An approach to enable rapid and safe evacuation in building emergencies requires accessing the dynamic information about the buildings, occupants and fire propagation. Building facilities' information includes building's structure; floor plans; location of stairs, ramps, exits, doors and windows; facility's materials; and fire protective equipment. On the other hand, the attributes of occupants are presence, number, location, age, mobility condition, ID, etc. In addition, the required information regarding fire propagation includes sensory data about smoke, heat, and toxic gases.

Building Information Modeling (BIM) is emerging as a digital representation of a building with the geometric/topological and semantic entities that describe the elements, materials, and relationships between them. Also, highly accurate and detailed data about the current state of building elements can be provided by BIM [6]. Industry Foundation Classes (IFC) as a platform-independent standard for BIM, is an object-based file format that has been developed by Building SMART Alliance (BSA). IFC is based on a taxonomy standard that describes building ontology [7]. Besides, IFC can facilitate interoperability in the Architecture, Engineering, Construction, and Facilities Management (AEC/FM) industry [8]. Although IFC is an object-oriented building model, modeling all objects related to the building is complicated. Thus, BSA presents an extensible architecture for extending IFC [9].

Integration of BIM and sensor networks for increasing the accuracy and effectiveness of disaster-response decision-making has been discussed extensively in building disaster management [10, 11]. With the spread of Internet of Things (IoT) technologies and intelligent buildings, the need for integrating sensors and sensory data with BIM has also increased. Advanced sensors can collect real-time information about occupants, occupancy, surrounding environment and incidents. Among other applications, such sensory data can provide accurate and useful information to support building evacuation planning and emergency response [12].

For BIM-based fire evacuation planning, several relevant elements along with their common attributes have already been introduced in IFC (e.g., actuators, sensors and occupants). However, creating smart disaster-response decision-making applications requires enhancement of the current standard in at least two major directions. Firstly, to migrate from a static (stateless) to a dynamic (state-full) BIM by adding the sensory data history and associating it with the elements of BIM. Secondly, since having access to comprehensive and accurate data is critical in disaster management, the attributes of some entities (such as IfcSensor and IfcOccupant) need to be enriched and also relationships among such entities must be established.

The objectives of this paper are: (1) extending IfcSensor entity for occupant’s sensors; (2) adding new attributes to IfcOccupant to support emergency response operations and defining a new entity for occupancy; and (3) defining the relationships between sensors, occupants, occupancy, time series, and building components in the context of building evacuation.

2 Review of Related Works

2.1 Building Fire and Evacuation Planning

In disaster management applications, time is one of the most critical factors to decrease casualties and properties' damages. Furthermore, precise information about an incident, structure [13] and human’s behavior [14] can decrease the risk of life threats and asset damages [15]. Dilo and Zlatanova [16] showed that the success of emergency response is related to the perception of environmental elements and events. This awareness is directly linked to the dynamic information in the emergency event. Situational awareness about changes in building components’ conditions can minimize the uncertainty in finding directions and improve safety [17]. Many studies have focused on network modeling, indoor navigation and route finding [18] based on the shortest path [19]. In addition, some studies have used dynamic data about people, to find less congested paths [14].

In the context of indoor emergency response, Tashakkori et al. [15] argued that indoor situational awareness helps in effective emergency management. They used a set of required information for route finding to develop a 3D spatial indoor-outdoor model. However, their solution did not include dynamic information. Tangs and Ren [20] provided a simulation spatial indoor model for fire. This model includes static and dynamic information, such as occupants, fire field, and building geometry.

To summarize, a safe fire evacuation depends on an awareness of the static and dynamic features, especially geometric obstacles, smoke spread and occupants’ behavior. These features have a critical effect on individuals’ decisions and the evacuation process [20]. Therefore, the provision of a dynamic indoor emergency spatial model that supports situational awareness for building evacuation is vital. Such a model will cover both static and dynamic information including both occupants’ behavior and indoor spatial information (e.g., building's structural layout, and fire propagation).

2.2 BIM and IFC

BIM allows to visualize construction processes through 4D simulation and gives an opportunity to manage cost and time effectively [21]. Recently, BIM has been used to improve building disaster management by understanding physical and functional characteristics of objects and visualizing building spatial information in three dimensions [22]. However, effective fire emergency methods should rely on the real-time and dynamic information [10].

BIM, as the base model of a building, can integrate with sensory data to have real-time information about the disaster and occupants. Consequently, occupants can be guided to safe exits rapidly form risky locations. Kensek [23] investigated the feasibility of integrating BIM and sensors such as light, CO_2 and heat. She used Arduino as a single board computer, Revit Architecture as a BIM software, and Dynamo as a visual programming environment to demonstrate how sensory data could change the 3D model. Also, the changes in the 3D model could be actuated on the physical model.

One of the primary goals of BIM is to provide interoperability between different platforms for data exchange, which is currently achieved by the IFC as a common open standard. This standard is used to share physical and functional features of buildings among stakeholders [24].

IFC is a data standard of BIM that has a hierarchical and modular framework consisting different entities. These entities represent tangible components (e.g. walls, doors and windows), as well as conceptual components (e.g. schedules, activities, and spaces). Each entity has common properties (including ID, name, geometry, etc.) as well as relationships to other components [25].

Currently, although IFC is a complex data standard, it can only support a limited number of use cases in the AEC/FM industry. Nevertheless, being an extendible standard, it can be extended to be used for new use cases [9, 25].

2.3 Occupant and Occupancy Information

In disaster management, in order to have occupancy-based control, different sensors are used to accurately determine the occupancy of building spaces and the parameters concerning occupants in real time, such as number of occupants in the spaces of the building. Melfi et al. [26] proposed occupancy resolutions at four levels (occupancy, count, identity, and activity) in three aspects (spatial resolution, temporal resolution, and occupancy resolution). A fifth level was suggested by Labeodan et al. [27] for tracking occupants' movement in different zones. The higher level of accuracy in occupancy detection will lead to better decisions improving safety [12].

2.4 Integrating Real-Time Information in BIM

An intelligent building is a building with smart technologies installation. In such buildings, there is usually a network of sensors and actuators with access to Internet, which can automatically control building components using knowledge-based algorithms and environmental data. For instance, intelligent buildings can monitor occupant's behavior and control building response to decrease energy consumption [28].

The first step towards modelling and managing an intelligent building is adding real-time information to BIM because the current BIM uses static information only. A dynamic BIM, which integrates real-time information and BIM, provides the opportunity of reacting to emergencies in real time by visualizing and monitoring the current situation in the building [29].

Currently, there are several kinds of BIM software (e.g., Autodesk Revit, ArchiCAD, Bentley Building, Solibri, and Vectorworks among other most commonly used tools). Revit is a widely used BIM software for visual analysis, documentation, and design, which also supports IFC. However, these tools can not store and visualize sensory data. To achieve a dynamic BIM with the ability to store and manage real-time information, some add-ins should be developed [29].

2.5 Extending IFC

There are three mechanisms to extend IFC if the current release does not support a specific need: (1) defining new entities, (2) using proxy elements; and (3) using the property sets [28]. Among the three alternatives, defining new entities can be the best method to extend the IFC standard because the newly defined entities can be used in the same way as the existing ones [9]. However, adding new entities to an IFC release can only happen after availability of some "proof of concept", followed by long discussions within the Model Support Group of the BSA; hence, does not really fit the aim of research projects [28]. The other two alternative mechanisms can extend the scope of IFC without changing the schema, although they require additional implementation agreements about the definition of property sets and proxies when they are used to share data with other software. Therefore, the other two alternatives are more practical to meet specific local requirements [9, 25, 28].

Several research projects proposed new objects, entities, and relationships for extending the IFC standard [9, 28, 30]. However, there is limited research about an extension for occupants. Also, IFC still has challenges to represent the live sensor readings.

3 Proposed extension for IFC

To have a real-time fire emergency management, related information can be classified into two main classes (indoor and outdoor). In both classes, the information can be divided into static and dynamic information. To provide the classes with comprehensive data, they should be connected to external databases. For example, occupants' ID can extract more detailed information from the external database, such as age, mobility and health condition. Furthermore, indoor static information can be modeled in BIM as well as dynamic information collected through various sensors, as shown in Figure 1. Then, sensory data should be fused with the spatial and semantic information in the BIM platform.

Figure 2 shows how the BIM model can be overlaid by the real-time information and how datasets can be related to each other. Occupants and fire sensory data can be enriched by connecting to long-term static data. The static data are rarely changed, such as ID, mobility condition, and heath condition. Thus, a comprehensive and real-time dataset containing sensory data and static data can be added to BIM.

After checking the availble information in IFC4 EXPRESS diagrams, an extended data model, including the required attributes and the relations, is prepared using the Unified Modeling Language (UML) format.

3.1 Occupant and Occupancy Data

Basic occupants' information, such as name and type of actor are availble in IfcOccupant. However, the following detailed occupants' information should be added to IfcOccupant: (1) ID; (2) age; (3) location; (4) mobility condition (e.g., wheelchair users); and (5) health condition (e.g., occupants with heart and breathing problems need special help). In addition, the occupancy of a space can be defiend at a lower spatial resolution. For this purpose, a new entity, IfcOccupancy, is defiend with the following attributes: presence of occupant and number of occupant. Figure 3 shows the relationships between existing and new entites.

3.2 Sensors and Sensory Data

Using sensors helps to have awareness about the surrounding conditions. The following relationships should be captured and modeled: (1) the relationship between sensors and building physical/conceptual elements, (2) the relationship between sensors and sensory data expressed by time series, and (3) the relationship between sensory data and occupants' information.

In the current version of IFC, the geometry and definition of all types of spaces (e.g., room spaces) are described by IfcSpace entity. IfcSpace represents a bounded area or volume that provides a certain function within a building. Also, definitions of building elements, such as walls and ceilings, are described by IfcWall and IfcCovering. Furthermore, some mechanical and electrical devices, such as sensors and actuators are available. The sensor is defined as IfcSensor and the sensor type is defined by IfcSensorType, such as gas sensors, temperature sensors, and fire sensors. The static properties relating to the IfcSensorType are defined by the IfcPropertySet. Each property set includes common attributes, such as name, usage, materials, ports, composition, assignments, and representations [7, 31].

To define the dynamic information for the sensors, sensory data should be measured in real-time. IfcMeasureValue is defined to keep different types of measured values, such as volume, time, ratio, mass, count, and area. Also, in order to collect real-time data, IfcTimeSeries entity can be used. This entity describes a set of time-stamped data entries and allows a natural association of data collected over intervals of time [31]. Creating a relationship between IfcSensor and IfcTimeSeries provides a dynamic BIM.

Various types of sensors are defined in IfcSensorType. However, sensors for counting the number of occupants (OccupantCountingSensor) and sensors for determining occupants' location (OccupantTrackingSensor) are proposed to be added in this research. Adding these sensors to IFC and defining a relationship between sensors and time series can help to have dynamic occupants' information in the context of disaster management. Figure 3 shows the proposed model for new types of occupants' sensors and relationships.

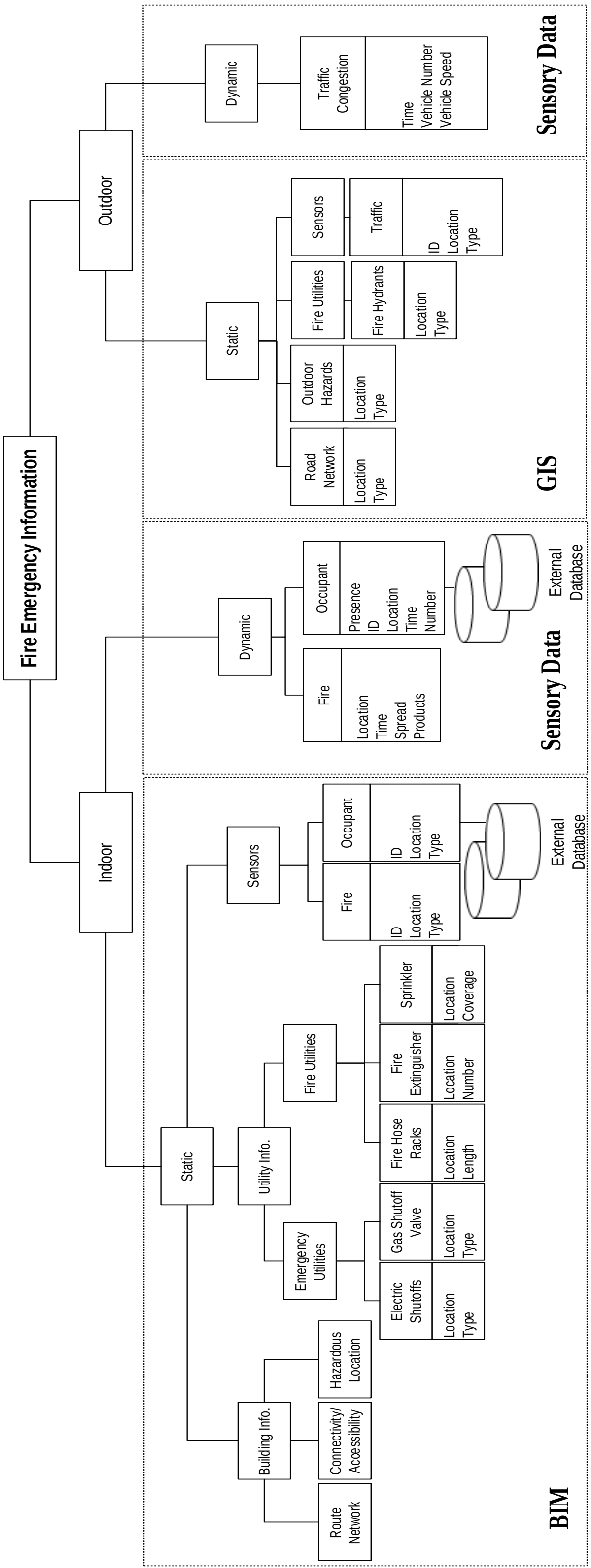

Figure 1. Information classification in fire emergency

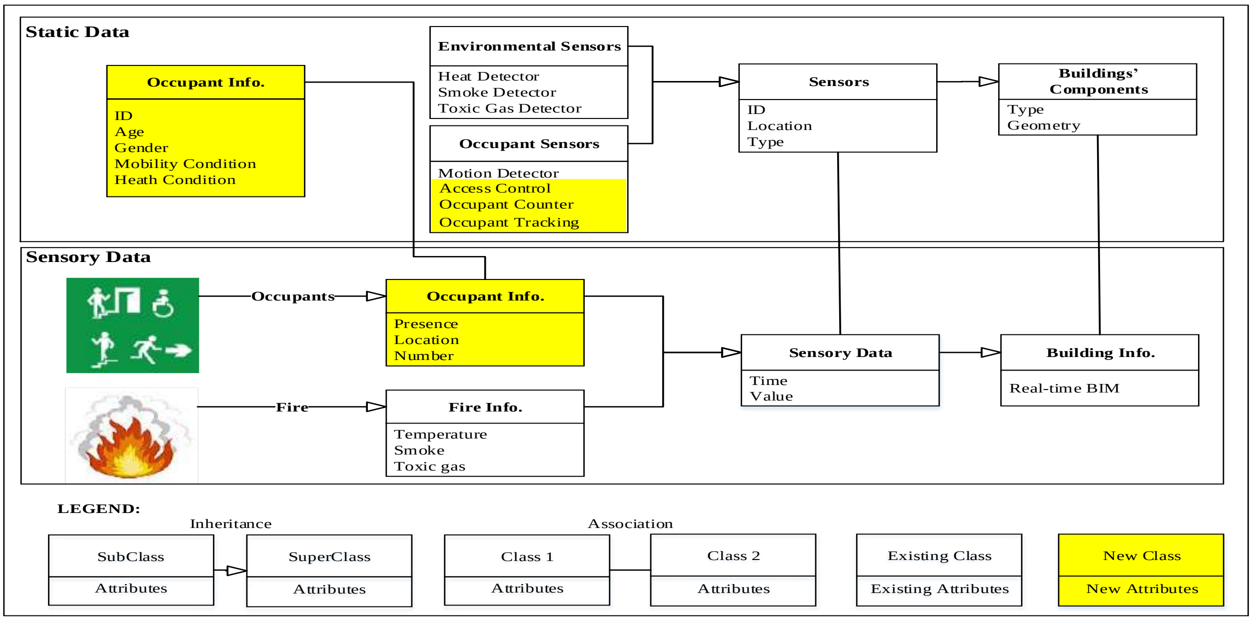

Figure 2. Relationship between sensory data and static data

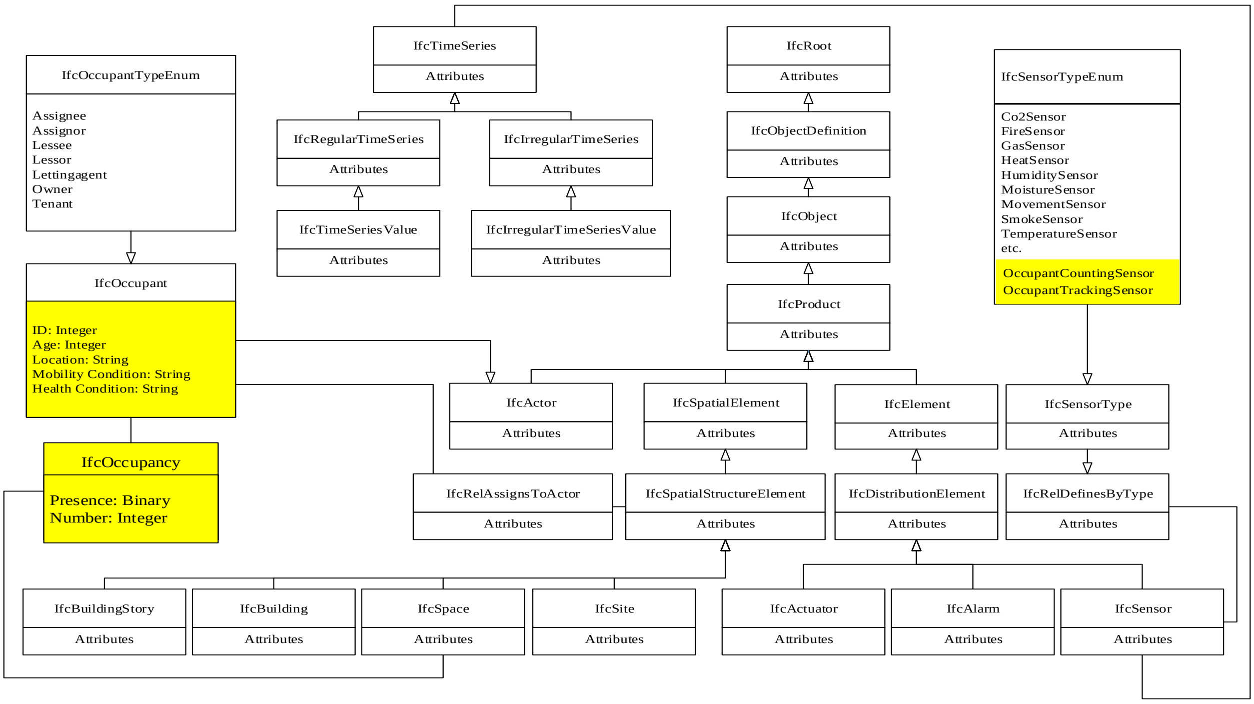

Figure 3. Data model for sensor types and building occupants' information

4 Case Study

In order to validate the proposed method, the 9th floor of the EV (Engineering & Visual Arts) building at Concordia University was chosen as experimentation area. Different types of sensors, including smoke detectors, temperature sensors, heat detectors and occupant's sensors, installed in the facility were used to collect sensory data of fire and occupants.

Collected sensory data from Siemens-Room Temperature Sensor, and Quuppa Intelligent Locating System (which enable real-time occupants tracking), were used to test the proposed method for extending IFC. Then, a fire in the floor was simulated and the temperature data were visualized in BIM.

4.1 Data Acquisition and Integration with BIM

The floor was modeled in Autodesk Revit Architecture 2018. Sensors were added to Revit under the electrical category (as shown in Figure 4). Then, the model (geometry and spaces) was exported to IFC format.

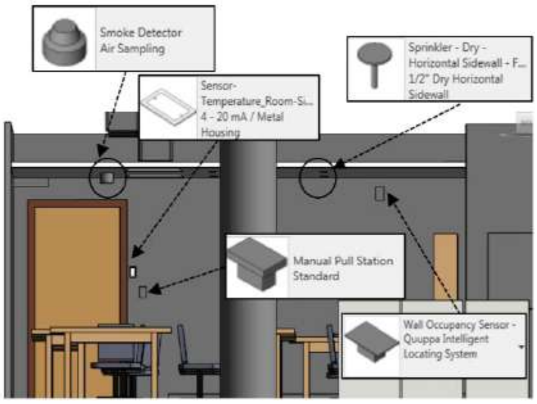

Figure 4. Revit model of a students' lab

Temperature measurement based on date and time were collected by temperature sensors installed in each room and the corridor. Also, Quuppa system gathered information (ID, date/time and X-Y coordinates) of five occupants through wearable tags. The two sets of information were initially recorded as .csv files. In order to avoid overpopulating the IFC file, the procedure of assigning sensory data to BIM can be divided into three major phases: 1. Pre-disaster phase: In the normal condition, the system is in the "monitoring" mode; i.e. sensing the environmental and occupational information, but not storing the results in the IFC. The sensor elements (both heat sensors and the Quuppa sensor system) were modelled as IfcSensor entities (i.e., Heatsensor and OccupantTrackingSensor types respectively). General properties such as the coverage area and the set point temperature were modelled for the heat sensors. Moreover, the hazard threshold was defined for this sensor type as an IfcPropertySingleValue, representing rate of temperature rise, to be sensed as being hazardous. 2. Disaster detection phase-gate: Once the reading in the sensor reaches the set-point threshold, the system starts storing in the IFC, the data collected by the two sensor types. This may update the state of the IfcSpace form "safe" to "hazardous" and will associate the environmental as well as occupation sensory data into it. 3. Disaster/evacuation phase: temperature data collected every second is modelled as an IfcRegularTimeSeries. Storing the occupant information is more complex. For one, the data must be associated with the IfcOccupant, as well as the IfcSpace. Moreover, the data read (by Quuppa e.g.) has more attributes than the heat sensor. Each data-point in this dataset has the ID of the occupant, date, time, and the X-Y location of the occupant. The data is collected and stored every second; hence IfcRegularTimeSeries was used for storing occupant information during the hazard. The IfcTimeSeries was associated with the IfcOccupant (from whom the data were collected).

The values of the IfcTimeSeries are in fact ordered pairs (representing X and Y location of the occupant at the given time). In our study, however, we used two separate time series for the two coordinates. Table 1 shows the attributes of the IfcTimeSeries used for storing the occupants' locational information (X coordinate as an example) during the disaster.

Table 1. IfcRegularTimeSeries attributes for the Quuppa intelligent locating system data

#	Attribute	Type
1	Name	XCoord
2	Description	X Coordinate of the occupant
3&4	StartTime EndTime	IfcDateTime YYYY-MM-DD Thh:mm:ss
5	TimeSeriesDataType	Continuous
6	DataOrigin	Measured
7	UserDefinedData-Origin	N.A.
8	Unit	LengthExponent
9	TimeStep	1 sec
10	Values	An array of X location (in m) for the occupant, with 1 sec interval time updates

4.2 Data Visualization

In the IFC format, new attributes and relationships for sensors and occupants were added to the EXPRESS file, based on the IFC4 standard. Then, the modified IFC model was viewed by BIM Vision as a freeware IFC model viewer that enables users to work on the file in the format IFC4.

In order to visualize sensory data (environmental and occupants) in BIM, as well as linking sensory data back to the Revit model, the visual programming tool Dynamo was used. Firstly, for visualization of the temperature data the following steps were taken: (1) modelling the 9th floor of the EV building, (2) assigning a number to each space; (3) defining parameters of the model, such as temperature and spaces for visual programing; (4) classifying the space temperature as shown in Table 2; (5) assigning a certain color to each class of temperature; and (6) visualizing the temperature classification of the space automatically on the Revit model using the colors as shown in Figure 5.

Table 2. Space classification based on temperature

Temperature (°C)	Zone Color	Condition
T < 23	Green	Very safe
23 ≤ T ≤ 30	Yellow	Safe
31 ≤ T ≤ 50	Orange	Near dangerous
T > 50	Red	Fire/ dangerous

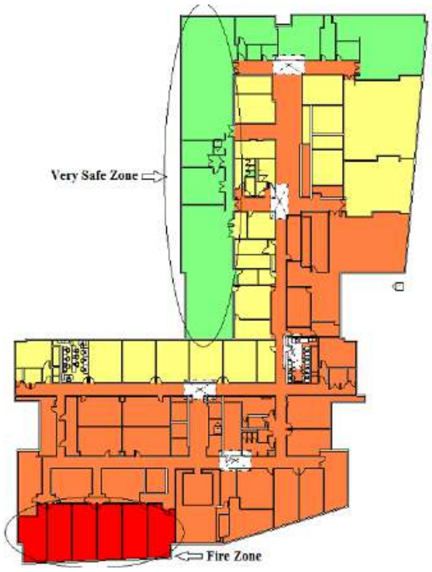

Figure 5. Space classification based on temperature in Revit

Secondly, the locations of occupants in one shared office for graduate students on the same floor (collected through Quuppa system and stored as time series) were visualized through the following steps: (1) modelling the office, (2) changing the coordinate system of the model to match with the local coordinate system used by Quuppa; (3) reading the data related to each occupant for each time step; (4) assigning a certain color to each occupant; and (5) visualizing the locations of the occupants automatically based on the time in the model as shown in Figure 6. This figure shows the locations of two occupants that were present in the office.

5 Conclusion and Future Work

This paper elaborated on the motivations and needs of new types of occupants' sensors and new occupants' attributes to have comprehensive real-time awareness in the case of a fire in a building. An extended IFC model was suggested to identify the entities, attributes, and relationships between sensors, occupants, occupancy, time series, and building components. The proposed model was tested in a hypothetical case study, temperature data and occupant location were added to BIM for visualizing the space conditions under a fire.

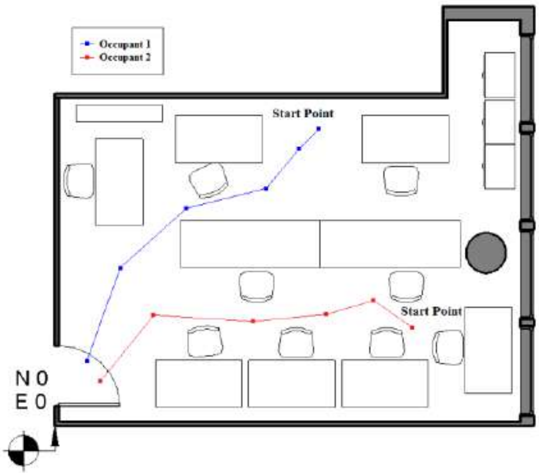

Figure 6. Visualizing the occupants' locations in Revit for the duration of 6 seconds

The proposed method was useful in providing real-time information for effective fire emergency management. Moreover, this work can be used to enhance the emergency first responders' perception by using 3D visualization of the dynamic conditions of the building under fire and occupants' condition.

Our future work will include the following: (1) Further implementation and testing of the proposed method, including the interaction between the occupants and the simulated fire propagation during building evacuation; (2) Extending the proposed model based on the first responders' view of indoor/outdoor fire emergency management; and (3) Developing a platform for the next generation of intelligent building emergency management that can integrate with BIM and IoT.

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Signature-based matching of IFC Models

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Abstract –
This paper presents the problem of model comparison in platform-neutral collaboration of Building Information Models. The paper describes that model matching and comparison strategies for platform-neutral models (i.e. IFC models) are the keys to solve the problem of iterative change management during BIM collaboration workflows. It is highlighted that the current model comparison strategies are centric towards using GUIDS which may not lead to accurate results due to the complexity of modelling operations and internal data structures of modelling tools. The paper proposes a signature-based model matching approach for IFC models that use model object characteristics to define object signatures for object recognition and comparison. Examples of creating signatures from IFC object characteristics are presented. The proposed methodologies for creating IFC object signatures are implemented in a custom-built tool, XBIM Signatures exporter, which then demonstrates a successful export of object signatures on a test case. The paper concludes that the proposed object signatures can be useful to establish accurate candidates for comparison and can reduce the workload of the overall model comparison process. However, a robust solution for IFC model comparison would require a weighting formula for various object characteristics to formulate an object recognition and comparison strategy.

Keywords –
BIM, IFC, Model Server, Model Comparison

1 Introduction

Building Information Modelling (BIM) has presented effective solutions to resolved information collaboration problems in the AEC industry. The technology to create efficient Building Information Models is now mature and can support the development of discipline-specific (i.e. Architecture, MEP, Structural) Building Information Models. As the information in a BIM grows during an iterative design and production process and even beyond into maintenance, a critical issue is how to manage the iterative changes because of the collaboration operations and workflows that involve various project participants and heterogeneous applications. The problem of interoperable information exchanges using heterogeneous BIM application has been well researched and has led the development and implementation of Industry Foundation Classes (IFC) over the last 20 years. IFC has now become a widely accepted open and neutral data format specification to facilitate interoperable information exchanges using Building Information Models in the AEC industry.

Today, a platform-neutral BIM enabled collaboration relies on effective management of IFC models using a Model Collaboration System or a Model Server. A model server is a type of database system that allows upload, download, sharing and coordination (e.g., model comparison, and model checking) of models or components by multiple users [1].

An IFC enabled model server is expected to facilitate the exchange of information between the applications used throughout a building project lifecycle (e.g., design tools, analysis tools, document management systems, facility management tools) used throughout a project's lifecycle [2]. The workflow of such a collaboration is built around the concept of finding changes in two versions or variants of IFC model instances and merging them together with the shared data repository. Thus, the issue of IFC model comparison becomes critical to keep track of the changes during the information exchange workflows. The purpose of IFC comparison process is to identify similarities and differences between two IFC models. A fundamental requirement of an effective IFC comparison process is identifying comparable objects or identifying candidates for comparison in the two matching IFC files. Existing IFC Comparisons mechanisms are usually based on using Globally Unique Identifiers (GUIDS) to establish candidates for comparison, in a shallow or a deep tree comparison procedure. GUIDS are a reliable base if these are properly maintained during the IFC roundtripping and the involving editing operations using BIM software applications. However, GUIDS exports are not always consistent due to the complexity of modelling operations, application imprints and different internal data structures of BIM tools, which leads to costly calculations, quality compromises and inaccuracies due to inconsistent GUIDs in IFC model comparison processes.

To address these issues, this paper presents a signature-matching approach that advocates using dynamic object identities, calculated from the value of its properties and attributes using hash keys that can create a unique signature for an object. In BIM collaboration operations, a change can be in (1) an object's position, (2) its shape and its (3) properties. Therefore, an object's position, shape and properties can be used to formulate partial, default or complete signature for an object, which would be useful in establishing candidates for IFC comparison process, independently from GUIDs, and would reduce the overall workload of the IFC compression process. Signature matching is useful even if a complete solution is not feasible, as signature matching can be used to eliminate a significant proportion of elements to downsize the comparison criteria for any further comparison.

2 The Problem of IFC Model Comparison

A critical issue in managing collaboration operations on a model server is the management of iterative changes during BIM collaboration operations. The shared data repository on the server must be updated with any changes because of modifications made in a check in/check out the operation, such as new data instances added, deleted or changed. The information in the shared repository (i.e. Model server) is defined in terms of a moment in time and associated versions in other moments in time, resulting in several versions and variants of a shared repository instance and discipline-specific information models. Thus, the issue of IFC model comparison becomes critical to keep track of the changes during the information exchange workflows.

Typically, the IFC model comparison is a post-rationalisation activity in a collaboration operation where the data management system (i.e. model server or another comparison tool) must deal with what has already happened on a set of data with no or limited knowledge of prerequisites about the incoming data. The comprising IFC files may include changes, application imprints and other data instances due to IFC round-tripping. The process of IFC comparison will require establishing right candidates for comparison before a comparison algorithm can be applied to determine similarities and differences. In post rationalization situations, establishing the right candidates (corresponding objects in comparing versions) for comparisons becomes difficult, for which Globally Unique Identifiers (GUIDs) are typically used in a shallow or deep tree comparison of IFC models [3]. The use of GUIDs in IFC model comparison has been heavily criticised in the literature [[4][5][5][7] as it leads to costly calculations, quality compromises and inaccuracies due to inconsistent GUIDs in IFC data round-tripping. Moreover, different BIM authoring tools may have different semantic representation for a same physical object which triggers another concern that is how to compare models which are constructed independently using different tools because the tools internal representation differs from the IFC exchanged representation

Furthermore, support is required from the client-side application when submitting changes to the model server, for example, to maintain object owner history and the consistent preservation of GUIDs. However, the internal data storage structures of client-side BIM applications tend to be different from each other, with limited support for database level change management within proprietary BIM applications for server enabled collaboration. For example, if a structural engineer decides to change the position of 4 columns, there is no predefined standard workflow for executing this change. The engineer may change each column individually, leading to four changes in the model; or may decide to change one, delete the other three and then copy and paste the first one three times (Figure 1). This will result in one change, three deletions and three new columns in a model, but ultimately the design change would be the same in both cases.

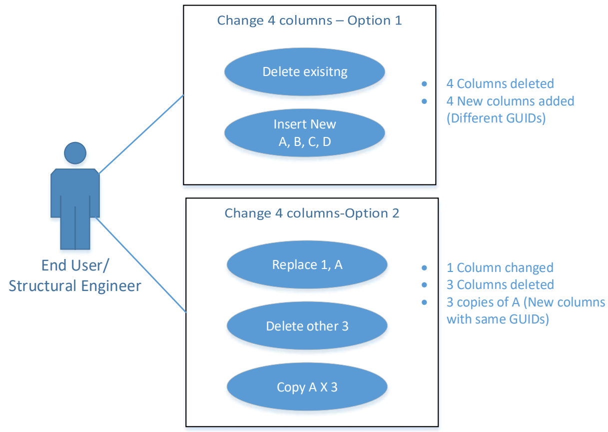

Figure1: Use case of a structural engineer modifying columns in a shared model

In such design modifications, when exporting the latest version of an IFC model, the IFC versioning can be different, as the two editing operations could result in different GUIDs for the same model elements. If the objects' GUIDs are identical, there is clearly a match for comparison (as GUIDs are designed to be unique).

However, two objects can still constitute a comparable pair even if their GUIDs are different. Most model comparison applications (e.g. Solibri, BIMServices, or proprietary applications etc) use GUIDs to establish candidates for comparison and therefore fail if these are different for two comparable objects. Tracking comparable objects across versions is a fundamental task in managing the workflows of model server enabled collaboration on BIMs. In summary, GUIDs are helpful when tracking such changes, but there is a need to consider other characteristics, such as location (same bounding box), containment (same address), name, specification, in addition to using GUIDs for object recognition and identification in a comparison process.

3 Previous Work

Several authors and research projects have addressed the general issue of change management in IFC models [7]**Error! Reference source not found.Error! Reference source not found.** and only a few studies have focused on IFC model comparison strategies [11]**Error! Reference source not found.**[13][14].

Traditional plain text-based comparison tools do not consider specific data organization and representation of comparable files and therefore are not suitable for IFC Comparison. Alternatively, GUID-based comparison strategies were presented to compare IFC models [15] [13]. GUID-based strategies consider two instances in two comparing files as same if their GUIDS are matching and vice versa. [13] developed EVASYS (EXPRESS Evaluation System), one of the first tools that can calculate a number of identical instances in two comparing IFC models under EXPRESS schema. The comparison algorithm proposed in EVASYS was based on using GUIDs (Globally Unique Identifiers) to identify matching object pairs and then used a sequence of steps to filter out matching and different objects by comparing object types<instances<attribute value. GUID (globally unique identifier) is a unique identifier for object instances that follow the universally unique identifier standard (UUID) that provides a way of uniquely identifying an object. **Error! Reference source not found.** reported four weaknesses of EVASYS: (1) it ignores redundant instances; (2) it does not provide any mechanism to analyses IFC owner history; (3) it does not consider if GUIDs are changed but that the property values are maintained; and (4) it is limited to counting structural instances in comparison, ignoring semantics. In IFC models, only entities inherited from IFCRoot will have GUIDs, while many other entities (e.g. IfcPropertySingleValue) not inherited from IfcRoot have GUID **Error! Reference source not found.**. In addition, the GUIDs of instances are often changed during the data exchange between different systems even without a modification to the model itself [14]. Although GUID-based comparison approach is simple and can provide fast results but is error-prone and therefore cannot be relied on.

A graph-based approach is presented by [16] which compares two oriented graphs generated by two IFC files. Similarly, [13] proposed converting IFC file into RFD-RDF graph-based signature algorithms for computing differences of IFC models. However, the matching process in graph-based comparisons still complies with GUIDs comparison.

Error! Reference source not found. proposed a flattening-based comparison approach, which suggests replacing all referencing with actual values in two IFC files and then compares the flattened data instances instead of original files. The comparison process becomes simplified to a string comparison as it overcomes the differences of reference numbers included in attribute values. However, the proposed flattening process can result in quite long strings of data due to complex inheritance and reference of IFC instances. Therefore, the flattening-based approach is time-consuming and not suitable to compare large IFC files [14].

Another IFC comparison approach uses a tree-based comparison of two IFC models using the hierarchal structure of IFC to map instances of two comparing files. This approach was presented by [11] and implemented in an IFC comparison tool “BIMServices”. This approach uses IFC spatial and containment hierarchies to base model comparison as the path along model hierarchy tree will typically have incremental changes, starting from IfcProject, across different versions of the same IFC model. Also, the IFC spatial hierarchy (geometry) is a relatively reliable base across BIM authoring tools and end users, which can help better understanding of the comparison results. The bimServices tool provided a better way of comparing IFC models through a sequential pass to calculate differences and similarities by using a tree comparison. However, the identification of comparable pairs still relies on the assumption that GUIDs of two instances will match in the comparing models. More recently, [16] presented a similar tree comparison approach which uses data instances, instead of GUIDS, to establish candidates for comparison to initiate the comparison process. Their approach extracts three basic terms (i.e. instance name, entity name and attribute values from each data instances) and their referencing relationships to construct IFC file hierarchy to perform the further comparison. This approach can reduce the number of redundant instances and can provide fast comparison results without relying on the matching GUIDS. However, various BIM tools use the different naming structure for instances and can export two different names for the same object in an IFC Import/Export operation. Therefore, constructing the IFC tree comparison using instance or entity names may not lead to accurate candidates for comparison to support the rest of the comparison process.

Previous authors have recognised that in order to get a more meaningful result for IFC model comparisons an extended set of metrics need to be considered that is not solely based on GUIDs but also consider other physical, structural and semantic properties of the IFC models [6], [8]. Preservation of GUIDs is unanimously stressed by previous researchers, as accurate GUIDs can provide quick and useful comparison results. If BIM authoring tools can preserve GUID in the round trip IFC exchange, then it will simplify the IFC comparison problem to a significant degree, however, GUIDs are often lost or changed during a data exchange due to BIM authoring tool imprints or end-user modelling preferences. A fundamental problem with inaccurate GUIDs is an inaccurate selection of candidates for comparison that can lead to completely wrong results. Therefore, a more sophisticated approach is needed to establish candidates for model comparison using different model matching strategies in addition to GUIDs.

4 A Signature Matching Approach for IFC Models

This paper proposes a signature-matching approach to establish object identities in model matching and comparison processes. In a signature-matching approach, the identity of an object is not static but calculated dynamically from the value of its properties and attributes creating a unique signature for an object[17].

[18] defined that "the signature is the collection of values assigned to a subset of syntactic properties in the model elements". The set of values that can be used to determine a signature for an object is called "signature type" [17]. Furthermore, [18] divided signature types into three categories, which are (1) a complete signature that covers all the syntactic properties associated with a model element; (2) a partial signature that covers a certain range of element properties; and (3) a default signature that is only composed of name properties. The selection of a signature type for an object requires user configuration which can be defined using a query language. A signature can be calculated using any number of properties associated with an object that can provide a distinguisher for the object. For example, a signature for an object can be its name, type and location or a combination of these characteristics (e.g. wall, wall type, position coordinates).

A signature does not rely on precedent identity (e.g. GUIDs); therefore, it can also be applied to the models which are created independently of each other using different tools (i.e. as in the case of IFC models populated from Revit or AECOsim). However, the creation of unique object signatures needs to define a series of functions to calculate accurate signatures for model objects based on their signature types. Using the pre-defined signature types, a hash value can be computed for the relevant properties sets which are used to establish a match during the comparison process. A hash function is used to map digital data of arbitrary size to digital data of fixed size, the values returned by hash functions are called hash values or hash codes or hash keys or simply hashes. Signature matching is useful even if a complete solution is not feasible, as signature matching can be used to eliminate a significant proportion of elements to downsize the comparison criteria for any further comparison.

4.1 Signature Matching Application in IFC Models

This paper proposes that characteristics of IFC objects can be used to create signatures for IFC objects, which then can be used in addition to GUIDs, to effectively compare corresponding objects an IFC model comparison process. This leads to a new research question: "What should constitute an effective signature for IFC objects?". It is suggested that this can be answered by considering the structural and semantic characteristics of an IFC model and the type of changes an IFC object can undergo. Fundamentally, a change can be in (1) *an object's position,* (2) *its shape* and its (3) *properties.* Position and shape are absolute as if two objects, in a comparing process, are at the same position and contains the same geometrical shape, then these are likely to be a similar object and thus, are candidates for comparison. Therefore, the characteristics of an object related to its position and shape can be used to create a signature for object recognition. For example, in an 'IfcDoor', the 'IfcLocalPlacement' defines the local coordinate system that is referenced by all geometric representations. The three-dimensional (3D) shape of 'IfcDoor' is represented using 'SweptSolid', 'SurfaceModel', or 'Brep' to define the door geometry. Most BIM authoring tools exchange arbitrary shape extrusions in IFC, which can be used to create a unique object signature.

On the other hand, creating a signature from element properties is complex as it involves a degree of change in object properties. For example, in versions A & B of the same IFC model, change in properties can have following scenarios

Properties of object A (version 1 of a dataset) = P [A]
Properties of object B (version 2 of a dataset) = P [B]
P [A] = P [B] = No change in properties
P [A] > P [B] = some properties have been deleted
P [A] < P [B] = some properties have been added
P [A] ~ P [B] = Properties have been updated/edited

Therefore, it is important to determine what properties are important and if we can determine the degree of importance in IFC properties, then it can be used to create a signature based on the key properties. Several signatures can be created from object properties, such as (1) The total number of property count can be used as a signature; (2) A name key for all the property sets names attached to an object can be used as a signature; (3) A name key of property names can be used as a signature and (4) A property value key can be used as a signature etc. These signatures can be used as passes to determine the degree of change in a potentially matching pair in a model comparison process.

Moreover, the position and shape are a way of reflecting an object on a drawing and in a 3D presentation. Therefore, these two components are compelling candidates to create a unique object signature. However, the case with object properties is different as it involves the degree of change that needs to be incorporated into creating the signature. The following examples demonstrate the development of IFC object signatures from shape and position characteristics.

Example 1: creating a signature from geometric representations (Shape)

The geometry of an IFC element is defined by a shape definition (i.e. 2D, 3D body and 3D path), the IfcProductDefinitionShape & IfcLocalPlacement allowing multiple geometric representations. For example, an IfcDoor may have a profile, footprint, bounding box and several 3D body definitions at different levels of detail. There is an unlimited number of shapes within the IFC schema, but it is schema requirement that it must have at least one 3D body. Therefore, the 3D shape of an element can be a signature type as it is populated every time for an IFC element. Another aspect is bounding box representation, as an IfcBuildingElement may be represented as a bounding box, which shows the maximum extent of the body within the coordinate system established by the IfcLocalPlacement. The bounding box representation is the simplest geometric representation available. The same element shape should always be contained in a same bounding box representation. Therefore, bounding box representation & 3D shape definitions can be used as strong signature types. In simple words, if two objects occupy a similar 3D space then they are candidates for similarity checking. For example, if in two comparing datasets, DS1 = IFC model version A; and DS2 = IFC model version B

RadiusBoundingSphere signature matching

Signature Type: Partial signature
Description: A hash code signature can be calculated by the radius from the middle point that contains all the points in the *shepheId* that contains the shape of an element. MatchElement RadiusBoundingSphere. (DS1, DS2)

>Element. RadiusBoundingSphere.hashcode.DS1 = Element. RadiusBoundingSphere.hashcode.DS2 = Filter for further analysis as potentially matching pairs

>>Element. RadiusBoundingSphere.hashcode.DS1 ≠ Element. RadiusBoundingSphere.hashcode.DS2 = Filter as changed object or new object

See Figure 2 for graphical representation

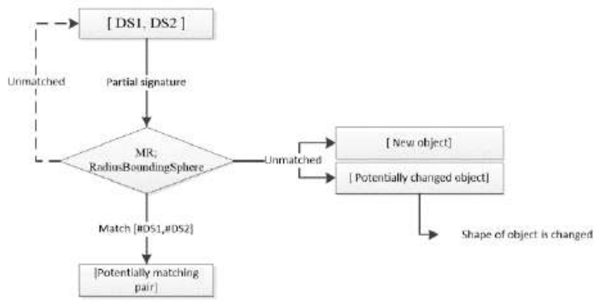

Figure 2. Matching rule for RadiusBoundingSphere signatures

A key aspect in defining shape signature type is to determine how 3D shapes are being generated from BIM authoring tools, as different BIM authoring tool may populate same 3D shape using different profile definitions, due to their internal structural differences and end-user domain applications. For example, Autodesk Revit uses arbitrary profile definitions to generate 3D shapes, whereas Tekla Structures uses parameterized profile definitions (IfcIShapeProfileDef, IfcEllipseProfileDef etc) as these profiles can create more efficient shapes related to structural elements (e.g. beam, columns etc). Therefore, shape signature is not a compound or complete signature, but it can have its contribution to reducing the size of the datasets for comparison. A shape-based partial signature is particularly important in determining the changes, rather identifying the candidates for comparison.

Example 2: Creating signature from Local placement

The geometry of an IFC element is defined by a shape definition and a local placement (i.e. IfcLocalPlacement). The IfcLocalPlacement defines the relative placement of a product in relation to the placement of another product or the absolute placement of a product within the geometric representation context of the project (BuildingSMART, 2014). A signature for local placement can be calculated by the X, Y & Z positions from the middle of an element (Centroid x, Centroid y & Centroid z). A matching centroid value will indicate an equivalent element with no change, whereas an unlatching centroid value will identify a change in the position of the object. For example, if in two comparing datasets, DS1 = IFC model version A & DS2 = IFC model version B

Position (Centroid) signature matching
Signature type: Partial signature
Description: A hash code that represents position signature of an element calculated from its local placement; Centroid for x, y & z

>ElementIfcLocalPlacement.Centroid. hashcode.DS1 = ElementIfcLocalPlacement.Centroid. hashcode.DS2 = Potentially matching pair, filter for further analysis, no change in position

>>ElementIfcLocalPlacement.Centroid. hashcode.DS1 ≠ ElementIfcLocalPlacement.Centroid. hashcode.DS2 = Filter as changed object; Position of the object changed

See Figure 3 for graphical representation

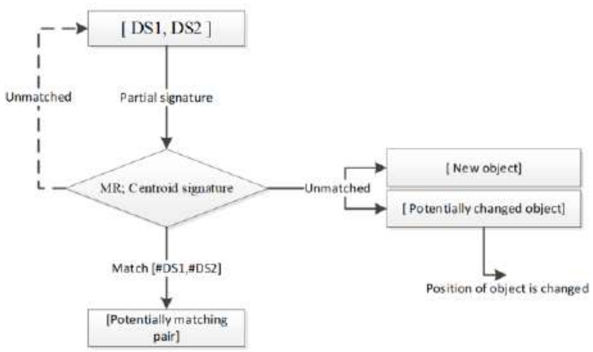

Figure 3. Matching rule for position (centroid) signatures

Likewise, the shape signature, the local placement signature cannot decide on its own for identification of corresponding element pairs in the comparison process, but it can be used in combination with other signature types, to detect potentially matching pairs or also to reduce the amount of work in calculating and identifying potential changes. If two elements have same local placement and shape, it is quite strong to say that it is a potentially equivalent pair, and can be a candidate for comparison. If the local placement coordinates are different for an element, in relation to its corresponding element in a comparable dataset, then it indicates that the element is "moved" in the updated version of the dataset, thus helps to identify the changes undergone. Similarly, signatures can be created from other IFC object characteristics (e.g. Schema type, Object Type, Name, Property Count- see Table 1) and can be used to support establish similar candidates for comparison. It is to be noted that GUID itself can be used as a signatures type as matching GUIDs would constitute a match but different GUIDs can be ignored (i.e. same objects can have different GUIDS).

4.2 Implementation: XBIM Signature Exporter

The proposed signature matching approach is implemented in a custom-built software tool, xBIM signature exporter, a tool that can create a unique signature using various characteristics of IFC building elements according to the proposed methodologies in this research. The xBIM signature exporter is developed on the platform of the xBIM toolkit, the eXtensible Building Information Modelling (xBIM) Toolkit, which is an open source, software development tool that supports IFC schema. The xBIM toolkit supports IFC models for geometric, topological operations and visualisation that can be used to create bespoke BIM middleware for IFC-based applications. The XBIM signature exporter was developed in a commercially funded research project; Therefore, the source code of the tool is not discussed.

The XBIM signature exporter has extracted serval signatures from the test model; however, only a few signatures are useful in IFC model comparison process. The xBIM signature exporter tool is implemented to calculate signatures for "Standard classroom" model using IGC 2.0 coordination view specifications. The test model contained an IfcDoor (1), IfcSlab (2), IfcWallStandardCase (5), IfcWindow (6) and an IfcOpeningElement . The XBIM signature exporter has extracted serval signatures from the test model using the signature types defined in Table 1. Examples of extracted signatures for "Door" and "Slab" are also presented in Table 1.

The limitations of this paper do not allow to present the test case and demonstrate the comparison results obtained using the extracted signatures. Therefore, only examples of extracted signatures are presented in Table 1 to follow the discussion.

Table 1: IFC object signatures definitions in XBIM signature exporter

Signature Type	Description	Example of a "Door" Signature	Example of "Slab"
Model ID	A number that represents the internal ID of an element inside the model. E.g. 2552 for an IfcDoor.	2552	249
SchemaType	A name for a type of building element. E.g. IfcDoor for a door.	IfcDoor	IfcSlab
DefinedTypeId	A total number of defined types attached to an element. E.g. the value for the defined type of IfcDoor is calculated as 2539, in the test model.	2539	0
GUID	A fixed 22-character length string, which is associated with each element and is exchanged with the IFC exchange file structure.	3A3Tihl61FQRUYE_9VB72L	3A3Tihl61FQRUYE_9VB75i
Name	The name of an IFC element is a label in the term by which something may be referred to, i.e. IfcLabel = String (Max.255 characteristics).	IntSgl (1):1010 x 2110mm:1010 x 2110mm:195846	Floor:Ground Bearing Concrete:195839
ObjectType	The type of object of an element.	1010 x 2110mm	Floor: Ground Bearing Concrete
PropertyCount	A number representing the count of total properties given to an element by the author in addition to what it would have by default (i.e. Extension properties in Revit)	56	29
PropertySetNamesKey	These are single value property sets that can be used to generate a signature, considering that the complex property sets are hardly ever used in real examples of IFC models	-863509959	1452519724
PropertyNamesKey	Similarly, a hash key is created from "Names" of the properties (e.g. level, the height of offset from level etc) by sorting out names of the properties in an alphabetical order and creating a hash code signature.	1703689443	1976711505
PropertyValuesKey	Similarly, a signature is calculated for the values of the properties.	570000713	1589767974
MaterialId	This is the name of the material attached to an IFC building element.	(empty, no material assigned)	Floor: Ground Bearing Concrete
Centroid X	This is the position signature calculated by a x,y,z positions of the middle of an object.	-3908.871582	-1556.871582
Centroid Y	Thus, centroid determines the local placement of the object that can be used as a unique	4958.726563	828.9765625
Centroid Z	identification signature for the object recognition and also detect if there is any change in the object's position.	1072.5	-250
RadiusBoundingSphere	This is a number that represents radius from a middle point that will contain all the point in the shepherd that contains the shape of an element. In simple words, it is the radius of the bounding box of the shape of an element. If the shape of an element is changed, it will change the bounding box and vice versa. Thus, it can be used as a unique signature for the shape of an object.	1205.268555	6259.641113
ShapeId	This is the shape ID that defines the shape of an object	-914375451	-444593825

The results suggest that the schema type, GUID, position and bounding box signatures are strong signature types. Considering the volatile nature of GUIDs, schema type, position and centroid signatures provide enough evidence to establish candidates for comparison in the first pass, even if the GUIDs are not matched. After establishing matching pairs for a comparison analysis, signature matching can also help to reduce the size data for detecting fine grain changes if there are any. For example, if a matching pair has a different PropertyCount or PropertySetNamesKey, it means some properties have been added or deleted, and it should be checked for more detailed analysis. Thus, the signature types, such as NAME, Object Type, properties, can reduce the amount of workload to precisely detect changes in further analysis. It is not a brilliant way of calculating differences, but it reduces the amount of work required for further analysis.

5 Conclusions and Future Work

This paper describes that model matching and comparison strategies for platform-neutral models (i.e. IFC models) are the keys to solve the problem of iterative change management. A critical issue IFC model comparison is establishing right candidates for comparison, regardless of what comparison mechanical is being used. Typically, GUIDs are being used to identify corresponding objects in IFC model comparison methodologies, which is criticised for their accuracy and efficiency. This paper proposes that the characteristics of an IFC object can be used to create unique signatures for IFC elements, in addition to GUIDs, to effectively compare corresponding objects in a model comparison process. An object's position, shape and properties can be used to formulate partial, default or complete signature for an object, which can be used as passes to establish candidates for comparison and to highlight changes in a comparable object pair. This approach is useful in establishing accurate candidates for comparison without GUID dependence and can reduce the workload of the overall model comparison process.

In terms of creating an element's signature, there are several issues that need to be considered in the broader perspective of change management in a model server environment. This research has only developed signatures for IfcBuildingElements as it has the highest importance for an end-user from a change management prospectus. Even for IfcBuildingElement, the research has defined signatures for IFC object characteristics which are largely optional and may have different population if models are created using heterogeneous applications. In the context of creating unique signatures from these optional attributes, such questions need to be answered that what level of utilisation these optional properties are in the IFC models? And how likely these are to be found in real-world examples? Potentially, a subset of data can be derived, with the statistical reasoning that some characteristics, relationships and properties of IFC objects can be neglected or be focused on in creating object signatures, depending upon the usability proof from a wider and real-world dataset. This abstraction would require further empirical evidence from the analysis of real-world IFC models, reflecting a cross-sectional view of different BIM authoring tools that are used in creating IFC models. A critical issue is to consider associated weighting of different signature-type attributes of IFC objects to constitute an effective signature for IFC objects.

This study is limited to using optional object properties to create a property-based signature (such as PropertyCount, PropertyValuesKey), however, these optional properties can be referring to the same object but on a different Level of Detail (LOD). Therefore, Future research is needed to explore property signatures in more details, considering associated Level of Details and degree of change in an object's properties. Future research will explore the application of the proposed signature-based matching strategy on IFC models with different level of details and complexity within a model server enabled collaboration environment.

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A data-mining approach for energy behavioural analysis to ease predictive modelling for the smart city

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Abstract –

Analyzing urban districts to promote energy efficiency and smart cities control could be very complex as big data have to be analyzed filtered to discover unpredictable patterns. Using clustering method, specifically K-means algorithm, allows to create an energy profiling characterization of urban district models with multiple advantages: as first, large quantity of data can be managed and synthesized, easing the creation of algorithm patterns that could be replicable. Thus, it is possible to operate in a large scale and in a small scale in the same time, choosing the level of detail that is more appropriate for the specific analysis. In the large scale, the disadvantages are the dependence from data, i.e. if there are missing input values, it is hard to rebuild them because of the quantity of data. Missing values can confuse the analysis because scripts cannot identify the entire row missing it. Working with clustering analysis it is thus useful when large amount of data should be organized and interpreted and the technique can help the planner to make faster the analyses process. The research aims at demonstrate the efficiency of clustering methods when adopted for energy consumption issues at city level. In the paper, the clustering process concerning building energy profiles of a European city for the identification of building models is described. This means that an energy template on urban scale is used and clusters are applied on energy profiles based on architectural and energy similarity in order to find representative models. In particular, the study is focused on the relationships between building characteristics and actual building energy profiles.

Keywords –

Clusterization, behavioural modelling, smart city data mining, energy profiling

1 Introduction

In the last years, energy analysis has been progressively boosted to reach high efficiency in buildings, increasing savings and reducing CO_2 emissions according with EU objectives. EU government has set three targets to be achieved by the 2020: 20% reduction of greenhouse gas emissions (starting from 1990 value), 20% increase of EU energy from renewables, 20% improvement in energy efficiency [1].

The building sector is responsible of 40% of European Union's total energy consumption.

The population growth and the strong urbanization process showed in 2014 that the 54% of the world's population is living in urban areas. This proportion is expected to rise to 66% by 2050. Moreover, an increase of 90% is expected to be concentrated in Asia and Africa, according UN report [2]; this situation requires a more consistent energy management in order to reduce wastages and to increase comfort. This goal could be reached by the use of energy monitoring devices that can help to optimize energy consumption. Several studies show that is essential to analyze building energy profiles in order to understand how the occupancy variation affects the energy behavior [3][4] and data gathered are the key factor to understand the consumption distribution and thus to manage the smart city [5][6].

Nowadays, data mining is a powerful framework to promote consciousness and thus achieve strategies efficiency. Cooperation between different clusters of consumers, prosumers and energy production spots and plants [7], methods to analyze big and giant data are crucial to develop models [8] to represent, predict and renovate the cities through IoTed solutions and digital based technologies [9][10]. Digitalization is changing the way we approach the concerns in many fields however the smart city and the energy management is one of the first and exploited sectors in which digital models and predictive as well simulators are adopted extensively since many years. The digital revolution requires a high level of specialization in many fields such as data analysis and coding, computing, data engineering, machine learning, artificial intelligence (AI).

Digitalization is basically dependent on data and for that reason, IoT is increasing and data are gathered in every system up to redundancy. Nonetheless, the amount of data is not a guarantee of amount of information because of unstructured data or data organized in different ways compared to readable ones is leading to a big amount of unused data (90%). The initial vision of the final use and meaning and the correct plan of data collection should drive the "thirst" of data to make them useful. In AEC sector, the adoption of computers is increasingly fundamental as more and more data have to be analyzed and knowledge extracted to outline the predictive models and promote a robust analytical assessment.

2 Methodology

The methodology adopted is based on mathematical methods that are used to operate a data mining process and clusterization of big data. In the following subsections, the specific methods considered together with advantages and weaknesses are described before to go in deep with the methodology and application to the case study of the present research.

2.1 Clustering methods

With the grown quantity of data, clustering methods have been developed to make easier the data mining procedure using many clustering methods such as Hierarchical, K-means, K-medoid, etc. Clustering is an unsupervised learning task that aims at decomposing a given set of objects into subgroups or clusters based on similarity. The goal is to divide the data set in such a way that objects belonging to the same cluster are as similar as possible, whereas objects belonging to different clusters are as dissimilar as possible. Cluster analysis is primarily a tool for discovering previously hidden structure in a set of unordered objects [11].

Clusters are useful for creating and analyzing building energy profiles in order to organize data collected into groups easing to analyze and evaluate them also increasing the relevance of measures and indicators. For example, data could concern the energy consumption related to the use of kitchen and laundry appliances, electronic devices such as TVs or computers. Clusters can be prepared based on the different kind of appliances or based on the different users' behavior in the analyzed buildings [12] and collected through smart meters [13]. Based on specific induction principle many algorithms have been developed for clusterization and the main approaches are hierarchical methods and partitioning methods.

2.1.1 Hierarchical methods

These methods could be called top-down or bottom-up methods since they identify clusters following these two main directions. There are two main types of hierarchical methods and the difference sets in the starting point of the analysis:

- *Agglomerative hierarchical clustering* starts with single objects and each object represents a cluster. Then clusters are merged until a default structure is obtained.
- *Divisive hierarchical clustering* begins with one single cluster that contains all the objects and the subdivision in more clusters occurs successively.

The result of the analysis is a dendrogram representing all different considered groups, which are subdivided into levels (Figure 1).

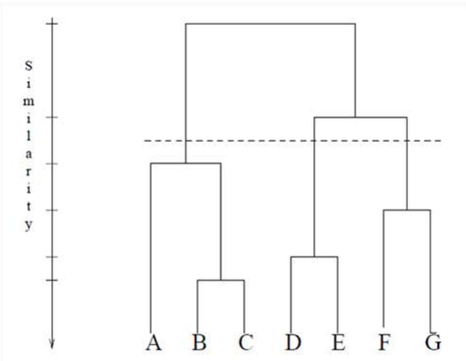

Figure 1. Dendogram: example of hierarchical results representation.

Checking the desired level of similarity, the clustering of objects could be obtained.

In the hierarchical method, more subdivisions that are possible come from the way of the similarity measure of clusters:

- *Single-link clustering* considers the distance between two clusters to be equal to the shortest distance from any member of one cluster to any member of the other cluster. If it is based on similarities, the similarity between couples of clusters is considered equal to the greatest similarity from any member of one cluster to any member of the other cluster.
- *Complete-link clustering* considers the distance between two clusters to be equal to the longest distance from any member of one cluster to any member of the other cluster.

- *Average-link clustering* considers the distance between two clusters to be equal to the average distance from any member of one cluster to any member of the other cluster.

The hierarchical method has the disadvantage of the inability to scale because of the time complexity that is non-linear with the number of objects. The method also has a high degree of rigidity.

2.1.2 Partitioning methods

Partitioning methods consist in move instances from one cluster to another, starting from an initial partitioning. The characteristic of this method is that the number of clusters has to be pre-set. To grasp the optimization an exhaustive enumeration process of all possible partitions is required [14]. There are different types of partitioned-based clustering. The most frequently used are the error minimization algorithms, which works perfectly with compact and isolated clusters.

When the distance of each instance to its representative value is measured, a certain error occurs. These algorithms try to minimize that error. The Sum of Squared Error (SSE) is the most known method and it measures the squared Euclidean distance of instances to their representative values. The most used error minimization algorithm is the K-means algorithm, which divides objects into K clusters, chosen randomly and each cluster is represented by a center or mean. The center is calculated as the mean of all the instances belonging to that cluster:

$$\mu_k = \frac{1}{N_k}\sum_{q=1}^{N_k} x_q$$

Where N_k is the number of instances belonging to cluster k and μk is the mean of the cluster k.

The linearity of K-means method is the key of its success over other clustering methods and even if the number of objects is huge, this algorithm is computationally attractive (Figure 2).

The weakness of this method is the choice of the initial number of clusters: the process of clustering is based on this number and the initial choice can change the entire result since there can be differences between global and local minimum.

Another partitioning algorithm that is part of the error minimization algorithms is the K-medoid or PAM (Partition Around Medoids); this algorithm is very similar to the K-means but it differs from the latter since the representation of the different clusters is dissimilar.

The principle is the same: each cluster has a center that, in this case, is the medoid; a medoid is the most centric object in the cluster and it is not influenced by extreme values and for this reason is more solid than the K-means method. Throughout evaluation methods, clustering criteria compute the optimal number of groups for a dataset calculating the index for each case. They measure the compactness of clusters and the homogeneity of them and choose the cluster for each element.

Graph-Theoretic clustering is a method that provides clusters via graphs. Instances are represented as nodes and this method connect all nodes. There is a connection between hierarchical method and the graph theoretic clustering since there is similarity between the hierarchical representation and the Minimal Spanning Tree (MST).

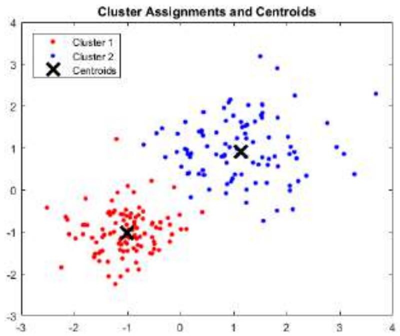

Figure 2. Example of K-means results representation.

2.2 Application in the research

The research consists into analyzing data about energy behavior of a big quantity of buildings gathered by means of smart meters used to register energy consumption during the all year with a step of 15 minutes. Thus, every quarter of hour, smart meters sent the registered data to the central system for monitoring. The analysis is used to identify the specific consumption patterns related to uses and building models. The smart meters have an identification number and for this reason, every smart meter represents the ID (Identification Code/Document) of a specific flat or activity set in a certain building. The research methodology is based on collecting data, sorting data and analyzing them following the scheme (Figure 3).

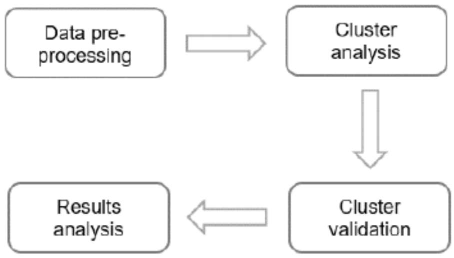

Figure 3. Methodological workflow.

2.3 Data analysis

The methodology start from a first analysis on data metered, after that, the different trends about electrical consumptions have been represent. The representative plots are performed using the ggplot2 R package.

In order to have a clear knowledge about the general trend of data, the smart meters' profiles of the entire year were plotted and compared in order to visualize. the data to be organized to allow the clustering analysis.

With the intention of creating a resume table with mean, median, maximum, minimum and the standard deviation, the main database has been partitioned selecting the unique ID of the smart meters. A table composed by 659 observations (i.e. 659 unique Smart meter IDs in the original database) and n. 6 variables has been created. After the creation of clusters, analysts are able to start the process of clustering validation that is the measure of distances of each data from the center of cluster (centroid) to understand the dissimilarity within each group [15]. This process helps to get a clearer vision about the objects giving a summarizing plot and data tables, which allow comparing results in an efficient way. Than the filtering data procedure started to divide into smaller packages to be handle. Data analyses and cluster methods permits to collect the different information in an easier way than in the past and these methods are suitable for smart cities analysis and strategies [16].

2.4 Cluster analysis

Data analysis allowed collecting various information about thousands of buildings including the geometry, the energy consumptions and the location; hence, it was possible to have insight on the composition of the analysed built environment. The information were about the typology of the analysed buildings such as the use, the year of construction and if changes occurred during the years. Throughout the data, it was possible to perform the analysis on the energy consumption that is strongly influenced by the use of the buildings.

After the data analysis, clusters were organized and the method adopted was the partitioning method with the help of the K-means algorithm.

This process is composed by two steps:

1. A first evaluation by using NbClust R package has been performed. This package provides n. 30 indices for determining the number of clusters and proposes to users the best clustering scheme.
2. The second step was to put the number of clusters that has been identified by the evaluation into the K-means function of R in order to create the subdivision following the similarities of the smart meters' profiles.

As described in section 2, clustering is the partitioning of a set of objects into groups in order to obtain groups with similar objects grouped in the same cluster. Most of the clustering algorithms depend on assumptions with the intention to define the subgroups present in a dataset.

The evaluation process had to tackle difficult problems such as

- the quality of clusters;
- the degree with which a clustering scheme fits a specific data set;
- the optimal number of clusters in a partitioning.

The evaluation was performed with NbClust. All these clustering validity indices combine information about intra-cluster compactness and inter-cluster isolation, as well as other factors, such as geometrical or statistical properties. There are n. 30 index but in the present research, two main indexes has been considered:

- D-index;
- Hubert-index.

2.4.1 D-index

The D-index is based on clustering gain on intra-cluster inertia that measures the degree of homogeneity between the data associated with a cluster. It calculates their distances compared to the reference point representing the profile of cluster that is the cluster centroid in general. The equation [17] representing this index is:

$$w(P^q) = \frac{1}{q}\sum_{k=1}^{q}\frac{1}{n_k}\sum_{x_i \in C_k} d(x_i, C_k)$$

The D index is a graphical method of determining the number of clusters. In the plot of D-index, we seek a significant knee (the significant peak in D-index second differences plot) that corresponds to a significant increase of the value of the measure.

2.4.2 Hubert-index

The Hubert-index r statistics is the point serial correlation coefficient between any two matrices. When the two matrices are symmetric, r can be written in its raw form as the equation:

$$\mathrm{r(P, Q)} = \frac{1}{N_t}\sum_{\substack{i=1\\ i<j}}^{n-1} P_{ij}Q_{ij}$$

Where:

- P is the proximity matrix of the data set;
- Q is an n x n matrix whose (i, j) element is equal to the distance between the representative points (vc_i,

vc_j) of the clusters where the objects x_i and x_j belong.

High values of normalized *r* statistics indicate the existence of compact clusters. The Hubert index is a graphical method of determining the number of clusters. In the plot of Hubert index, we seek a significant knee that corresponds to a significant increase of the value of the measure i.e. the significant peak in Hubert-index second differences plot [18].

After the evaluation, for the application in the case study (section 4) the NbClust function suggested a number of clusters k=5 plotting two graphs: the first one indicates the D-index values and it is possible to understand the number of cluster from the graph seeing the knee of the trend (Figure 4). The second graphs indicates the second differences D-index values and it suggests that the n. 5 is the ideal number of clusters throughout a peak [19]. With the intention of operating the clustering algorithm, the K-means function has been used setting n. 5 different clusters and using the Hartigan-Wong algorithm [20]. This kind of clustering algorithm determines a cluster assignment of a point peaking it repeatedly. It is based on the sum of squares of errors (SSE) and it searches the optimal within-cluster SSE for assigning an object to the proper cluster.

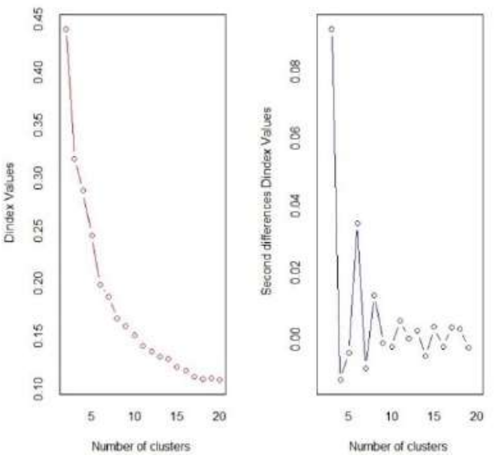

Figure 4. Indications by Hubert and D-index indices for the case studies.

3 Case study

The case study has been a district with 10.000 buildings of a European city where a smart metering strategy has been applied and data collected.

The organization of the buildings' data was based on the ID used in the data processing. After having sorted data, the next stage has been to analyze them trying to find out a significant clustering algorithm. To achieve that, an analysis on the buildings' use has been performed in order to collect Smart Meters with energy values within a correctly sized wide range. Then, a classification of the most frequent destinations of buildings was operated. The most frequent uses in the case study are listed below:

- Banks;
- Coffee shops and restaurants;
- Retirement Homes;
- Municipal Houses
- Residences,
- Private properties and Residential buildings;
- Administration buildings
- Industries and factories.

It is possible to define the type of buildings and the most frequent typology analyzing the residential use: the most recurring was the multifamily houses, followed by the single-family houses. Therefore, the analysis of the multifamily houses was developed since this category had the largest number of samples (Figure 5). Data processing delivers a list collecting the energy consumption value during the entire year identifying day by day, hour by hour, the effective energy usage.

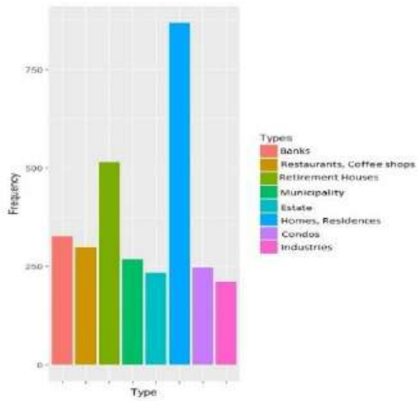

Figure 5. Buildings' use frequency diagram.

The research allowed getting a database composed by 22'994'372 observations with 659 unique Smart Meters IDs. This means that for each ID there are *n* rows indicating day, month, year, hour, and minute for the entire year. The variables of this data frame are n. 9.

This database is significant in order to design energy profiles for each smart meter, to get many other databases analyzing as an example data into workdays or festive days, analyzing month by month the energy use, visualizing systematic trends of these profiles.

4 Results

In order to understanding the results of the clustering analysis, a series of plots have been performed. The first representation of this study consists of plotting singles clusters in order to understand the differences between the groups. In Figure 6 the data for each cluster for one working day are plotted with the representative elements.

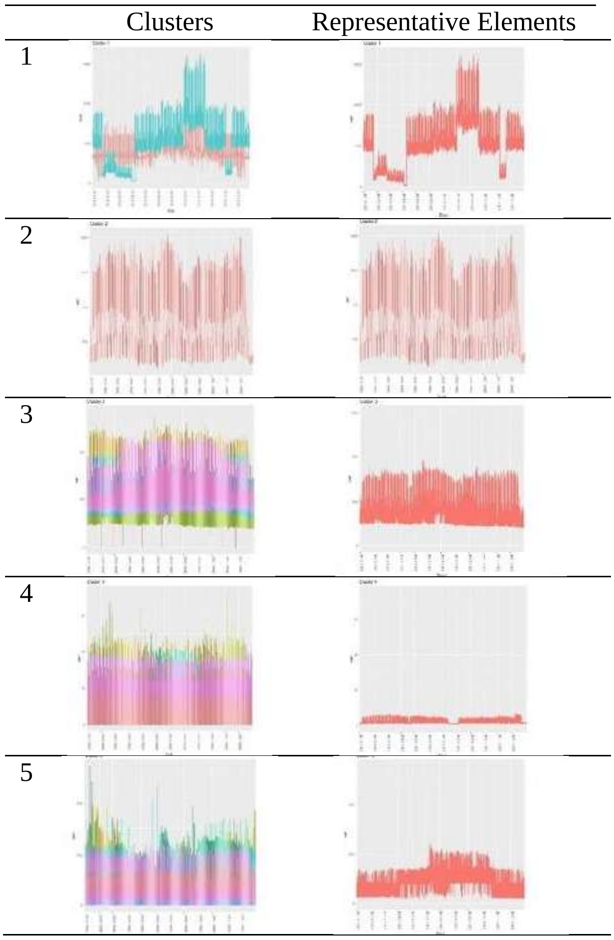

Figure 6 Working January One day profile.

The energy consumed during a year (2014) is thus plotted for each cluster considering the data time step of 15 minutes. In the following, the clusters are listed and data discusses:

- Cluster 1 is characterized by kWh values ranging between 0 and 1600 kWh. This cluster contains two cases and it has the highest range of kWh values.
- Cluster 2 is the smallest one and it gathers one observation that ranges between about 400 kWh and 1260 kWh with a value of around 860 kWh per year.
- Cluster 3 is composed by 8 objects and it has a range that goes from 0 kWh to almost 300 kWh.
- Cluster 4 contains 618 profiles and it is the largest one. The energy values ranges between 0 and 75 kWh and it is the cluster with the lowest range of values.
- Cluster 5 gathers 30 smart meter's profiles and it has an average value of almost 300 kWh with data ranging between 0 and 280 kWh.

In Table 1 the characteristics values of the clusters are reported. It easy to understand that cluster 4 is the cluster in which residential buildings are gathered and which is the most populated cluster. Cluster 1 could be the industrial buildings one and the municipal house could be cluster 2. The idea is that analyzing the data is not needed to go in deep into the identity of the building (with eventually privacy problems) but is possible to define the values trend and to suggest possible implementation strategies through the analysis of the archetypes, also calculating measure to redefine peaks and trends.

Table 1 Clusters Characteristic values

Characteristics	Clusters 1	2	3	4	5
Size	2	1	8	618	30
Mean	12.03	16.47	2.63	-0.13	0.73
Median	11.27	17.93	2.42	-0.13	0.60
Max	13.22	13.52	2.02	-0.14	0.95
Min	0.91	23.38	2.61	-0.08	0.22
SD	12.75	13.85	1.68	-0.13	0.89

In Figure 7, the whole profiles are shown to the left side, a working day (Monday) data are plotted to the right side.

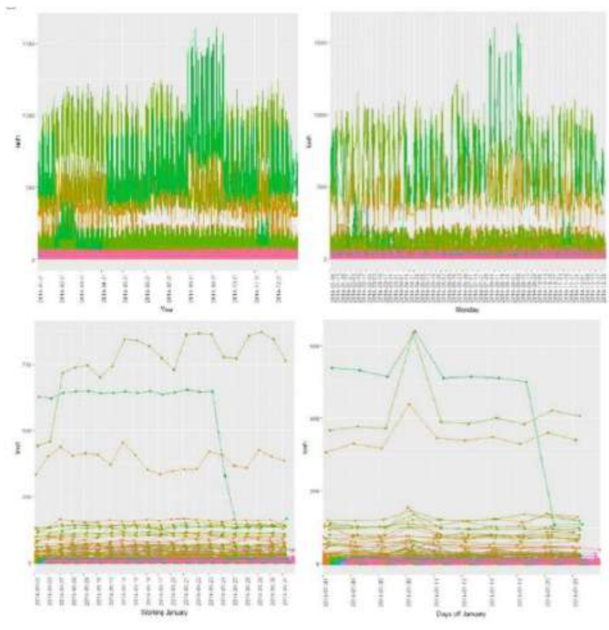

Figure 7 (above) One year smart meters profile and Monday profile and (below) week working day (January) and weekend daily profile.

It is possible to check that the different profiles are defining the city uses and buildings in which the energy consumption is concentrated.

There are the big consumers (Cluster 1 and 2) and all the other profiles with less consumption each but with a great number of units and variability due to occupancy distribution and different behaviors.

Cluster 4 is thus the largest with 618 profiles and this represents the housing stock in the sample used as a case study. For the main cluster 4 is thus shown in Figure 8 for the working day in January and the week end day in the same month.

In the left side diagrams, the yearly-recorded data are plotted and to the right side the daily profile are shown.

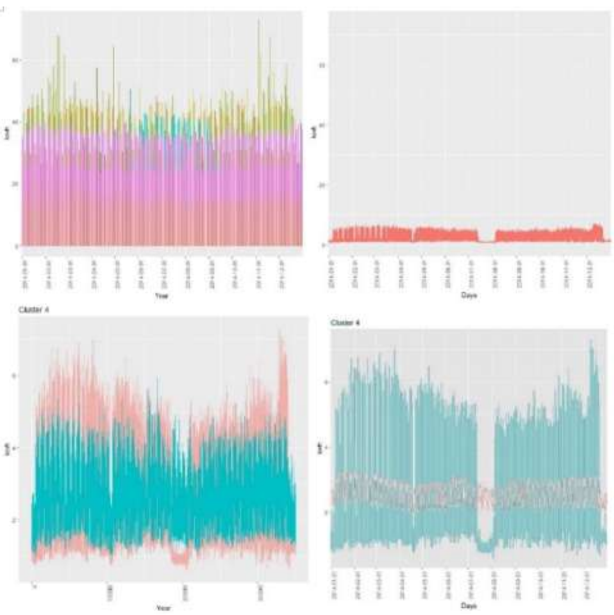

Figure 8 Week working day profile (January) and weekend daily profile.

The representative element of the Cluster represents the profile of a building and an ideal element that has been created through the average and the weighted average of the cluster.

The research showed that the weighted average is most suitable to define this representative profile because as multiple elements are used in the weighted average, the ideal centroid moves away from the representative element.

5 Conclusion

Hence, the digitalization has brought a strong advantage that is the possibility of managing a larger database that can make the pre-analysis process and that can analyse itself faster with a very significant improvement for the time management. A less time expensive but detailed analysis allows to the reduce costs which is one of the main aspects considered by the clients. Europe and the entire world is getting effort in order to achieve important results regarding the reduction of GHG emissions to decrease the global warming effect. The environmental benefits that energy savings through technology advancement are bringing and the way digital revolution is helping the management of energy sources are very important to achieve these goals.

There is a transition from old business models to the new ones that means that private sector and utilities companies are investing on renewable energy and new technologies, for example through smart meters. Smart meters (SM) are very helpful in order to collect a very large quantity of data and since the IoT (Internet of Things) is emerged, massive amounts of data are available and they are easier to manage. SM are bringing many benefits for consumers and for utilities: customers can be constantly informed about their consumptions and the way of communication can be remotely controlled with historical data and locally the consumers are informed by real-time data with a significant improvement of customers' knowledge about their energy costs and carbon emission. These devices allow the electrical appliances to be automatically controlled and this feature is very interesting since consumers can easily manage the electrical system selecting days off where the consumptions can be reduced and, oppositely, the days when users request more power to the system.

In this way, waste of energy can be reduced. For utilities, the advantages are that they can influence the energy profiles of their users; they can have a reduction in 'costs to serve' rationalizing their services and they are able to sensitize customers about global warming issue.

Smart Meters and IoT bring a large quantity of data, as we said, and clustering methods have been and will be critical in order to manage in a better way this data [21]. Clustering method has many advantages: first, it increase productivity through specialized inputs, access to information, synergies [22]. The data management through clustering methods allows creating an energy profiling characterization of urban building models suitable to study and define balance strategies and flatting peaks procedures coupled with policies on energy sources to be adopt considering IoT and Smart Management of the city. The advantages of using clustering methods, specifically K-means algorithm, are that it eases to manage a large quantity of data, synthesized them and create an algorithm pattern that could work for further different cases and thus could be transposed. Therefore, it is possible to operate in a large scale and in a small scale in the same time, choosing the level of details which is more appropriate for the analysis and the calculation useful for energy planning and to support and explain future development.

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A 3D model Compression Method for Large Scenes

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Abstract –

Three-dimensional (3D) models are increasingly becoming an important tool in project management. At the same time, the 3D data of construction industry is more and more large, whether it is caused by large model scene or the requirement of model accuracy. In order to meet the requirements of the model application, the 3D model needs to be simplified. Mesh models are one of the most common ways to display 3D models, which provide well-defined object boundaries. The simplified algorithm of the existing mesh model cannot keep the important detail features of the original model once the data volume of the model is further reduced. Combined with Quadric Error Metrics (QEM) algorithm, this paper improves the edge collapse algorithm to solve the problem of undetected model structure and over-simplified model details. The proposed algorithm can preserve the integrity of the model while maintaining a high compression efficiency. Experiments show that the proposed method works well for the compression of large-scale scene models, which includes the compression ratio and the structural preservation in the model. This compression method is well suited for the model with huge amounts of data generated by large scene objects in the construction field.

Keywords –

Mesh model; Simplification; Structure-preserving; Edge collapse

1 Introduction

Three-dimensional (3D) models are increasingly becoming an important tool in project management. 3D model can reproduce building scenes and display building structures, which plays a significant role in construction quality, construction progress, construction site safety [1] [2], such as dimensional measurements of structures [3], remote management of the construction site [4].

At present, in the field of architecture, engineering and construction (AEC), polygon mesh models are one of the most common ways to display 3D models. They provide well-defined object boundaries that are suitable for clearly presenting the structure of 3D objects, which greatly improve the visualization of the construction site. These models have been able to achieve centimeter-level display of the details of the object [5]. In general, a polygon mesh model usually consists of complex triangular mesh, which may contain tens or even millions of vertices and polygons [6]. In particular, there are more vertices and polygons for some models of large scenes. There are higher requirements for grid model applications, including adequate storage capacity, high computational power, and to access over bandwidth-limited links [7]. This is often difficult to achieve. Therefore, to compress 3D model effectively is urgent.

The research on 3D model compression started with Deering, who proposed to reduce the amount of data by quantizing all the components of the input mesh into a certain number of bits [8]. Later, the compression of the mesh model evolved. For the current research, the simplified algorithm still deserves further study in the relatively large 3D model, no matter in the compression effect or in the compression time [9].

Combined with Quadric Error Metrics (QEM) algorithm, this paper improves the edge collapse algorithm to solve the problem of undetected model structure and over-simplified model details [10]. The contents of the article are as follows: the second part is the existing model compression method. The third part presents the proposed algorithm. The fourth part and the fifth part are the verification of the algorithm and the conclusion respectively.

2 Related Work

Generally, two different 3D models are available after collecting construction data. One is point cloud model consisting of a large number of points containing the characteristics of the target surface, the other is mesh model in which objects and the entire environment are drawn by polygons. 3D models have a huge amount of

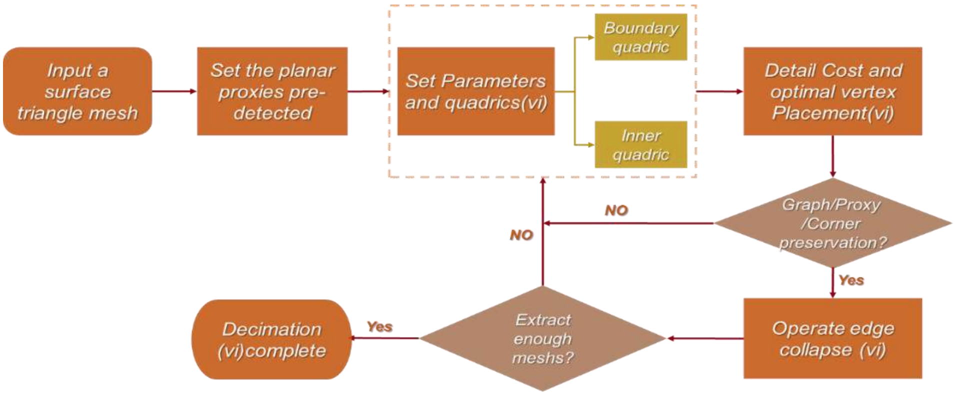


Figure 1 Triangular mesh model simplification process

data. For example, the Faro Focus 3D delivers more than 976,000 3D points per second [11]. The state-of-the-art, light-based 3D camera produces 30 frames per second, roughly 300 MB of raw data [12]. Therefore, to store and manage three-dimensional data while preserving useful information as much as possible, it is important to improve the compression technique of the 3D model.

According to the decompression method after model compression, the 3D model compression algorithm is divided into single-rate compression [13] and progressive compression [14]. Single-rate compression technology compresses an entire model and then sequentially decodes the recovery model, focusing on saving bandwidth between the CPU and the graphics card [15-17]. With the increasing volume of 3D geometric data, this technology takes too long to receive the complete model, which cannot meet the real-time rendering requirements [18]. The advent of progressive compression algorithm has provided the possibility of real-time rendering of model compression. This algorithm first compresses the general framework of the model and then gradually supplements the remaining geometric details of the model. Therefore, the 3D model can be continuously reconstructed by the decoder from coarse to fine Levels of Detail (LOD) when receiving the bit stream [19].

The study of 3D point cloud compression algorithm is mainly divided into tree structure method and height map method. Height map-based method is to compress the 3D point cloud information into a two-dimensional matrix. This method was first proposed by Pauly [20]. Later, there have been some improved algorithms, such as adding geometry [21] [22], or preprocessing the data for compression [23]. The core of the tree-based method is to partition the point cloud space. The common tree structure methods include kd-tree [24] [25] and octree [26] [27]. The 3D point cloud can represent a geometric model of arbitrary shape with a simple structure and its compression technology has been relatively mature [28].

Compared with the point cloud model, the surface structure of the 3D mesh model is slightly complicated. However, the polygon structure can improve the visual effect of the model, which is especially suitable for visual inspection of large scene objects in the field of architecture. The study of model simplification includes vertex clustering [29], vertex deletion [30], wavelet transform algorithm [31] [32], edge collapse [33] [34]. These method is under development. How to compress mesh models well with increasing data volume is still a problem worth exploring.

3 Methodology

The proposed algorithm takes a surface triangle mesh of the model as input, since arbitrary polygons can be easily triangulated. Then preprocess the model to detect a set of the planar proxies. By performing a limited number of edge collapse operations on the above model, a simplified model that retains the structural features of the original model is output. The specific process shown in Figure 1. Edge collapse is one of the most common algorithms in model simplification. However, previous edge-collapse algorithms often caused over-simplification of the model.

In this paper, on the basis of the quadric error metric method (Abbreviated as GH) [10] and the volume-preserving approach (Abbreviated as LT) [35], the concept of planar proxies is introduced to ensure that important features of the model after input can be detected. To prevent the model from being oversimplified, inner quadric and boundary quadric is introduced to measure the error and the rule of model structure preservation is formulated.

3.1 Planar proxies

Before the implementation of the algorithm, the 3D model should be initialized to realize the storage format of the triangular mesh data structure and the vertex data structure. Set the planar proxies pre-detected

Suppose a triangle is selected on a plane, so the plane equation and normal vector of this triangle can be calculated. Center around this triangle and spread to the surrounding area of the triangle. Calculate whether the normal vector of the surrounding area is close to the normal vector of this triangle, and if so, it means that the triangle has high planarity. By analogy, calculate the planarity of different triangles, the triangle from which the best planarity is chosen represents the local area. As a result, the region has been expanding. This process is called planar proxies.

It is assumed that the input mesh presents a near-flat portion that can be detected by common shape detection methods. These near-plane parts are represented by planar proxies. More specifically, a plane proxy consists of a set of vertices and a plane ax+by+cz+d=0, denoted as [a b c d], where n = [a b c] is a flat unit normal vector. As shown in Figure 2, a processed 3D model, in which different colors represent different plane proxies.

Figure 2 the model of the plane proxies detected

3.2 Edge collapse operator

All text must use the Times New Roman font. Edge Collapse $e=v_0v_1 \rightarrow v$ is a mesh operation that merges two vertices v_0 and v_1 into a unique vertex v. The grid extraction algorithm based on the edge collapse is usually as follows: (1) For each edge fold $v_0v_1 \rightarrow v$, the cost associated with the error metric and its corresponding placement strategy are defined to design the local optimal point location for finding v. (2) Calculate the initial priority heap of the edge folding operator at a cost increase. (3) Iteratively extract the lowest cost operator from the heap and calculate its best location. Collapses the relevant edges and updates the priority heap on the edge of the local neighborhood. Based on the quadric error metric for each defined operator, details of the cost and optimal location are determined.

3.2.1 Title Page Error Quadrics

In the early years, GH associated each vertex with a quadratic matrix, which represented an approximation of the error between the current and initial grids. The quadratic plane is designed as a 4*4 matrix, represented by (1), and then the square sum of the distances to these quadratic planes can be further calculated.

$$Q_P=PP^T=\begin{pmatrix} a^2 & ab & ac & ad \\ ab & b^2 & bc & bd \\ ac & bc & c^2 & cd \\ ad & bd & cd & d^2 \end{pmatrix} \quad (1)$$

The sum of the square of the distance from point v to the plane list (Pi) is represented in (2). The advantage of this quadratic form is that it can be encoded with only 10 coefficients, and this formula can calculate the distance from one point to any plane.

$$\sum d(v,P_i)^2=\sum v^T P_i P_i^T v=v^T\left(\sum Q_{P_i}\right)v \quad (2)$$

Based on the previous matrix method by GH, this article optimizes the square sum of the distance from point to point from the following three aspects: (a) to reduce the square sum of the distance from the vertex to the plane of the triangle mesh adjacent to it; (b) to reduce the sum of the squares of the distances from the vertex to the plane where it is adjacent to the plane proxy set; (c) to reduce the boundaries of agents and grids.

Inner quadric The proposed method adjusts the inner matrix of the structure and optimizes Q_p proposed by GH. For a triangle $t\in T_K$, plane P_t where t is located, we denote as Q_{Pt} the quadric of P_t. For the plane proxy φ, we denote as Q_φ the quadric where proxy is located. The set of proxies that contain t is represented by Proxies (t). The quadric Q_t for each triangle t of T(e) is given by (3).

$$Q_t=\begin{cases} Q_{P_t} & \text{if Proxies(t)}=\emptyset \\ (1\text{-}\lambda)Q_{P_t}+\lambda\sum_{\varphi\in \text{Proxies(t)}} Q_\varphi & \text{otherwise} \end{cases} \quad (3)$$

Then, the quadric form of the edge e is defined in (4)

$$Q_{inner}(e)=\sum_{t\in T(e)}|t|Q_t \quad (4)$$

Here, λ is called an abstraction parameter and provides a way to fidelity conversion between mesh and proxy. For example, when parameter λ = 1, that is, both proxies go through edge e, vertices are selected at the intersection of plane proxies. When the parameter λ=0 or no plane proxies passes edge e, the quadric only approximates to the local error measure of the mesh. A larger value for λ means faster removal of proxy details during decimation and faster abstraction. The higher value for λ results in a lower proxy error, but the approximation error is larger compared to the original mesh.

Boundary quadric For any edge e'∈R, a plane e'∈R, define $Q_{e'\varphi}$ as the quadric of the plane that passes through edge e' and is orthogonal to plane R. $E_{\partial K}$ represents a set of edges in K|φ that is only contained by one triangle. For model boundaries $e'\in E_{\partial K}$, t_e' is the only triangle in K|φ that goes through e'. The boundary quadric of an edge e is then defined in (5).

$$Q_{bdry}(e)=\sum_{e'\in E_{\partial K}}|t_e'|Q_{e',t_e'}+\sum_{E_{\partial K|\varphi}}|t_e'|Q_{e',\varphi} \quad (5)$$

In (5), the first part avoids overly simplifying the mesh boundaries to prevent the flat mesh from collapsing to a single point at any cost. The second part preserves the structural characteristics of the proxies. The proxy φ accommodates more information by restrictive triangulation than just an infinite plane. This process increases the sensitivity of the mesh to a simplified structure.

3.2.2 Cost and Placement

The GH algorithm consists of calculating the initial quadric Qv for each vertex v and then summing the distances from each edge collapse operator to the plane. More specifically, for the collapse operator $e=v_0v_1 \rightarrow v$, the quadric of e (Qe) is calculated by adding quadrics of its two vertices v_0, v_1 so that the optimal vertex position v is obtained via the minimized cost V^TQ_VV. Compared with the GH, we recalculate Qe from the current mesh before each collapse operator in terms of improving the efficiency of approximation error.

The process of our method is as follows.

The decomposition quadric matrix Qe is given by (6).

$$Q_e=\begin{pmatrix} A & -f \\ -f^T & g \end{pmatrix} \tag{6}$$

Among (6), A is a 3*3 matrix, f is a vector. Minimizing V^TQ_VV involves solving linear problems Ax = f. When all vertices adjacent to e are distributed in only one or two planes, the determinant of A is 0.

Compute the singular value decomposition *A* in (7).

$$A=U\Sigma V^T \tag{7}$$

where U and V are 3*3 matrixes, whose column vectors are mutually orthogonal. Σ is a 3*3 diagonal matrix whose diagonal values, called singular values, decrease from the upper left corner to the lower right corner.

The diagonal value in Σ is defined in (8), λ_i is the eigenvalue of A.

$$\Sigma_{ii}=\sqrt{\lambda_i} \tag{8}$$

The diagonal value Σ_{ii} decreases in descending order, then truncate the small eigenvalues of Σ and store the result in Σ^+, as shown in (9).

$$\Sigma_{ii}^+=\begin{cases} 1/\Sigma_{ii}, & \text{if } \Sigma_{ii}/\Sigma_{11}>\varepsilon \\ 0, & \text{otherwise} \end{cases} \tag{9}$$

where Σ_{11} denotes the largest singular value, and the parameter ε is set to 10^{-3}.

$\hat{x}$ denotes the center of gravity of the vertices of v_0 and v_1, the singular value decomposition of Qe is shown in (10).

$$x=\hat{x}+V\Sigma+U^T(f-A\hat{x}) \tag{10}$$

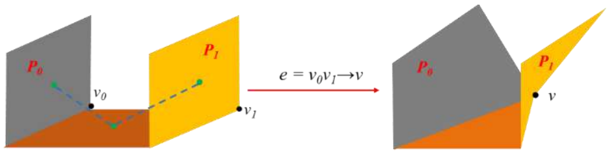
Calculate the optimal position of the vertex v after the collapse operation $e=v_0v_1 \rightarrow v$. Proxies(v) set is determined by Proxies(v_0) $\cup$ Proxies(v_1) when collapsing the edge e, and the quadric of e is defined in (11).

$$Q_e=(1-\mu)Q_{inner}(e)+\mu Q_{bdry}(e) \tag{11}$$

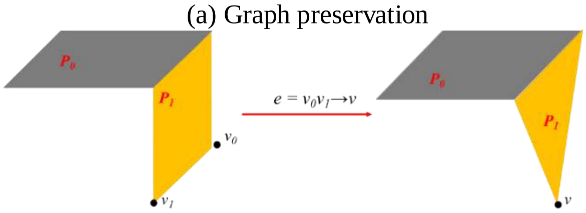
Where $\mu\in(0,1)$ is a parameter used for internally simplifying transaction boundaries. The optimal position for *v* is obtained by the solution of Qe and the cost V^TQ_VV of folding edge *e* is decided.

3.3 Structure-preserving

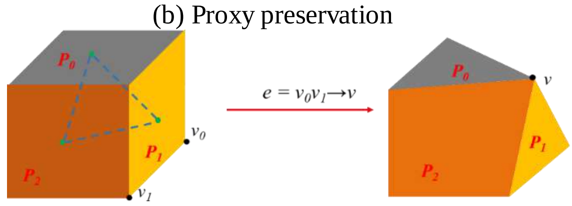
During model simplification, the best graph of the proxy coincides with the corresponding adjacency graph, such that a cube is represented by a double octahedron. In practice, however, it is not possible to have all the proxies correctly detected, and all the vertices are arranged on the same plane as the one to which they belong. Using the sufficient information about the adjacency graph in terms of the arrangement of the structure, three model structure preservation rules are formulated to prevent the structure of the model from being destroyed. These three rules are graph preservation, proxy preservation and corner preservation, Figure 3 is the rule diagram.



(a) Graph preservation



(b) Proxy preservation



(c) Corner preservation

Figure 3 Three types of edge collapsing prohibited

Graph preservation The two parts that are not connected in the graph should not be connected during the simplification. Only when all the proxy pairs in $Pv = Pv_0 \cup Pv_1$ are edges in the original set of G, do we perform edge collapse $e=v_0v_1 \rightarrow v$. Like Figure 3(a), the original two planes P_0P_1, which do not intersect, cannot intersect.

Proxy preservation A planar proxy may degenerate into a vertex or an edge during model simplification. To prevent this situation, as shown in Figure 3(b), the improved QEM algorithm refuses to perform this edge folding operation when the number of vertices forming this proxy is below the user-specified parameters after the edge-folding operation.

Corner preservation To prevent losing corners or migrating vertices away from corners, like Figure 3(c), we need to accurately detect and protect these corners during simplification. The vertices intersected by every three proxies are generally different, so we need to find the best vertex position for the intersecting proxy, taking advantage of the scale-space traversal.

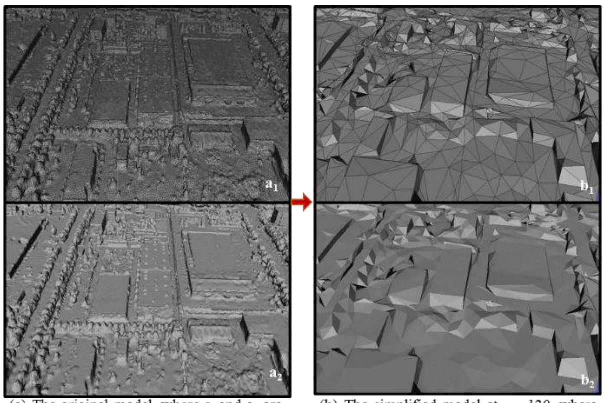
4 Results and Discussions

The focus of this paper is to study mesh model compression techniques to enable the construction industry to conveniently apply 3D models. Therefore, this paper selects two 3D models, an industrial building and a residential building, respectively, for model compression experiments. Table 1 shows the specific information of the two models before and after compression. Figure 4 and Figure 5 show the factory model and the resident building model, respectively.

It can be seen from Table 1, Figure 4 and Figure 5 that the simplified model still retains certain details when the simplified multiples reach high levels. In particular, some of the more complex structures, such as trees, etc., are less simplified than the rest of the model. For large complex models such as factories and residential buildings, the proposed algorithm can maintain the approximate shape of the model and reduce the loss of structural details of the model, while achieving a large simplification multiple.

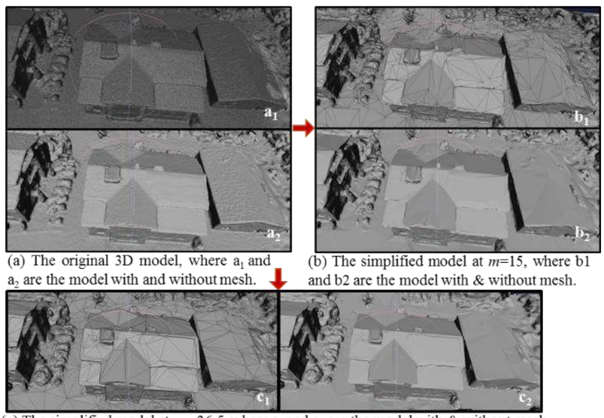
This algorithm is further compared with GH and LT methods, taking the resident building model as an example. The effect is shown in Figure 6.

Both methods show the approximate shape of the simplified model. However, the proposed method is highly simplified in the planar area, and the meshes in the highly complex details are basically preserved, and the reduction effect is better. The flat part of the model, such as the roof part, etc., because of its simple structure, can be relatively more streamlined to save more space. This method flattens the roof plane into several large triangles, saving space for characterizing the undulating models. Non-planar parts, such as trees, cars, etc. in the model, are less simplified to better illustrate these details, which reduces the loss of structural details. In contrast, the proposed algorithm simplifies the various parts of the model in different degrees according to the complexity of the structure. The proposed algorithm can preserve the integrity of the model while maintaining a high compression efficiency, whose compression method is feasible for models with a large amount of data.



(a) The original model, where a_1 and a_2 are the model with & without mesh. (b) The simplified model at $m=120$, where b_1 and b_2 are the model with & without mesh.

Figure 4 The factory model



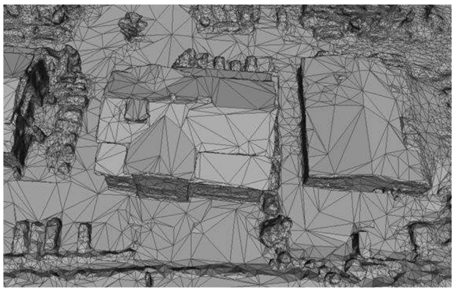
(a) The original 3D model, where a_1 and a_2 are the model with and without mesh. (b) The simplified model at m=15, where b1 and b2 are the model with & without mesh. (c) The simplified model at $m=26.5$, where c_1 and c_2 are the model with & without mesh.

Figure 5 The resident building model

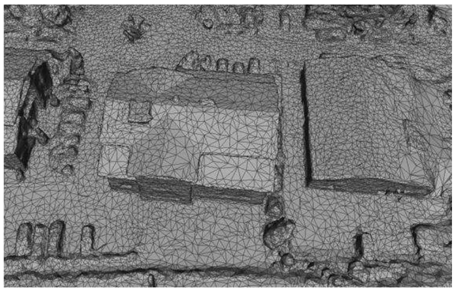
Table 1. the specific information of the models before and after compression

Model	The number of		Data size (KB)	Simplify multiple (m)*
	vertices	faces		
Original factory	234118	467672	8682	——
Simplified factory	1920	3999	74	120
Original resident	533995	1067818	19815	——
Simplified resident 1	35079	69999	1300	15
Simplified resident 2	20191	39999	745	26.5

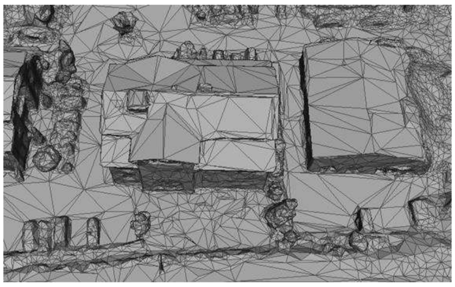
* Simplify multiple (m) is approximately equal to the ratio of the number of vertices or faces, or data size in the original model to the number of vertices or faces, or data size in the simplified model



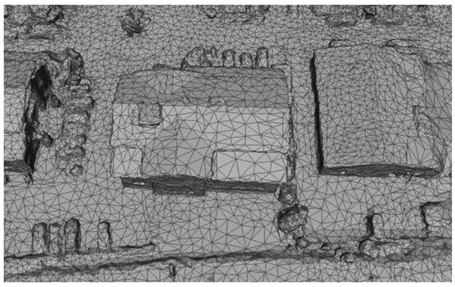
(a) The simplified model at *m=15%* by the proposed method



(b) The simplified model at *m=15%* by GH & LT



(c) The simplified model at *m=26.5%* by the proposed method



(d) The simplified model at *m=26.5%* by GH & LT

Figure 6 Compression of the two methods for residential building models

5 Conclusion

In this paper, an improved method for simplifying complex models of large scenes in architecture is proposed, which can better preserve the details of the model compared with the classical algorithms. Experiments show that the proposed algorithm simplifies the various parts of the model in different degrees according to the complexity of the structure. This preserves the details of the model as much as possible. With the same simplify multiple, the proposed method has a greater advantage in displaying the details of the model. The proposed algorithm greatly improves the accuracy of the simplified model under the premise of ensuring the compression ratio. However, this paper uses the region growing algorithm to detect plane proxies. This process is complicated and takes some time, which increases the compression time of the model. Future directions will be to refine algorithms to reduce the time required for model compression.

Acknowledgement

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Multiskilled Human Resource Problem in Off-Site Construction

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Abstract –

Using multiskilled manpower refers to the ability of dynamically reallocate labour from one stage of production process to another one in response to bottlenecks configuration. This paper investigates improvements in tangible performance measures which can be achieved by incorporating multiskilled workforce in off-site construction. To this end, scheduling in off-site construction analysed in flowshop environment with multiskilled human resource in which operations processing time depends on the amount of human resource allocated to it. The objective of this optimisation problem is to minimise production makespan taking into account labour costs associated with different flexibility strategies. To this end, a mathematical framework incorporating flowshop principles developed, formulations coded in an open source programming interface and solved with a commercial solver providing free license to academic usage. Production data from a prefabrication factory based in Melbourne, Australia fed to the model providing a basis for comparison based on different indicators of productivity. The findings of this study are insightful for human resource development in off-site construction by providing cost and productivity corresponding to different multiskilling strategies.

Keywords –

Multiskilling; Prefabrication; Optimisation; Labour; Flowshop; Skill

1 Introduction

Several factors including increasing workforce wages [1], shortage of skilled workforce [2] and a general boost in construction completion time [3] contribute to decrease productivity in the construction industry. Using prefabricated construction is one of managerial and technological innovations to compensate aforementioned pitfalls [1]. Precast construction enhance productivity in different manners including but not limited to reducing costs of site supervision [4], reduction in delay [5] and better construction quality [6]. However, disintegrated processes is a fundamental consequence of prefabricated construction [7]. Crosstraining of workforce is an appropriate way of dealing with task heterogeneity [8].

Crosstraining of workforce simply means learning multiple skills to workers so they can be assigned when and where they are needed [9]. Crosstraining of workforce is beneficial for the employer by enhancing productivity and quality [10] and advantageous for employees by increasing employability, safety and job satisfaction [11,12]. The drawback of incorporating crosstraining is outlined as decreasing efficiency with increasing the number of skills [13] learning and forgetting effects [14], switching costs [15], training cost [16], and extra salary [17].

Despite, body of literature investigating crosstraining in on-site construction is considerable [3,10,13,18,19], off-site construction literature mainly focused on single skilled crew [20]. Considering high potential of enhancing productivity with incorporating multiskilling in manufacturing [9] and semi-manufacturing environment like prefabricated construction [7] enhancing productivity by using crosstrained workers in off-site construction is a significant area of research.

The novelty of this research originates from employing and modifying operational research techniques to evaluate the effect of construction related human resource strategies on performance measures of prefabricated construction with a reasonable solution time. Presented method has the capacity to incorporate a wide range of human resource policies and can be calibrated to deliver different objective functions.

To this end, this study identifies principles of flowshop applicable to off-site construction [21] and presents a mathematical modelling approach to optimise makespan of production as the most famous productivity measure in shop environment [22], incorporating multiskilled workforce taking into account crosstrained manpower cost.

2 Literature Review

Crosstrained labour allocation problem is a subset of human resource allocation problem in which all or some of workers should be multiskilled. Human resource allocation problem is to optimise the use and allocation of human resource with an aim to maximise or minimise certain functions [23].

Despite, there are several techniques in operations research and management science literature for resource allocation problems [24] no one is directly applicable to the construction industry and modifications should be applied on them [19]. Therefore in the following section, selection process of an appropriate framework to solve multiskilled human resource problem in off-site construction argued.

Since, the critical path method does not properly works in precast production [20] considering general production layout, repetitive routines, precedence and dependency of different products, it is suggested to implement principles of flowshop scheduling in precast production [5]. Additionally, optimisation of production performance such as makespan and flow time in prefabricated construction shifts the problem formulation toward shop scheduling in general and flowshop scheduling specifically [20].

A classical flowshop problem defined as a problem which consists of two main elements: a group of M machines and a set of N jobs which should be processed in these machines [22]. There are four basic assumptions for a classic flowshop problem: the jobs should be processed in all of the machines, job splitting is not allowed, operations are non-preemptive and set up times are included in the processing time [22]. There is a wide range of assumptions for different settings of a flow shop problem however, flowshop problem with and without permutation are the best fit to optimise off-site construction scheduling [21].

Considering applicability of flowshop principles to off-site construction with single skilled human resource policy few studies investigated performance of makespan pertaining to specialist manpower [1,20,25,26]. To the best of our knowledge so far there is no study which investigates enhancing productivity in precast construction implementing crosstraining techniques using flowshop fundamentals.

Referring to management science and operations research literature few studies investigated productivity enhancement within flowshop framework via full crosstraining of workforce [27,28] and partial crosstraining of crews [29]. Considering our research follows same objective in off-site construction context, on one hand, and taking into account similarity of off-site construction and manufacturing [21], on the other hand, reviewing this literature exposed same principles with some modifications can be used in our study.

3 Problem Description

Notation (n,m) is an indication of processing product n in workstation m when $\mathrm{N} = \{1,2,\ldots,\mathrm{N}\}$ is set of products and $\mathrm{M} = \{1,2,\ldots,\mathrm{M}\}$ is set of workstations. $\mathrm{W} = \{1,2,\ldots,\mathrm{w}\}$ is set of workers and $\mathrm{K} = \{1,2,\ldots,\mathrm{K}\}$ is set of status meaning the number of workers which can be allocated to a specific operation. $\mathrm{T} = \{1,2,\ldots,\mathrm{T}\}$ is set of time periods where T is upper bound on makespan. Equation (1) requires each procedure to have a unique status and corresponding specific completion time.

$$\sum_{k=1}^{K}\sum_{t=1}^{T}\theta_{nmkt} = 1\,, \qquad n \in \mathrm{N}, m \in \mathrm{M} \qquad (1)$$

Equation (2) presents behaviour of binary variable θ_{nmkt}.

$$\theta_{nmkt} = \begin{cases} 1 \; if\ operation\ (n,m)\ with\ k\ labour\ finished\ at\ t \\ 0 \; otherwise \end{cases} \qquad (2)$$

Given d_{nmk} is duration of procedure (n,m) when k workers are assigned to it, actual duration of procedure (n,m) indicated by D_{nm} is computable according to the equation (3).

$$D_{nm} = \sum_{k=1}^{K}\sum_{t=1}^{T} d_{nmk}\,\theta_{nmkt}\,, \qquad n \in \mathrm{N}, m \in \mathrm{M} \qquad (3)$$

Completion time of procedure (n,m) indicated by C_{nm} can be calculated as formula (4).

$$C_{nm} = t\sum_{k=1}^{K}\sum_{t=1}^{T}\theta_{nmkt}\,, \qquad n \in \mathrm{N}, m \in \mathrm{M} \qquad (4)$$

Constraints (5) and (6) satisfy the requirement for flowshop problem with permutation.

$$C_{nm} \geq C_{n(m-1)} + D_{nm}, \qquad n \in \mathrm{N}, m \in \mathrm{M} \qquad (5)$$

$$C_{nm} \geq C_{(n-1)m} + D_{nm}, \qquad n \in \mathrm{N}, m \in \mathrm{M} \qquad (6)$$

Let a_{wmt} and s_{wm} be binary variable and binary parameter behaving as equations (7) and (8), respectively.

$$a_{wmt} = \begin{cases} 1 \; if\ worker\ w\ is\ allocated\ to\ station\ m\ during\ [t-1,t) \\ 0 \; otherwise \end{cases} \qquad (7)$$

$$s_{wm} = \begin{cases} 1 \; if\ worker\ w\ is\ trained\ to\ be\ staffed\ in\ station\ m \\ 0 \; otherwise \end{cases} \qquad (8)$$

Inequality (9) denotes that workers can just be allocated to workstations for which they are crosstrained.

$$s_{wm} \geq a_{wmt}\ , \qquad w \in \text{Ẁ}, t \in \text{Ţ} \tag{9}$$

Total labour cost, denoted by Q, can be computed as equation (10) considering q_w be daily cost of labour a_{wmt}.

$$\sum_{m=1}^{M}\sum_{t=1}^{T}\sum_{w=1}^{W} q_w a_{wmt} = Q \tag{10}$$

Constraint (11) insures that in each interval of time each worker can just be allocated to one workstation.

$$\sum_{m=1}^{M} a_{wmt} = 1, \qquad w \in \text{Ẁ}, t \in \text{Ţ} \tag{11}$$

Equation (12) match operations status with needed number of labour.

$$\sum_{k=1}^{K}\sum_{t=1}^{T}\sum_{w=1}^{W} \theta_{nmkt}\, a_{wmt} = \sum_{k=1}^{K}\sum_{t=1}^{T} k\ \theta_{nmkt}\, , \quad n \in \text{Ņ}, m \in \text{M̧}, \tag{12}$$

Equation (13) force labour to remain in workstation for the whole duration of operation.

$$\sum_{k=1}^{K}\sum_{t=d_{nmk}}^{T}\sum_{l=t-d_{nmk}+1}^{W} \theta_{nmkt}\, a_{wml} = \sum_{k=1}^{K}\sum_{t=1}^{T} a_{wml} d_{nmk} \theta_{nmkt}\, , n \in \text{Ņ}, m \in \text{M̧}, w \in \text{Ẁ} \tag{13}$$

4 Case Study

The case which is adopted in this study is a modular prefabrication factory that produces bathroom pods located in Melbourne, Australia. Figure 1 shows twelve processes in the production line corresponding to their order in the real fabrication layout. S and L are indications for workstations and labour, respectively. Table 1 shows workstations operation in sequence. At the moment, no crosstrained worker employed in this production line equivalent to no flexibility scenario in which traditionally one worker is allocated to each workstation. There are three bottlenecks in this production line in labour, carpenter and electrician

Table 1. Workstations' operation

Work station	Operation	Work station	Operation
S1	Labourer	S7	Carpenter
S2	Caulker	S8	Electrician
S3	Mechanical contractor	S9	Water-proofer
S4	Tiler	S10	Glazer
S5	Plumber	S11	Joiner
S6	Plasterer	S12	Painter

workstation. Site manager of case study factory believed single skilled workforce should be allocated to bottlenecks. Figure 2 is an illustration of this decision. Figure 3 and 4 illustrate direct capacity balancing and chaining multiskilling strategies which already investigated in off-site construction [7,8]. Red lines show secondary skills making single skilled labour multiskilled. Last strategy is hiring multiskilled workforce and allocate them to bottlenecks which is already investigated in linear construction projects [17].

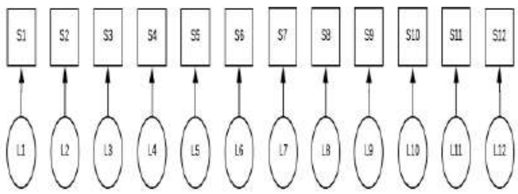

Figure 1. No flexibility

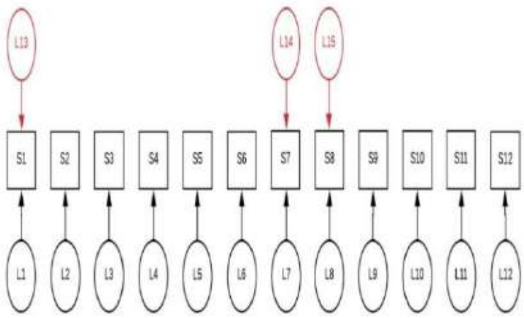

Figure 2. Hiring singleskilled crew

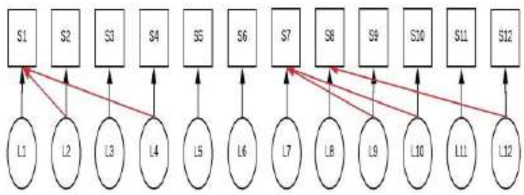

Figure 3. Direct capacity balancing

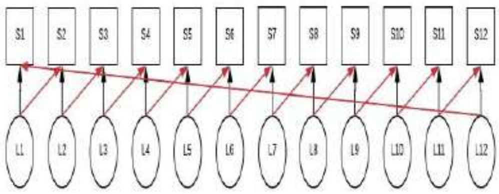

Figure 4. Chaining

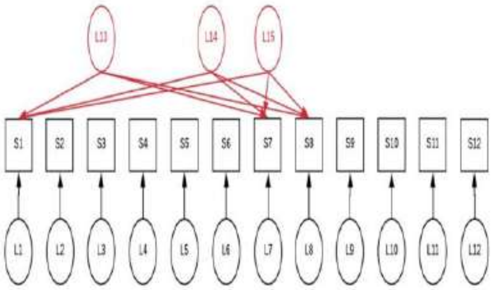

Figure 5. Hiring crosstrained crew

5 Results

Table 2 reflects outputs of computation pertaining to different human resource strategies' in terms of makespan and cost for production of 10 bathroom pods. No flexibility, hiring singleskilled crew, direct capacity balancing, chaining and hiring crosstrained crew abbreviated as NF, HSC, DCB, Ch and HMC, respectively. Also, makespan, makespan variation, cost and cost fluctuations abbreviated as M, MV, C and CF. Considering no flexibility strategy, makespan is 44 days with labour cost of 73776 AUD. To deal with bottlenecks site manager suggested to hire three single skilled workforce and allocate them to bottlenecks. Despite, by applying this strategy there is 27% improvement in makespan however significant amount of 78% enhancement in labour cost suggest this is not a good strategy. Direct capacity balancing led to 32% improvement in makespan and 25% decrease in labour cost which makes this strategy attractive. Implementing chaining leads to 27% decreasing in makespan and 26% enhancement in labour costs. The result of hiring crosstrained workforce is significant by bringing the most improvement in makespan equivalent to 41% and enhancement in labour cost equivalent to 17% which makes this strategy appropriate to deal with tight deadlines.

Table 2. Performance measure corresponding to different human resource strategies

	Human resource strategies				
	NF	HSC	DCB	Ch	HMC
M	44	32	30	32	26
MV	0	27%	32%	27%	41%
C	73886	131789	54850	93249	91062
CF	0	78%	-25%	26%	17%

6 Conclusion

Review of literature exposed optimisation of multi-skilled human resource problem in off-site construction is a promising area of research. Flowshop environment is recognised appropriate to incorporate prefabricated construction principles. A mathematical programming approach adopted to model scheduling processes in prefabrication context to allocate crosstrained crew to appropriate operations to optimise production makespan. An open source programming interface and a commercial solver employed in coding process. The findings of this study facilitate decision making with regard to appropriate crosstraining configuration considering makespan and labour cost. Also, this study presents a new understanding with regard to interaction of crosstraining configurations, labour costs and production makespan as a measure of productivity. Formulations which are presented in this study have the potential to incorporate other performance measures such as idleness and tardiness which can be used in future studies. Other industries in which productivity directly interacts with the number of human resource can use principles of this study.

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Extension of a High-Resolution Intelligence Implementation via Design-to-Robotic-Production and -Operation strategies

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Abstract –

This paper extends the development of a responsive built-environment capable of expressing intelligence with respect to both ICTs and Adaptive Architecture. The present implementation is built with mutually informing *Design-to-Robotic-Production & -Operation* (D2RP&O) strategies and methods developed at *Delft University of Technology* (TUD). With respect to D2RP, a responsive stage built with deliberately differentiated and function-specific components is revisited and modified. With respect to D2RO, a partially meshed, self-healing, and highly heterogeneous *Wireless Sensor and Actuator Network* (WSAN) is expanded to integrate proprietary-yet-free cloud-based services. This WSAN is equipped with *Machine Learning* (ML) mechanisms based on *Support Vector Machine* (SVM) classifiers for *Human Activity Recognition* (HAR). The frequency and/or absence of certain activities, in conjunction with processed data streamed from environment-embedded sensing mechanisms, trigger actuations in the built-environment in order to mitigate fatigue, encourage activity / interactivity; and to promote general well-being in the user. A voice-enabled mechanism based on Amazon®'s *Alexa Voice Service* (AVS) is integrated into the ecosystem to connect the built-environment with services and resources in the *World Wide Web* (WWW). Furthermore, a notifications mechanism based on Google®'s Gmail© API as well as Twilio®'s REST© API enable instances of fatigue to be reported to third-parties. The present interdisciplinary development attempts to promote an alternative approach to existing *Ambient Intelligence* (AmI) and *Ambient Assisted Living* (AAL) frameworks.

Keywords –

Design-to-Robotic-Production & -Operation, Ambient Intelligence, Wireless Sensor and Actuator Networks, Adaptive Architecture.

1 Background and Introduction

This paper builds on the implementation presented in the *34th International Symposium on Automation and Robotics in Construction* (ISARC) 2017 [1]. As such, it continues to promote the concept of *high-resolution intelligence* in the built-environment driven *by Design-to-Robotic-Production & -Operation* (D2RP&O) [2] strategies and methods developed at *Delft University of Technology* (TUD). D2RP&O establishes an unprecedented direct link between design, robotic production, and operation. While D2RP is informed by variations of structural, programmatic, performative (both physically and computationally), and assembly considerations, D2RO operates as a distributed and decentralized system architecture, which is employed to serve as the nervous system of the building. The resulting built-environment is characterized by adaptiveness and interactivity with respect to ICTs as well as to *Adaptive Architecture*.

The present development continues to build on the responsive stage by combining the previously detailed features and scenarios (see [1]) with the following new features both with respect to the built-environment:

1. *Proof-of-concept* implementation of global and local ventilation systems in order to ascertain both optimal temperature and humidity ranges (as determined by the *Comité Europeen de Normalisation* (CEN) Standard EN15251-2007 [3]; and air-quality via a variety of air pollution (see Figure 2, Section 3.1).

And with respect to *remote / cloud-based services*:

2. Integration of *Amazon*®'s *Alexa Voice Service* (AVS) [4] into the system (see Figure 3, Section 0);
3. Integration of (a) SMS notification capabilities via Twilio®'s *REST© API* [5] and Siemens®*'s T35 GSM* component/shield and standard prepaid SIM-card (see Figure 4, Section 3.3); (b) email notification capabilities via Google®'s Gmail© API [6].

As well as with respect to a new modified deployment scenario, where the adaptive stage invites the user to engage in activity if prolonged physical inactivity is detected (Figure 5, items 21 and 22).

2 Concept and Approach

The present implementation expands on a previously developed WSAN [1] to include four main subsystems, briefly summarized as follows:

1. *Local System*: A variety of Microcontroller Units (MCUs) and development platforms (e.g., Raspberri Pi 3 (RPi3) and Zero W (RPiZW)) serve as nodes dependent on a local structured environment. More powerful nodes may be clustered dynamically to yield a single node with higher computational power depending on load-requirements. All nodes exchange data in a combination of wired (e.g., Ethernet, USB, Serial) and wireless (WiFi, BLE, and ZigBee) protocols, depending on latency and frequency requirements.
2. *Wearable devices*: A set of three LightBlue Beans™ (LBBs) conform the location-dependent wearables while a Fitbit® Charge HR™ activity tracker represents the location-independent wearable. The LBBs detect movement in the upper-body, upper- and lower-extremities and advises the system to listen for *Open Sound Control* (OSC) packets corresponding to accelerometer data sent from a smartphone for *Human Activity Recognition* (HAR). The activity tracker enables a constant feed of physiological data while the user is outside of the structured environment.
3. *Ad hoc Support devices*: In the last five years, smartphones have become convenient and ubiquitous tools for HAR via *Machine Learning* (ML) [7, 8], which in conjunction with their battery life and rechargeability render them a preferred means of accelerometer-data gathering in intelligent built-environment implementations.
4. *Remote / Cloud Services*: Six cloud-based services conform this subsystem: (I) external ML mechanism via MATLAB® (in case the local ML mechanism fails); (II) data exchange with Fitbit®'s servers via its API [9]; (III) cloud data-storage and -plotting via Plotly®'s API [10]; (IV) Amazon®'s *Alexa Voice Service* [4]; (V) automated SMS notifications, both via Twilio®'s API [5] as well as via a T35 GSM module; and (VI) automated email notifications via Gmail©'s API [6].

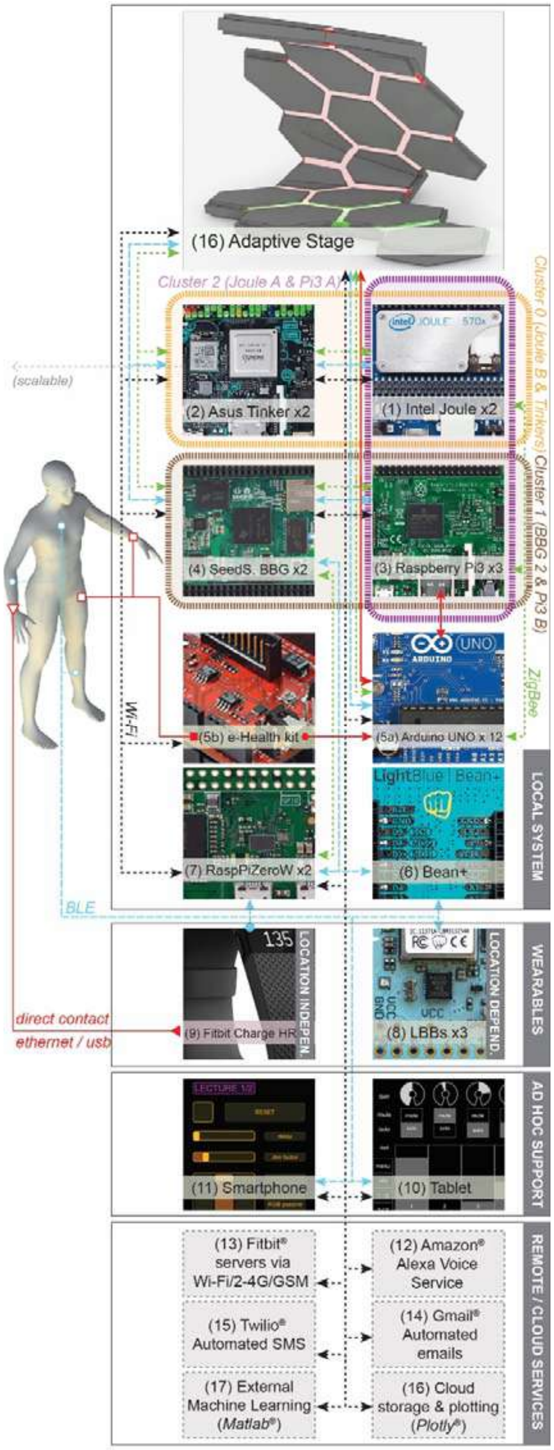

Figure 1. Heterogeneous System Architecture.

3 Methodology and Implementation

3.1 Global / local ventilation mechanism

This mechanism is first implemented and tested via an abstracted surrogate model equipped with twelve DHT-22 temperature and humidity sensors, twelve air-quality sensors (viz., three of each MQ-3 *Alcohol*, MQ-4 *Methane*, MQ-7 *Carbon Monoxide*, and MQ-8 *Hydrogen Gas*), and twelve small DC-motor fans connected to three RPiZWs and one RPi3 (see Figure 2, *Top*). Since the *General-purpose input/output* pins (GPIOs) of these devices are digital while the air-quality sensors are analog, 10-Bit MCP3008 ADCs are used to create a bridge.

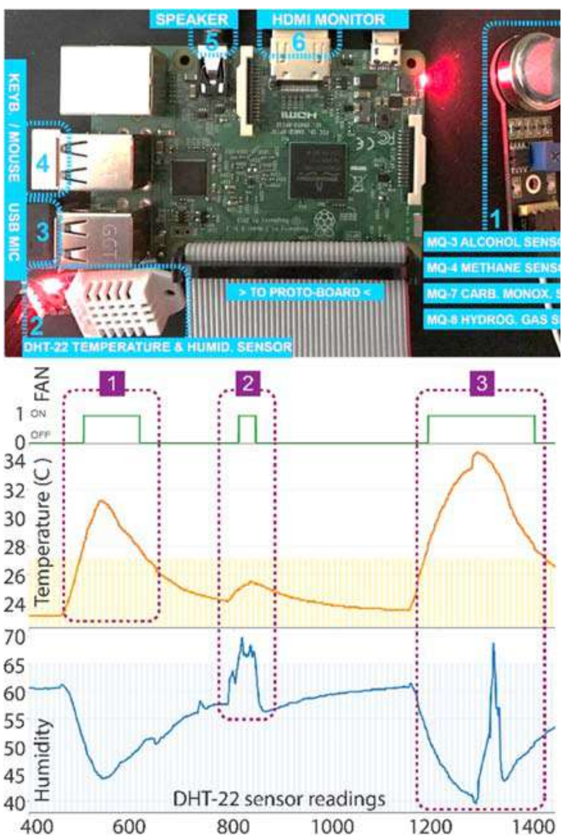

Figure 2. Top: Typical node: (1) Air-quality sensors: *MQ-3 Alcohol* or *MQ-4 Methane* or *MQ-7 Carbon Monoxide* or *MQ-8 Hydrogen Gas*; (2) *Temp. & Hum.* sensor; (3) USB Mic.; (4) Keyboard / Mouse (only necessary for config.); (5) Speaker; and (6) HDMI Monitor (optional). Bottom: Activation of ventilation fans in relation to temperature and relative humidity comfort thresholds (shaded).

As corroborated by the *Comité Européen de Normalisation* (CEN) Standard EN15251-2007 [3] as well as the *American Society of Heaeting, Refrigerating and Air-Conditioning Engineers* (ASHRAE) Standard 55-2013 and Standard 62.1-2013 [11], the *Thermal Environmental Conditions for Human Occupancy* with respect to comfort should be 67 to 82° F. (~19.5 – 27.8° C.) [12], while relative humidity in occupied spaces be less than 65% in order to discourage microbial. Furthermore, independent of human comfort considerations, frequent and consistent ventilation reduces the concentration of toxins in the air as well as the prevalence of airborne diseases [13].

In this TRL-5 setup, if the collective temperature or humidity levels exceed said recommended limits for comfort, all the fans activate, thereby drawing fresh air into the inhabited space (i.e., Global ventilation concept). If, however, certain areas exceed either or both limits, only those fans within and surrounding them activate (i.e., Local ventilation concept) (see Figure 2, *Bottom*). The same concept holds for instances of air-pollution

3.2 Voice-control mechanism via *Alexa Voice Service*

This mechanism is implemented and tested (see Figure 3) via the same RPi3 mentioned in the previous section (see Figure 2, *Top*), an open-source repository using Amazon®'s API [14], and a generic microphone as well as repurposed speakers. A secondary device is also built based on an RPiZW node both to serve as backup and to instantiate an emphatically low-cost (i.e., USD ~$15, as of writing) alternative to even the most affordable of Amazon®'s Echo™ product (viz., the Echo Dot™, at USD $49.99 [15]). The flexibility of developing custom—and more affordable—Alexa-enabled Devices permits virtually any built-environment device, whether deployed in an architectural or an urban context, to capitalize from AVS.

Two main objectives inform the present integration. The first is to enable a powerful and scalable voice-control mechanism within the present development. The second is to demonstrate a cohesive technological heterogeneity between an open-source WSAN and a proprietary commercial service without additional cost (with respect to Fitbit® and Gmail©) or with minimum cost (with respect to Twilio®). This latter consideration connects a local intelligent-built environment with vast resources in the WWW, enabling the user to engage in a variety of activities from streaming music to purchasing groceries via devices fundamentally embedded into the built-environment.

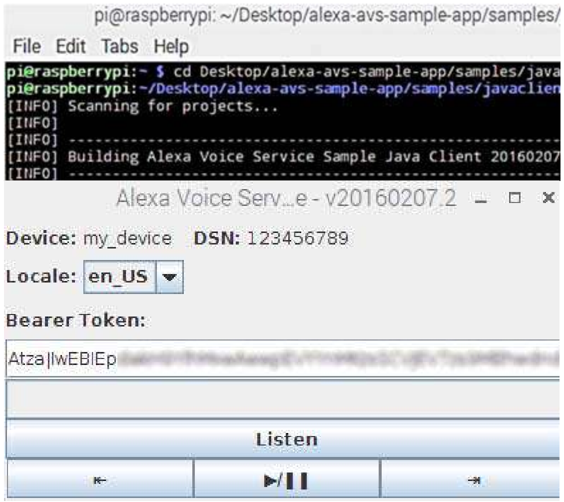

Figure 3. Top: Java Client service initialization. Bottom: AVS Java Client interface initialization.

3.3 Intervention via SMS and email notification mechanisms

This mechanism, inherited from an earlier implementation [16], is presently implemented and tested via a RPiZW node, a smartphone, and Twilio®'s as well as Gmail©'s APIs. Additionally, a non-web-based contingency device was developed using a Siemens® T35 GSM shield mounted on an Arduino® UNO™. The main objective with this implementation is to setup the foundations of an increasingly comprehensive intervention framework capable of reacting to emergency events, both with respect to the inhabitants of the built-environment and with this environment per se.

The Twilio® implementation represents a cost-effective SMS service, while the T35 GSM setup represents a standard prepaid SMS service. A scenario may be entertained where the built-environment's WiFi service is unavailable for a period of time, yet the integrity of the WSAN's *Local System* remains uncompromised as its constituents remain networked via ZigBee and BLE. In such a scenario, an emergency event may be reported via the T35 GSM setup, as it relies on standard cellular communication. Conversely, another scenario may also be entertained, where cellular services are unavailable due to lack of coverage. In this scenario, emergency events may be reported via Twilio®'s SMS service to any location worldwide.

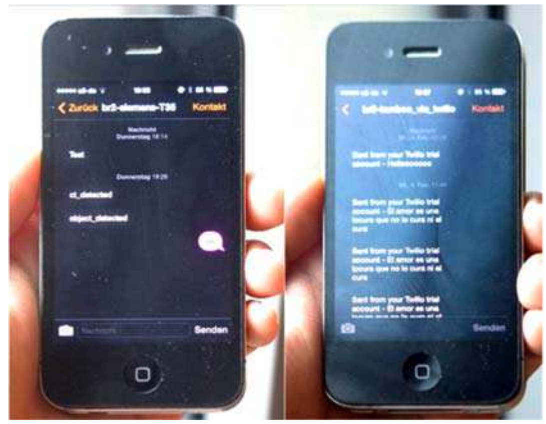

Figure 4. Left: SMS via WiFi (Twilio®). Right: SMS via *Siemens T35 GSM* module.

3.4 Closed-loop Runtime Implementation

In order to describe how the above-detailed mechanisms integrate into the proposed development, a point-by-point runtime description is provided as follows:

1. The *Local System*, as the core of the WSAN and backbone of the ICT ecosystem, initializes and establishes the network in multiple communication layers (WiFi, BLE, ZigBee). For security reasons, only registered MAC addresses are provided with IP addresses. Once the network is established, all *Linux*-running systems update and upgrade.
2. *Wearables* communications initialize. The WSAN draws available data from Fitbit®'s servers and begins to listen for LBB notifications as well as to listen and record BLE / OSC accelerometer data.
3. *Remote / Cloud-based Services* communications initialize—i.e., *OAuth 2.0* tokens are provided, authentication and authorization are established. Received accelerometer data are streamed to and plotted by Plotly® used for local HAR, if a suitable classification model is present.
4. Since the deployment context is that of GSM3, the system checks if the responsive stage is being used by a lecturer.
5. If a lecturer is on-stage, the system checks if a suitable ML classification model is available.
6. If no ML models are available, local HAR considerations are omitted from subsequent decision-making processes—e.g., whether to activate ventilation systems if the lecturer is assumed to be agitated via Fitbit® data (see points 12 and 13).
7. Presupposing the availability of the SVM model

mentioned in point 3, the HAR mechanism is initialized—i.e., processed accelerometer data are set against the model and prediction begins in real-time.

8. All sensing systems—embedded, ambulant, and location dependent wearable—are initialized and verified.
9. Raw data are gathered, cleaned, processed, and made available across the entire network.
10. The data from point 9 are written into the (i) local ML and (ii) remote ML datasets (optional) for a subsequent model generation.
11. Similarly, said data are streamed, plotted online, and made available for remote monitoring.
12. When the system detects the presence of a lecturer on stage, it determines that the lecturer is probably physically agitated if (i) sweat sensors (see Figure 1, item 5b) detect perspiration; (ii) temperature and humidity sensors detect an increase in temperature and relative humidity in the overall environment in general, and in user-occupied areas in particular; (iii) the wearable LBBs detect an increase in body temperature; and (iv) the most recent Fitbit® data evidence existing and sustained physical activity.
13. Having determined a high probability of physical agitation, all the fans in the ventilation system activate until readings return to CEN recommendations. In the interest of time, this ventilation mechanism is developed and tested via a scaled surrogate setup. The ICT-configuration concept presented is asserted to function across a variety of physical forms within human scale.
14. After symptoms of agitation cease (e.g., heart-rate normalizes, body temperature falls within recommended levels, and perspiration is not detected), the system continues to check if the temperature and humidity readings of the environment comply with CEN recommendations.
15. As a strategy for responsible energy consumption, if the environment's temperature and humidity readings remain too elevated for comfort after a given period of global ventilation (in this runtime: two minutes), the ventilation system switches to ventilate only the areas surrounding the user. If external conditions raise temperatures across the entire environment, it is pointless to condition unoccupied areas.
16. In parallel to point 14, the system also checks for air-quality via its MQ-*n* sensors (see Figure 2, *Top*) independently of temperature and humidity readings.

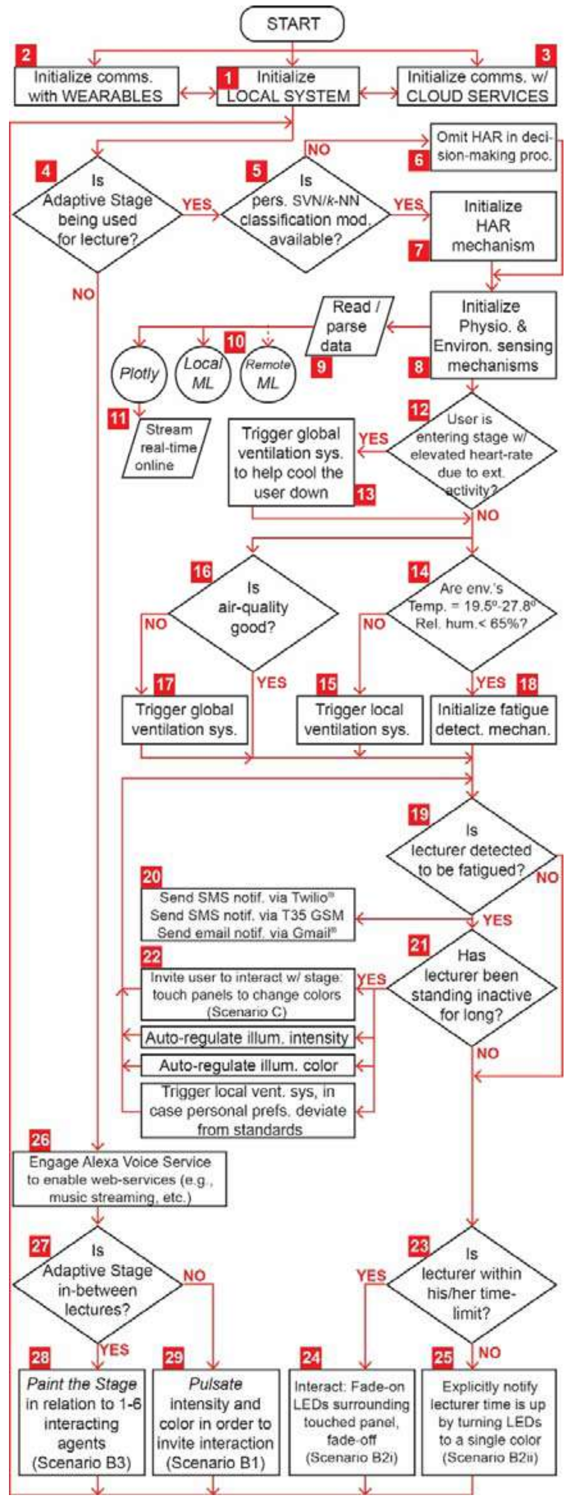

Figure 5. Runtime decision-tree.

17. The strategies for mitigating high-concentrations of toxins and reducing the prevalence of airborne diseases differ from the temperature and humidity strategies above in that global ventilation is engaged for the duration of detected poor air-quality. Even across unoccupied spaces, it remains in the occupant's interest to sustain air-quality.
18. Following point 14, if the lecturer is not agitated, and if the thermal conditions of the occupied space are optimal, the system begins to watch for potential symptoms of fatigue. In this development, fatigue is considered a possible consequence of sustained agitation and/or of normal wear while engaged in *Activities of Daily Living* (ADLs). That is to say, fatigue may be brought upon by concentrated and extraneous physical activity and/or simply by growing tired engaging in ADLs throughout the day. The fatigue-detection mechanism used in this development is inherited from ISARC 2017's implementation [1]—that is to say, it is a limited adaptation and modification of the *human state estimation system* developed by Nakaso *et al*. [17].
19. The fatigue-detection system relies on a camera—in this case a Microsoft® Kinect™ V2—and a face and eyelid-aperture detection classification model developed in MATLAB. If the lecturer is detected to be probably fatigued—e.g., his/her eyelids droop, activity levels decrease, acceleration in movement decreases—then the following two intervention mechanisms activate:
20. SMS notifications regarding the lecturer's state, including average heart-rate, temperature, acceleration, steps taken, and distance covered are sent via Twilio® and via T35 GSM. These notifications are shorter than the one sent via Gmail©, where an hour-by-hour overview of activity levels—in some predetermined period of time—are fully detailed. The degree of detail may vary depending on the purpose of the notification. In this development, these SMSs and email are triggered by detection of fatigue, yet these mechanisms serve as indicators of promising application potential.
21. In conjunction with triggering the above passive intervention mechanisms (i.e., such that notify yet do not mitigate or promote), the system considers activity data for the last hour to determine the amount and concentration of inactivity. If the lecturer has continuously stood still for longer than fifteen minutes, the system considers this inactivity as an exacerbating factor in the detected fatigue.

Figure 6. Interactive stage in action at GSM3 conference.

22. Accordingly, the responsive stage triggers four active intervention mechanisms (i.e., such that mitigate and/or promote) sequentially (see Figure 5, item 22). That is, upon detecting prolonged inactivity, components in the responsive stage fade-on varying colors and intensities to encourage the lecturer to touch them (see Figure 5, item 22, first row). This, along other scenarios (i.e., Figure 5, items 24, 25, 28, 29, and 26 assisting) turn the stage into *de facto* playware. The second and third active intervention mechanisms (see Figure 5, item 22, second and third rows) auto-regulate overall illumination intensity and color of the stage's LEDs in case these be exacerbating factors of the detected fatigue. Finally, the fourth active intervention mechanism triggers local ventilation in case the lecturer's preferences deviate from recommended thermal conditions, and this be an exacerbating factor of the detected fatigue (see Figure 5, item 22, fourth row). In order to avoid looping between points 19-22 indefinitely, a reconfigurable time-out mechanism is set in order for the system to move forward, if there are no indications of improvement within twenty minutes.
23. Assuming a time-out from the previous point, or a lack of fatigue detection from point 19, the system proceeds to check if the lecturer is within his/her allotted time-limit.
24. If the lecturer is within this time-limit, the stage enables the lecturer to activate instances of fade-on / fade-off by touching components for visual interaction. This scenario ends when the time-limit is reached.
25. If he/she is outside this time-limit, all LEDs turn on

to a single color as a visual queue to the lecturer that time is up. This scenario ends when the moderator confirms thus via OSC confirmation. Having concluded this or the preceding scenario, the system returns to point 4.

26. Returning to point 4, having explored the consequences of the reactive stage being occupied by a lecturer, the consequences of it not being occupied are now detailed. If the stage is empty, then AVS may be engaged for playful and/or entertainment purposes. That is, AVS is habilitated as soon as the WSAN is conformed (back in point 3), but in this development, it is only engaged when the stage is empty. In practice, as was carried out in initial sample runs of this point-by-point outline, AVS was engaged in a lecturer scenario.
27. At this point the system decides to engage one of two other inherited play / entertainment scenarios depending on whether it is in-between lectures or not. In this development, the state confirmation is provided via OSC confirmation.
28. If the stage is in-between lectures, the scenario in item 28, Figure 5 activates. In this scenario, the audience is invited to interact with the stage by *painting it*. That is, depending on the position and movement of identified body-parts of up to six people (via Microsoft® Kinect™ V2), different regions of the stage will change in color and intensity in direct correlation with the articulation of said parts. This scenario ends when a lecturer wearing the LBBs returns to the stage.
29. If, however, the stage is simply on a day off, the scenario in item 29, Figure 5 activates. In this scenario, the stage pulsates like a *beating heart* in order to invite interaction from anyone in a passive manner. This scenario ends via OSC confirmation. Having concluded this or the preceding scenario, the system returns to point 4.

4 Discussion and Conclusion

The detailed development attempts to promote D2RP&O strategies and methods as enablers of an alternative approach to intelligence in the built-environment, here identified as high-resolution intelligence. This approach merges ICTs as well as Adaptive Architecture considerations in order to yield a holistically and comprehensively adaptive, reactive, and interactive dwelling space capable of providing local and remote services. In this paper, these objectives were illustrated via the extension of a proof-of-concept implementation whose subsystems were developed to high TRLs and tested in naturalistic scenarios. Particular to this paper, three new features or mechanisms are presented and described, each retaining promising potential for expansion. In particular, the first mechanism, viz., Amazon®'s AVS is an especially important complement to the system in that its scope of service is open-ended. Via *Amazon Skills Kit* [18], custom skills may be designed and developed to accommodate environment-specific and purpose-built cost-effective devices, each capable of independent Internet access, effectively turning the dwelling space into a society of IoTs and people [19]. Furthermore, the possibilities extent to the urban scale, where public spaces may be envisioned to possess service capabilities that promote security, provide guidance, and support comfortable lifestyles.

At present, and in addition to on-going work on AVS's customized skills as well as more sophisticated ML mechanisms, work is being conducted to design and to develop an enclosable and integrated environment where an integrated ventilation system may ascertain *Interior Environmental Quality* [20], which is an indicator of comfort. It depends on thermal, acoustic, illumination, ventilation, and related parameters [21], and thus far only illumination, ventilation, and partial thermal aspects have been considered. Although IEQ lacks a globally accepted index [21], it is known that when its parameters deviate from comfortable thresholds, stress mechanisms are occasioned in the human body that—if left unmitigated—may potentially cause or exacerbate disorders and diseases [22]. Such considerations prompt an urgent reassessment of prevalent architectural strategies, especially since people spend the majority of their time indoors [23].

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A Methodology for Analysing Productivity in Automated Modular Construction

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Abstract –

Automation is generally assumed to improve project productivity. However, not enough research is done in the area of quantitative methods to evaluate productivity improvements through automation in construction. The aim of this study is to develop a methodology for analyzing productivity of any given automation system for construction. A case study of an automation system developed in-house is used for illustration and validation. This system involves automated connections of column modules and coordinated lifting of the column assembly. A laboratory experiment has been done using this system for constructing column structures using modular blocks. The experimental results are compared with their equivalent manual processes. These studies are conducted using EZStrobe simulations which are calibrated using experimental data. Of the various project performance parameters, only time has been included in this study. The results would throw light on the impact of automation on construction activities on-site.

Keywords –

Construction Automation; Modular Construction; EZStrobe

1 Introduction

Automation in construction industry has generated significant interest in the recent times. In many Asian countries, there is significant housing demand for addressing the growing population. Automated modular construction can potentially address this challenge by improving productivity through savings in time and cost. Even though it is generally understood that automated construction can reduce time and cost of projects, not enough research is done in the area of quantitative methods to evaluate productivity improvements through automation in construction. The general aim of this study is to develop a generic methodology for analysing productivity of any given automation system for construction. More specifically, our focus is on using simulation tools such as EZStrobe in combination with site measurements or laboratory experiments for predicting productivity parameters of different possible processes for a task.

2 Literature Review

Recently, there is renewed interest in performance analysis of construction projects using simulations. Many examples of simulation studies in different types of projects can be found in the literature [1-9]. The use of Discrete Event Simulation (DES) using tools such as EZStrobe is particularly gaining attention. Researches are done on the possibilities of combining Genetic Algorithm multi-objective optimization (GA) and Discrete Event Simulation (DES) using High-Performance Computing (HPC) to address the issues of time and cost in construction projects [10]. Limitations of queue-based DES and proposed a non-que-based DES have been studied [11]; There have been studies on the means of improving productivity of construction operations in New Zealand using EZStrobe simulation tool. These studies focused on improvement in planning using data from bridge launching operation [12]. Researchers have also used EZStrobe to study the productivity management of road construction in Thailand and arrive at optimised construction members with least unit cost [13]. There have also been studies on various simulation software used in construction industry and analysed their strengths and limitations [14]. Studies on Simphony simulation tool, its strengths and applications have also been conducted. The tool handles both discrete event as well as continuous simulations [15]. Some works have been done to develop activity-based cycle diagram for bridge construction process and applied it in simulation using

EZStrobe and studied its effectiveness [16].

Based on a review of recent literature in the area of simulation-based studies, it is very evident that there is hardly any work with regards to automation in modular construction. It is a significant area that requires attention and more research work is needed to answer the question: how much improvement in productivity can be achieved through automation in modular construction. This paper briefly illustrates a methodology for assessing productivity in automated construction.

2.1 Knowledge gap identified in the literature review

1. Various authors have worked in the area of modelling construction operations [17-29]. These works are focussed on certain areas such as earthwork, etc. There is hardly any research focussing on productivity studies of automation in modular construction of building structures [30-32].
2. A methodology that compares the automation of modular construction with manual modular construction and field construction practice has not been done so far.

3 Illustration of a Process-Performance-Assessment Methodology

A "Process-Performance-Assessment" methodology has been developed to achieve the objectives of this study. This involves performing discrete event simulations to calculate the time taken to complete the activities of the process. The productivity is computed by using the basic data related to the duration of completion of relevant activities. The overall construction process consists of a decomposition of tasks. Each task is further broken down into activities and sub-activities. The relationships between the activities are captured in the form of activity-cycle-diagrams (ACDs). The probability distribution of activities at the lowest level in the decomposition hierarchy are defined based on site data or laboratory experiments.

In order to illustrate the applicability of this methodology to a practical construction task, a specific example of column assembly is used here. The time performance of an automated construction scheme described in Figure 1 is evaluated using this methodology. It needs to be mentioned that the overall research involves the study of other parameters such as cost which are excluded in this paper. It is admitted that the cost of the automation unit is important from the point of large scale construction; however, this is outside the scope of this paper.

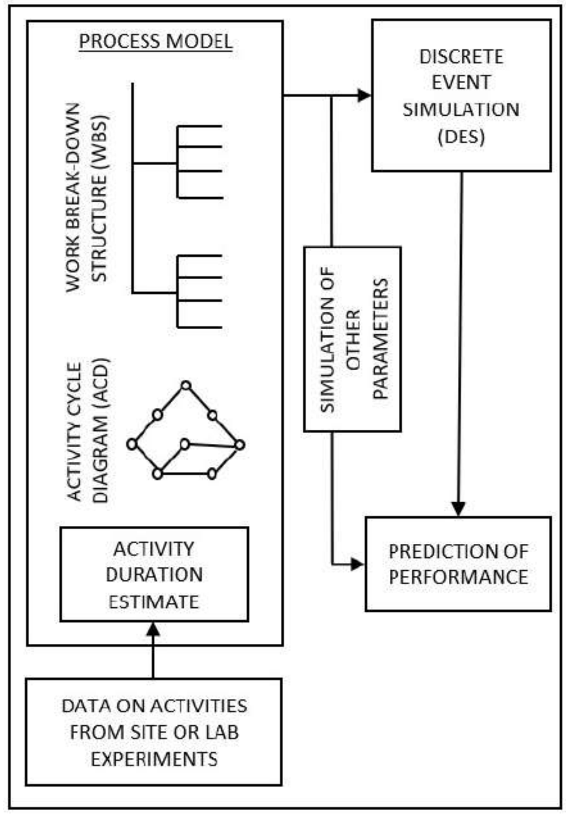

Figure 1. Process-performance-assessment methodology

Previously, an automated scheme using timber modules for the construction of structural frames of buildings has been demonstrated [32]. The idea proposed here is to construct the top floor first and then lift the top part in small steps in order to assemble the modules for lower floors. This will help in performing all the construction activities at the ground floor. This will also support automation since the assembly system can be permanently installed on the ground. The structure is constructed using small timber modules that can be easily assembled. The structural frame of the roof is constructed first. These are lifted using hoists and the columns are inserted below. Both the beams and columns are made of small modules.

The above automation scheme was later adapted for the construction of practical full-scale structures for residential buildings of 1-3 floors. An automated column assembly machine, shown in Figure 2, has been manufactured to illustrate the scheme. As an application example, the process-performance-assessment methodology is used to evaluate this construction scheme. The performance of the scheme is compared with equivalent manual processes in order to bring out the advantages of automation.

Figure 2. Modular column assembly by automation process: bottom to top assembly

Performance assessment involves two stages in this exploratory study:

Stage 1: collection of real time data of three construction processes: a) which is non-modular and non-automated; b) non-automated (manual) and modular; and c) automated and modular.

Stage 2: simulation study of the above three construction processes.

In this exploratory study, a typical column assembly construction is considered. A comparative study of automated process (Case-1) and manual process (Case-2) of modular column assembly; and field-based process of conventional Reinforced Cement Concrete (RCC) column construction (Case-3) is done. Further, simulation-based comparison of all these processes are done. Finally, an assessment of the productivity performance of automation process is analysed and reviewed.

3.1 Description of modular column and RCC Column

The modular column consists of a set of steel modular blocks with a set of connections. In this case, we have eight rectangular modules of dimension 400 (L) x 200(B) x 400(H) mm, as shown in Figure 3. These modules when stacked one above the other and connected will give a total height of 3200 mm. The RCC column is of dimension 300 x 200 x 3200. Reinforcement: 14mm rods 6 no.s; 8mm square hoops@ 100mm c/c and 25mm cover.

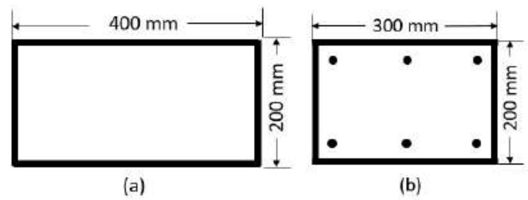

Figure 3. (a) Block module for column assembly and (b) Plan of RCC column

Assumption: It is assumed that the base foundation work is already completed. The column work is extended above the same. In the case of modular assembly, it is assumed that the top base of foundation has connecting component with respect to the first column module block. In the case of RCC construction, it is assumed that the top base of the foundation has extended reinforcement rods which shall be lapped with the column reinforcement during the RCC column execution work. The column reinforcement is already prepared by labour by tying the main rods and stirrups and it only needs to be attached by lapping to the foundation reinforcement. Shuttering is cleaned and oiled. Concrete batch is ready for pouring. Curing is done for 28 days.

4 Exploratory Study based on Laboratory and Field Experiments

The three cases mentioned previously are discussed below.

4.1 Case-1: Modular column assembly by automation process: bottom to top assembly

In Case-1, 8 modules to be assembled are stacked close to the automated assembly machine. Upon starting the machine by a technician, the lifting base would move to its initial position. The technician picks one module at a time, takes it to the machine and places it on the lifting base. The machine lifts up the module till it touches the partially assembled column above and makes the connection between the two using steel pins. Then the new column assembly is temporarily supported by load holding pins and the lifting base is lowered. The process is repeated until all the modules are connected.

4.1.1 Activities of Case-1 as modelled in the simulation tool

1. Start the column assembly process
2. Lifting of block 1: initial position: move to stack: hold one block: lift the block: move to assembly location: place in assembly location
3. Lifting of next block: initial position: move to stack: hold one block: lift the block: move to assembly location: place in assembly location above previous block.
4. Lifting of connector: initial position: move to stack: hold one connector: lift the connector: move to assembly location: place between current and previous block: Connection between blocks
5. Repeat steps 3 and 4 till total number of blocks is 8.
6. Stop the process.

4.1.2 Data collection for Case-1

The process of automated modular column assembly was performed in a laboratory setup in order to estimate the duration of activities involved. The experiment was repeated three times. In a typical experiment, the whole process was completed in 19 minutes and 1 seconds. Time taken for various activities are shown in Table 1.

Table 1. Typical observations of process duration in Case-1

Sl.no.	Process		Sub-activity	Duration (sec.)	TOT. duration (sec.)
1	At Initial Position	a	At Initial position	5	5
2	Lifting of block-1	a	move to stack	10	
		b	hold one block	4	
		c	move to assembly location	10	
		d	place in assembly location	4	
		e	Release the block	4	32
15	Lifting of block-8	a	move to stack	40	
		b	hold one block	4	
		c	move to assembly location	45	
		d	place in assembly location above previous block	4	
		e	Release the block	4	97
17	Back to initial position	a	Back to Initial position	45	45
	TOTAL		IN SECONDS		1146
			IN MINUTES		19.1

4.2 Case-2: Modular column assembly by manual process: bottom to top assembly

In Case-2, two labours are engaged in picking the module and positioning in the assembly location. One labour is positioned at the assembly location while the other moves to and from the stock. The moving labour picks one module at a time, moves to the assembly position and then both the labours place the module in position and check the correctness of positioning. Then the labour moves to take the next module and place it on top of the previous one.

4.2.1 Activities of Case-2 as modelled in the simulation tool

1. Start the column assembly process
2. Lifting of block 1: initial position: move to stack: hold one block: lift the block: move to assembly location: place in assembly location
3. Lifting of block 2: initial position: move to stack: hold one block: lift the block: move to assembly location: place in assembly location above previous block.
4. Lifting of connector-1: initial position: move to stack: hold one connector: lift the connector: move to assembly location: place between current and previous block: Connection between blocks
5. Repeat steps 3 and 4 till total number of blocks is 4.
6. Lifting of next block: initial position: move to stack: hold one block: lift the block: move to assembly location: board on base stool: place in assembly location above previous block: aboard from base stool
7. Lifting of next connector: initial position: move to stack: hold one connector: lift the connector: move to assembly location: board on base stool: place between current and previous block: Connection between blocks: aboard on base stool
8. Repeat steps 6 and 7 till total number of blocks is 8.
9. Stop the process.

4.2.2 Data collection for Case-2

The above procedure was tested in an experimental study and the time taken for each activity was recorded. Since this is only an exploratory study meant for illustration of the methodology, experiments were not repeated multiple times. Time lags were noticed in discussions, decision making, moving between the stock and assembly; positioning; connecting; and boarding and aboarding the base-stool for modules that were positioned above 1.6m. There were also issues of safety due to improper handling of modules during the assembly process. The whole process was completed in 1 hour 51 minutes and 24 seconds.

4.3 Case-3: RCC column construction by manual process

In Case-3, the sequence is Reinforcement placement; Shuttering; Concreting; De-shuttering and Curing. Six labours were engaged- two for reinforcement arrangements; two for shuttering and de-shuttering; and two for curing process. Initially, two labours were engaged in assembling the reinforcement by taking the already prepared reinforcement to be positioned at the RCC column assembly location. The reinforcements were tied by lapping with the rods projecting from the base of footing. Later two labours bring the shutters from the stock and position them at the lower part of the column, provide spacers and fasten the shutter panels. The two labours into concreting prepare the batch and take first batch to fill up to the top of shuttering level. The column is let to set for twenty-four hours and then it is de-shuttered by the two labourers and further positioned up to the next level and the same process is repeated. And finally, the shuttering is extended up to the top of the 3.6m column and concreting process is completed. After the setting and the de-shuttering, the column is cured by wrapping around with wet gunny sacks. The column is sprayed with water at 6 am and 6pm for 28 days starting from day-1 of de-shuttering of first batch casting till day-28 of the curing of the third batch casting.

4.3.1 Activities of Case-3 as modelled in the simulation tool

1. Start the RCC column assembly process
2. Reinforcement placement and tying:
   (a) initial position
   (b) move to stack: hold the rebar: lift the rebar: move to assembly location: place in assembly location: lap with the base rebar: tie with the base rebar
   (c) back to position
3. Shuttering:
   (a) Initial position
   (b) Move to stack: hold shuttering: lift shuttering: move to assembly location: place in assembly location: align in assembly location: fasten the shuttering
   (c) Back to position
4. Concreting:
   (a) Initial position
   (b) Move to concrete batch: hold one portion of concrete: lift the portion of concrete: move to assembly location: position in assembly location: pour the concrete
   (c) Back to position
5. De-shuttering:
   (a) Initial position
   (b) Move to assembly location: align in assembly location: un-fasten the shuttering: hold shuttering: lift shuttering: move to stack
   (c) Back to position
6. Repeat steps 3,4 and 5: twice, each after 24 hours.
7. Curing:
   (a) Initial position
   (b) Move to stock: pick gunny bag: Move to assembly location: Wrap around column
   (c) Move to water pipe source: turn on water: spray on column:
   (d) Move to water pipe source: turn off water: Back to initial position
   (e) Repeat steps c. and e. after 12 hours
   (f) Back to initial position
8. Repeat step-7 c-f till count is 28.
9. Stop the RCC column assembly process

4.3.2 Data collection for Case-3

Observations were done on construction sites in order to estimate the time for basic activities of the above process. Using this data, an estimate of the total time taken was made. The estimated total duration of the RCC column casting process was 31 days 4 hours 15 minutes and 19 seconds.

5 Simulation Study

EZStrobe is a general-purpose domain independent simulation tool that has been widely applied to construction operation studies. It functions primarily based on Activity-Cycle-Diagrams (ACD) and is used for productivity and optimization studies in construction. The process model consists of multiple queues representing activities that are repeated. The present simulation study is conducted for three scenarios namely: (1) process of column construction using modular blocks through automation; (2) process of column construction using modular blocks done manually; and, (3) manual RCC column construction process.

In the EZStrobe simulation model for Case -1, shown in Figure 4, the **Queue element** “Block” is assigned 8 numbers indicating the 8 modular blocks for the column assembly. It is linked to “Load” and releases one modular block at a given cycle. The **Conditional activity element** “Load” is linked to the Queue elements “Block”, “Holder_Idle” and “Move”. “Load” is assigned the duration in the range of 28 to 68. **Queue element** “Holder_Idle” is assigned 1 number indicating that at any given time, the holder of the assembly unit picks one modular unit. It is linked to “Load” in a cyclic loop. The **Bound activity** "Move" is linked to "Load" and "Assemble" as predecessor and successor activities respectively. "Move" is assigned the duration in the range of 20 to 68. "Move" activity functions after the "Block" loads one module to the holder of the automation unit. **Bound activity** "Assemble" is linked to "Move" as predecessor; and "Assembled_units" and "Release" as successor activities respectively. "Assemble" is assigned the duration in the range of 8 and 24. The module, after moving from the stock held by the holder of the automation unit, is placed at the assembly position.

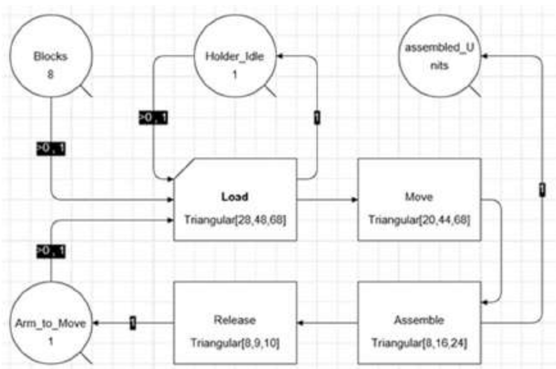

Figure 4. EZStrobe model of workflow for Case-1

Queue element "assembled_units" indicates the number of modular blocks assembled at the column assembly position. The **Bound activity** "Release" is linked to "Assemble" and "Arm_to_move" as predecessor and successor activities respectively. "Release" is assigned the duration in the range of 8 to 10. "Release" activity functions after a module block is assembled in position by the holder of the automation unit. **Queue element** "Arm_to_move" is the moving arm of the automation unit at whose end is the holder. The "arm_to_move" functions the moving between the stock and the assembly location for taking, placing and reverting to stock of modular blocks.

In Figure 5, EZStrobe simulation snapshot of Case-1 is shown. The EZSrtobe simulation controller displays the time taken for simulation with graphical display of stage of simulation. With the option of "Animate" and controlled "Animation Speed" we visualize the sequence of activities taking place. Here, we note the activities between assembling the block and releasing. The "triangular" indicates the minimum, mean and maximum time taken for the activity.

On running the simulation, a report is generated wherein there are series of parameters displayed and numerical values generated after completing the simulation runs. Some of the parameters are time of report, total amount of resource, average content, minimum content, maximum content and so on.

Up on simulation run, the durations of their assembly process are arrived. It is noted that Case-1 has the least duration of 18m 5sec.; Case-2 with the second least time duration of 1h 47m 38 sec., whereas, Case-3 took an execution time of 31d 4h 13m 57 sec. It also closely correlates with the field-based and laboratory measurements.

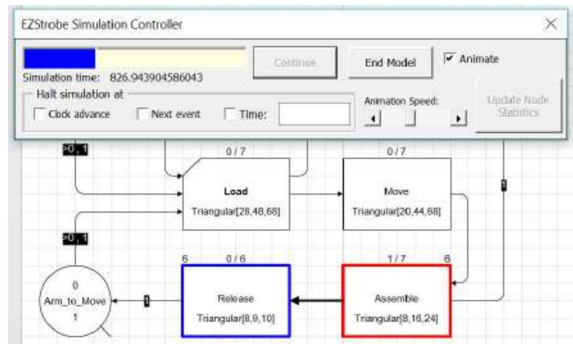

Figure 5. Simulation snapshot for Case-1

6 Comparative Results

The three cases represent three distinct approaches to construct a column and they show significant aspects of the assembly process. In Case-1 (i.e. Modular column assembly by automation process), it is noted that once the automation unit was stationed and positioned, the column assembling using the block is a cyclic process that went without any hindrance, obstacle or technical snag. The time duration taken for each activity and sub-activity is controlled and hence each repetitive activity took the same time duration. In Case-2 (i.e. Modular column assembly by manual process), it is observed that the two-labour executing the process had on and off discussions, deliberations, slowing and speeding up, erroneous assembling, etc. Further, they had to use a base-stool to climb above the height of 1.6m for assembling the modules that added time for work completions. There was also risk of tripping and falling; losing grip of the module from hand. Therefore, safety was also in question in this process. In Case-3 (i.e. RCC column construction by manual process), teams of two performed the tasks of reinforcement placement; shuttering; concreting; de-shuttering; and curing. And thus, this process involved the maximum labour resource. Also, the efficiency and quality of work kept varying throughout the execution. This impacted on the time delays and therefore on the overall productivity of the column construction process. In terms of time duration from these experiments, Case-1 took the shortest, while Case-3 took the longest duration. The simulation analysis further validates this.

7 Summary and Conclusion

This paper illustrated a process-performance-assessment methodology by which the productivity of automated modular construction can be evaluated. A selected automated modular construction process was compared with manual modular construction and equivalent common construction practice at site. A typical case of column construction was studied with modular blocks which were assembled manually as well as through automation. Equivalent study was carried out for an RCC column construction. All these cases were studied through EZStrobe based simulation and analysed. Results indicate that significant savings in construction time can be achieved through automation. Furthermore, the study demonstrates how a process simulation tool can be used to evaluate the overall performance of construction processes.

Future research involves testing the methodology on more complex tasks, collecting more on-site data and refining the methodology. Further research is planned to look into the decomposition of processes which shall lead to the greater degree of understanding on the levels of automation required in the construction process. This methodology also throws light on the positive impact of automation in the productivity of not only the assembly process but on further study shall also do so on the total project performance.

8 Acknowledgements

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Process of verification of earthworks execution using terrestrial laser scanning

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Abstract –

Interactive verification of construction works should provide for compliance between planned vs. completed works. The task of its fulfilment (especially for larger investment projects) is rather time and labor consuming. There is potential to reduce the duration of a verification process as well as to ensure the results are more accurate and clear with the use of digital tools and specialized software, moreover, substantial part of the process may be automated.

Faster and more accurate capturing of a data regarding actual position and shape of the construction works, resp. its parts, as well as the information about the quality of works has the potential to reduce number of disputes caused by unclear measurement data evaluation.

The technology of Terrestrial Laser Scanning (TLS) is suitable for this purpose allowing efficient data collection and automation of the process of verification. The article provides a case study comparing traditional approach vs. use of TLS for earthworks verification and the impact of different methods of measurement on the price.

Keywords –

Earthworks, Cost estimation, Quantity take-off, TLS

1 Introduction

Prior to the creation of the bill of quantity, the quantity surveyor must know the technology defined by project to set appropriate and indicative price. Indicative price includes items from the pricing database considering all relevant regulations and standards (safety, hygiene and fire protection). It is necessary to use the same or similar specifications and name conventions defined in national standard “STN 73 3050 Earthworks. General provisions” and at the same time in the software (based on reliable pricing database) where the indicative price was calculated. The bill of quantity is an integral part of the project to ensure that each tenderer can estimate the price according to the extent of work, without the risk of possible demand for additional extra work which can lead to budget overrun. The price estimation need to be well structured allowing to attach complete tasks list to invoice. This may be done after agreed period or frequency (weekly, monthly), on a task base or after complete delivery of work.

2 Terminology and Legislation

Pricing databases are based on **classification of the building construction TSKP** (Classification of Building Construction, Instruction No. 13/1977 of the Ministry of Construction of the Czechoslovak Republic on 30 December 1977 in co-operation with the Ministry of Construction of the SSR and in agreement with the FSÚ pursuant to Section 16 paragraph 2 b of Act No. 21 / 1971 Coll.) and **classification of works TSP** (Classification of Construction Works, declared by the Ministry of Construction and Regional Development Methodology No 1/2004, which entered into force on 1 January 2005. The class was issued on the basis of the Annex to Commission Regulation (EC) No 204/2002 on the statistical classification of production by activity in the European Community declaring the classification of construction works to be binding on the Member States of the European Union and on the basis of the Decree of the Statistical Office of the Slovak Republic No. 632/2002 Coll., which gives the statistical classification of production as amended issued on the basis of Act No. 540/2001 Coll. on State Statistics)[6]. According to TSKP, the earthworks are listed under code 800 - 1 Earthworks and according to the TSP Earthworks are listed under the code 01. Therefore, proper specification of the items is required.

For the proper use of items, it is also necessary to know the geology including the composition of soil that will be subject of earthworks from geological surveys. It is therefore necessary to know their class of rippability (*rippability is the ease with which soil or rock can be mechanically excavated)*, which is on national level classified in 7 classes. [1]

- 1st class - loose rocks - can be easily loaded by shovel, loader.
- 2nd class - rippable rocks - rippable by digging spade, loader.
- 3rd class - diggable rocks - rippable by digging spade, loader.
- 4th Class - solid crumbly rocks – rippable by spike, excavator
- 5th Class - Solid rocks with easy rippability – rippable by ripper, heavy excavator (over 40 tons), explosives.
- 6th Class - Solid rocks with difficult rippability - rippable by heavy rippers, explosives.
- 7th Class - Solid rocks with difficult rippability - rippable by explosives.

The items of the bill of quantity must be formally prepared so that all parties involved in the construction process have the same and unequivocal idea of the subject and that it would not be necessary to demand the extra work during the execution. In the case of a high-quality project, this requirement is fulfilled, because the most important influence on the price calculation of works on larger buildings is the chosen technology. The method of measurement is given by individual database makers. Example: The amount of excavation is determined in m^3 of soil volume in the unripped state from the dimensions given by the project, defined from the level of the adjacent terrain, while the adjacent terrain can be:

- for all terrain excavations, natural or terrain for the viewing of the orphanage or the carp after removal of the reinforced surfaces,
- in the shafts and rocks the bottom of each trench, except the bottom of the shafts and grooves,
- for pits, the bottom of the excavation or excavation or the bottom of the trench for the flowing water flows. [2]

The handling volume of the excavation obtained by the excavations in the dry environment and underwater subsoil (horizontal displacement, loading, etc.) is determined by the unripped soil volume on the trench. The volume of handling of the excavation obtained by the other excavations under water is determined in the solid state. [2]

3 Case study

The greenhouse construction of the object "SO08 Laguna" consisted in the first stage of the excavation of the Lagoon itself. Excavated soil was transferred and stored within the site (the property of investor). Next task was creation of waterproofing layer supplied with geotextile and drainage system for pumping the rain water into Lagoon. After the first stage of excavations, quantity quoted in the invoice was doubted by investor. Contractor declared that approximately half of the work was completed. Investor returned the invoice after control measurement was performed and asked for correction of values. The issue was, the results of the measurement of contractor and the investor varied. In both cases, the measurement was performed by a length scale (band).

Figure 1 Preparation of excavation works, Lagoon

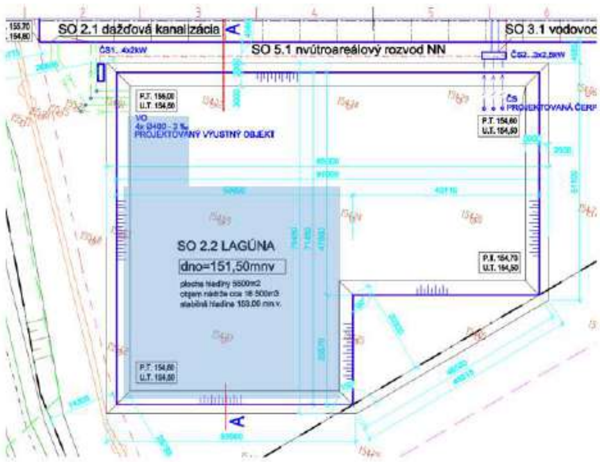

Figure 2 Layout of the Lagoon with identification of executed excavation (blue hatch)

Both the Contractor or the Investor (with notice from the other party) has the right to invite an third-party authorized person for independent measurement or to avoid dispute by specifying the subject of billing of earthworks (measurement and quantification) using an court expert in the form of a private expert opinion under *160/2015 Z.z. Civil Procedure Code, § 209* (If such a report has all the requisites prescribed and a clause that the expert is aware of the consequences of a knowingly false expert's opinion, then the procedure is followed as if it were an expert judgment ordered by the court).

3.1 Measurement and Legislation

An expert or authorized person has more options or devices to measure and verify the size of the work that was done. Differences in measurements by the construction manager and supervisor have arisen due to the use of various measuring instruments and various measurement errors. Measurement is a summary of activities to determine the value of the measured quantity. This value should be given along with the tolerance in which the right value of the measured quantity or the numbers corresponds to the corresponding values of the measurement result. This is particularly important today, where large numbers of computers are used for processing results. We do not get the correct value of the measured value by any measurement, since each measurement is made with error. The error characterizes the accuracy of the measurement by specifying deviation.

The base length is the meter (unit of length meter, symbol m is the length of the path that the light passes under the vacuum in 1/299 792 458 seconds) [4]

- a measurement unit is the specific value of a physical or technical quantity that is defined and accepted by agreement with which other values of the same species are compared in order to express their magnitude in relation to that specific value of the quantity,
- measuring instrument is device for determining the value of the measured quantity, including the measure, the measuring instrument, its components, the auxiliary equipment and the measuring device,
- the type of measuring instrument shall be a definitive design of the measuring instrument of a given design in accordance with the type-related documentation in which all components influencing the metrological characteristics are defined, manufactured by the same manufacturer,

Usage of specified instruments:

- Designated instruments may only be used for the purpose if they are validated if required.
- The entrepreneur or other legal entity is obliged (and - to use the prescribed instruments in cases where their use is stipulated (§ 8) and for that purpose there is a type of measure stipulated by a generally binding legal regulation, unless a special regulation7) has not granted an exemption, b - keeps the used measuring instruments in proper technical condition)

Designated meters according to Annex no. 1 to Decree No. 210/2000 Z.z. - Types of measured meters are rolling meters, bands, folding meters and winches in length measurements.

According to Annex no. 50 to Decree No. 210/2000 Coll., The measuring instruments referred to in point 1 (a) be broken down according to the principle of measurement

- balancing instruments,
- folding scales,
- winches.

According to the accuracy of the material length measurement, weighing instruments are divided into three classes of accuracy. The maximum permissible errors of the weighing instrument for initial and subsequent in-service verification are given in Table no. 1. [4]

Table 1 The largest permissible error

Accuracy class	The largest permissible error (positive or negative) in % of measured length
I	0,25
II	0,5
III	1

To determine the amount of work done within the excavation object in construction progress, measurement can be made by a measure (band or other meter) preferably with an accuracy class I, or with existing software support devices. Current technologies offer, in addition to measuring, simplification of measurement itself and processing of measurement results. [5] Their accuracy is significantly higher and data processing shorter.

3.2 Selected devices

The Lagoon was measured by contractor using the measurement bands and the resulting quantities are written in Table 2. The table is based on the transcript of the work done from the invoice attachment. The requirement to verify the number of works carried out arose from the investor side. The 3D Leica ScanStation2 scanner and Leica DISTO D 910 was selected to measure the excavation work on the Lagoon facility.

The procedure for determining the volume of the lagoon object consisted of:

- terrestrial laser scanning of an object,
- measurement by laser distance measure
- processing of measured data and creation of a 3D model and calculation of excavation volume

The Leica ScanStation2 was used for the measurement [6; 7; 8]. The spatial shape of the Lagoon was measured from two positions with a scanning density of 50 mm x 50 mm / 50 m. Opinions were linked through four landing points. The registering points were the Leica HDS target marks, which were stabilized on the measuring statues. The positioning points were determined in the S-JTSK coordinate system using the SK-POS Slovenian Space Observation Service.

Figure 3 On-site scanning of the Lagoon

Based on the position, the Cyclone software transformed the coordinates of the points from the individual positions of the instrument into S-JTSK and Bpv. The internal (relative) accuracy of the transformation is defined by the mean spatial error σxyz = 3 mm. The absolute accuracy of the transformation is characterized by a value of σxyz = 10 mm. The result of the transformation is the single point cloud of the object.

In order to determine the actual Lagoon volume, all shrubs and grassland that stood above the terrain were removed in the first stage of the measured data from the cloud point. (Figure 4)

In the second phase, a triangular network (TIN model) of the measured object was created from the combined dot cloud. The TIN model was created for the Lagoon itself (excavation pit) as well as for the original terrain.

The TIN model of the original terrain was created from the points of the Laguna surrounding. The volume of the Lagoon was determined by the difference model of the TIN models of the excavation pit and the original terrain.

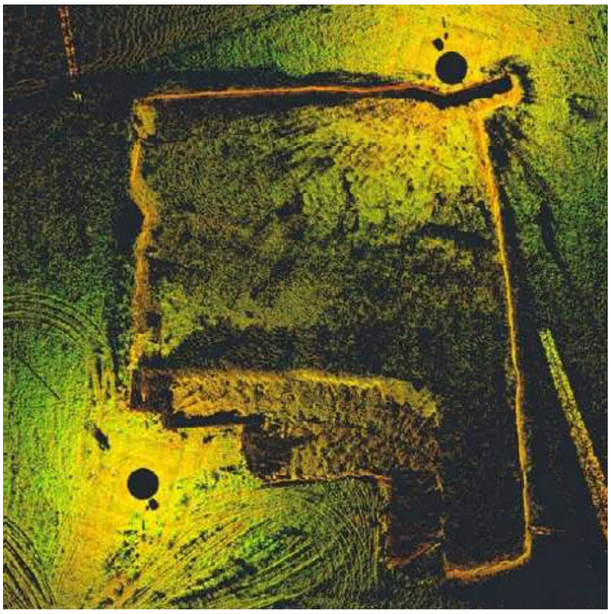

Figure 4 Point cloud, top view

3D view is generated using tools and commands in CAD programs. Moreover, it is possible to generate individual sections - Lagoon profiles and realized excavations. Using individual profiles and basic mathematical functions, volumes can be calculated, or model tools can generate volumes directly in the CAD program [9; 10; 11]. (Figure 5)

The second used tool for the measurement was Leica DISTO D 910. The Leica DISTO S910 (Figure 7) is the laser distance measurer that captures multiple, accurate measurements in three dimensions from a single location, radically improving the efficiency of common measuring tasks. The integrated Smart Base enables to measure distances (e.g. widths, distances) between any two points, angles or inclinations at the same time from one location.

Figure 5 Point cloud axonometry

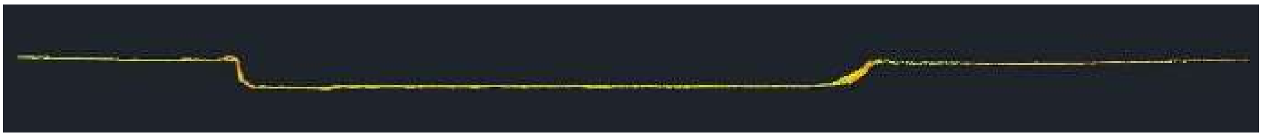

Figure 6 Point cloud, section through excavation

Figure 7 Measure with Leica S910

The Leica DISTO™ S910 can save all the measured points into a DXF file as a floor plan, wall layout or 3D point coordinates that can be downloaded to a PC via the USB interface. The schema of measurement is shown in Figure 8.

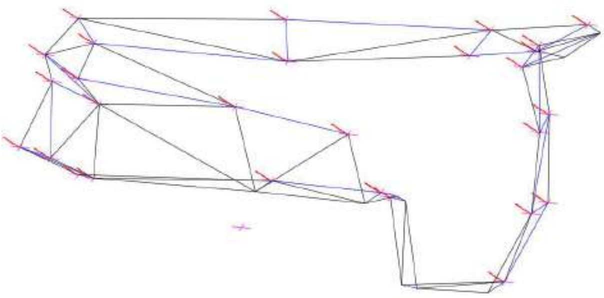

Figure 8 Measurement with Leica S910 – processed using CAD software

3.3 Measured values

In the table below, the values (dimensions) of each work are from the bill of quantity, as measured by the contractor versus scanner measurement (Tab. 3). Scanner surveys were carried out by an authorized surveyor. Cost of measurement by TLS exceeds the standard measurement (bandwidth or manual laser) available on the market, but the accuracy and processing of the results is on a diametrically different level. These instruments do not yet fall under the specified instruments, but the accuracy of the measurements is defined, and regular calibration is carried out. Scanner measurement and laser distance measure demonstrates a lower amount of actual execution of excavation work. Individual quantities multiplied by unit prices form a new total cost. The unit price is defined by the contract or by the open market [12; 13]. In the case of the use of the following materials in the excavations: concrete [14], underlying aggregates [15] or prospective materials [16], inaccurate measurement would result in increased price due to higher volume of material calculated.

Individual columns represent subsequently: number of the item, code of the task, task name, measuring unit, measurement value, unit price and price of task.

Tab. 2 Bill of quantity delivered by Contractor

1 – Earthworks 44 651,54

1	131201104	Excavation in soil, 3rd Class, over 10000 m3	m3	3 037,52	2,500	7 593,80
2	162301181	Transfer of soil in soil 1st -4th Classover 10000 m3, distance 50 to 500 m	m3	3 037,52	2,200	6 682,54
3	171203111	spreading of soil without compaction, max slope 1:5	m3	3 037,52	10,000	30 375,20

Tab. 3 Bill of quantity delivered by Surveyor (TLS)

1 – Earthworks 38 923,68

1	131201104	Excavation in soil, 3rd Class, over 10000 m3	m3	2 647,87	2,500	6 619,67
2	162301181	Transfer of soil in soil 1st -4th Classover 10000 m3, distance 50 to 500 m	m3	2 647,87	2,200	5 825,31
3	171203111	spreading of soil without compaction, max slope 1:5	m3	2 647,87	10,000	26 478,70

Tab. 4 Bill of quantity delivered by Surveyor (S910)

1 – Earthworks 40 359,18

1	131201104	Excavation in soil, 3rd Class, over 10000 m3	m3	2 745,52	2,500	6 863,80
2	162301181	Transfer of soil in soil 1st -4th Classover 10000 m3, distance 50 to 500 m	m3	2 745,52	2,200	6040,15
3	171203111	spreading of soil without compaction, max slope 1:5	m3	2 745,52	10,000	27 455,23

4 Conclusion

Measurement is a process that results in a measured value. Its accuracy often affects other aspects. The purpose of this case study was to compare the various measurement tools that allow to capture actual progress of work - in this case earth excavations. The measurement (volume of work) submitted by the contractor exceeded estimated quantity specified in the quantity take-off calculated from project documentation. To verify individual quantities, modern technologies and devices were used. TLS scanning and laser distance measurement in a combination with specialized software proven that the differences in the measured values are significant as the contractor used classical measurement methods.

As a result, the volume of 3 037.52 m^3 was measured by contractor. When multiplying by unit price, the amount of the work was calculated to € 44,651,544. By means of a verification, surveyor quantified the volume of works to 2 647.87 m^3 using TLS. After multiplying by unit price, the value equals to € 38,923,689. Secondary verification method – using distance laser measurement, the value of 2 745,523 m^3 was quoted. After multiplying by unit price, the value equals to € 40,359,188.

Both verification methods by professional devices (3D Leica ScanStation2 and Leica DISTO S 910) proven different – lower amounts of actual volume of work executed. The cost deviation between the calculation of contractor (using traditional technique) and surveyor is significant resulting in the reduction of costs by € 5,727.86 resp. € 4,292.35. In percentage terms, the savings are 9-12% compared to the original requirement of the contractor and that is considerable figure for both large and small-scale construction works in this sector. The cost of verification measurement is in most cases irrelevant to the potential savings of the investor and the digital technology needs to be an integral part of the construction industry.

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A Data-driven Framework to Estimate Saving Potential of Buildings in Demand Response Events

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Abstract –

In the U.S., the increasing electricity demand gives pressure on the power grids because of its limited capacity to serve demand. Instead of building new power plants to meet the increasing demand, Demand Response (DR) programs incentivize end-consumers to reduce certain electricity demand during certain periods (e.g., peak demand and emergency times). In the current practice, saving potential of buildings, i.e., the amount of electricity that end-consumers can save during an event, is usually determined using the technical specifications of equipment installed, which is unrealistic and leads to over or underestimation of the expected saving potential. In this study, the authors developed a data-driven framework to quantify the electricity saving potential in buildings. The framework was applied to nineteen campus buildings. Several prediction algorithms were used to fit models to the integrated datasets of these buildings, and models were evaluated using four criteria to avoid over-fitting and under-fitting. The best performance of the models resulting in 0.86 of R^2, which represents high capability to quantify the electricity saving potential. The contribution of this study is the proposed data-driven framework, which provides facility operators with reliable tools to accurately quantify saving potential of buildings. The conducted case study using the framework on 19 test buildings showed that facility operators could avoid unnecessary penalties by eliminating them to sign up for unrealistic targets, and help them to gain the most value out of the DR programs by knowing the true potential of their buildings.

Keywords –

Facility Management; Demand Response; Electricity Saving Potential; Data-driven; Decision Trees; Ada Boost; Random Forest; Energy Efficiency

1 Introduction

The electricity demand in the U.S. is in incline [1], which increases the pressure on power grids; hence the chance of electricity blackouts. In New York and California, electricity blackouts caused billions of dollars of loss to businesses and individuals [2][3]. Demand response (DR), one of the demand side management (DSM) techniques, is able to provide the necessary flexibility to the grid by incentivizing end-consumers to reduce their electricity demand during certain periods such as peak and emergency situations [4]. Meanwhile, building sector accounted for 74% of the total electricity consumption in 2016 [5], making buildings significant candidates for DR programs. In New York, buildings that were enrolled in DR programs managed to provide more than 31K MW/year of load curtailment and millions of benefits in recent years [6][7]. Hence, maximizing energy saving potential in buildings for DR is essential for peak reduction and energy savings.

The saving potential of a building (i.e., DR enrollment) refers to the amount of electricity that the building can save during a DR event. The problem in the current practice is that this potential is usually calculated based on simplified information such as design specifications of equipment in the building or historical metering data, resulting in the loss of opportunities to know the true energy-saving capacity of buildings. In the current practice, end-consumers usually work with third aggregators to determine the saving potential during DR events and customize their DR protocols. DR protocols are instructional statements for building operators to follow to operate major equipment in that building. For buildings which participated in DR program earlier, a yearly assessment is conducted by DR engineers and they will simply increase or decrease the DR enrollment by comparing the average performance on savings for events that happened in that year with the previous DR enrollments [30].

Buildings and the operation procedures are inherently much more complex than the simplified calculation due to their interconnections among their diverse systems [10]. Therefore, using the simplified calculation to estimate the energy saving potential can result in over or underestimation of the DR enrollment of buildings. Such performance issues were observed in the case-buildings analyzed for this study, as shown in Figure 1. The graph on the left indicates that *Building A* did not meet the DR enrollment (determined using the design information), which results in penalties for the end-consumer for exceeding the consumption beyond the enrollment value. The figure on the right illustrates that *Building B* saved more electricity during the event than the DR enrollment value, which indicates the potential money left on the table for the facility for not enrolling in more. Partly the problem was due to the lack of consideration of the context of the building during the event time such as different baseline values (i.e., the amount of the electricity that a building usually consumes under the same condition without DR operation), weather condition, and event time. These and similar examples from the literature [30] show that calculating saving potentials in DR programs simply using average benchmarking values from generic design specifications and not taking into account the context around event times result in a loss for building owners in either way. Hence, facility operators and third aggregators are in need of tools to accurately estimate the true potential of buildings by relying on integrated information including protocols, historical energy performance data, and contextual data around the event times (e.g., baseline values corresponding to the event times, weather data, etc.).

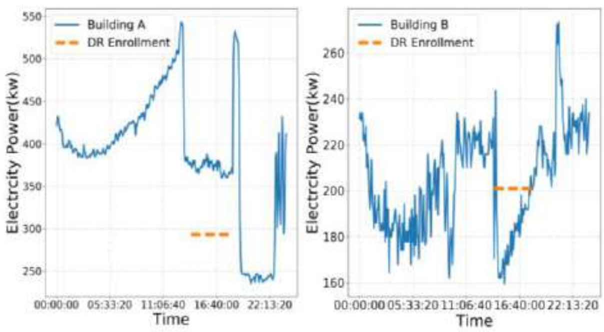

Figure 1. Performance of two buildings (Building A on the left, Building B on the right) during a peak event as compared to the DR enrollment (also marks the time range that an event occurred on the horizontal scale)

The objective of this paper is to quantify the true saving potential of buildings during DR events by integrated analysis of historical electricity consumption data, weather condition, DR protocol statements, and DR profiles (which provide information about DR event times, electricity consumption baselines, and DR enrolment values for buildings). Information from DR protocols can provide insights about buildings and equipment, and the electricity meter provides historical electricity consumption of buildings operated as the DR protocol instructions. In addition, the authors included weather condition information as it plays a crucial role in DR events and electricity consumption of buildings. A framework was developed by the authors for the stated objective, which is composed of two major modules: DR-dataset pre-processing and saving potential estimation. The details of the framework are presented in Section 3. The framework has been evaluated using data and protocols from nineteen buildings and six DR events that occurred in 2016.

The paper is structured as follows. A comprehensive review of the previous efforts on quantifying the saving potential of buildings in the literature has been provided in Section 2. In Section 3, the authors overview the framework and present the criteria to evaluate it. The implementation of the framework on nineteen buildings along with the results is discussed in Section 4. Section 4 also provides discussions on the challenges and future work. Conclusions are presented in Section 5.

2 Literature Review

There are three general types of models that have been used in previous studies to quantify electricity consumption and DR electricity saving potential: physical, statistical and simulation, and hybrid models [10]. Studies that developed physical models use equations and physics laws to predict saving potentials [8][9][18][19]. A large group of previous research studies concentrates on heating, ventilating, and air conditioning (HVAC) systems due to the fact that they account more than half of the energy consumption in buildings. Some of these studies developed simplified equivalent thermal parameters model to simulate saving potential for HVAC systems by adjusting the set-points [19-21]. While other studies implemented physical-statistical models to simulate the impact of adjusting parameters of HVAC systems on electricity consumption, which can further inform about the saving potential of HVAC systems during DR events [10][20][22][29]. Instead of using only HVAC system models, researchers also implemented physical models that include other systems that utilize electricity such as lighting, refrigerating, and appliances, and then quantified the saving potential by simulations of the testbeds [23][25]. These studies provide valuable insights of physical mechanism and potential knowledge. However, they usually are limited to the simplification of model equations and lack of consideration of the stochastic behaviors that happen in buildings- resulting in poor performance [10].

Statistical models, on the contrary, are developed based on experimental data. Large national level datasets of building energy use have been studied to identify the energy saving potential by comparing energy usage and data-driven saving analysis [26][27], yet the results from these studies are often in a very coarse-resolution, which cannot help DR engineers when determining the saving potential of a building for upcoming DR events. Researchers also compared the performance of both physical and simple statistical models for forecasting energy consumption in residential buildings as hybrid models and concluded that they both work with the slightly better performance than the statistical model (artificial neural network) [28]. Other than studies that emphasize the use of overall electricity consumption, load profiles of major household appliances were also utilized to identify their saving potential [24]. Despite the achievement of good results these models had in predictive modeling, they are often limited in the scope of certain purpose they aimed at in a restricted number of buildings/systems due to their inherent computational complexity [10].

This study is motivated by the need for accurately estimating the saving potential of different buildings during DR events. The framework developed in this study aimed at estimating the generic building-level saving potential instead of system-level saving potential by integrating the whole building energy consumption data, DR protocols, and contextual data around event times. This study differs from the studies in literature by providing a way to take into account contextual datasets that relate to DR assessment and analyze them in an integrated way using state of the art data-driven approaches.

3 Research Approach

3.1 Overview

The framework contains two main modules, which identify and extract the attributes to train the models, integrate datasets, and then fit models to estimate the electricity saving potential of buildings. The input of the DR dataset pre-processing is the DR protocol statements along with the building type, and a set of attributes for each building are extracted by the authors manually. Then, the extracted DR attributes dataset is integrated with other datasets from different sources, such as weather condition dataset, electricity meter dataset, and DR profiles (event time, electricity consumption baseline, DR enrollment). The second module, saving potential estimation, takes the integrated attributes dataset as input to fit machine learning models to estimate the electricity saving potential of buildings and provides the best performing model as a decision-making solution for facility operators for determining the true saving potential of buildings.

3.2 DR Dataset Pre-processing

In this study, the authors examined the DR protocols for a group of buildings to extract related attribute-pairs along with a building attribute: Building_type. The authors first categorized actions based on the equipment types and recorded the quantity of the impacted areas and equipment types. Details of this study are provided in a recent publication [11]. As stated in [11], DR protocols for buildings include five types of equipment: HVAC units (e.g., Air handling, fan coil, fan power units), fans, lights, elevators, and appliances. In this study, appliances are excluded because of its high dependence on occupancy data and lack of access to data on occupancy in spaces. For HVAC units, fans, and lights, the quantity of each equipment along with affected areas were extracted. Therefore, the data on attribute-pairs included: equipment_action and equipment_quantity for each equipment type.

The next step was to link the extracted data to the rest of the datasets. The weather information during the DR events is acquired from weather underground API [12], and the weather attributes included weather condition, temperature, humidity, and wind speed. The data on the DR profile of buildings included the electricity consumption baselines, the enrollment values and event times. More details of the datasets and the merging keys are provided in Section 4.2.

3.3 Saving Potential Estimation

3.3.1 Saving Potential Estimation Methodologies

In this module, the authors fitted several machine learning models to estimate the electricity saving potential of buildings. Because of the relatively small sample size and discrete categorical attributes in the studied problem, the authors chose decision tree regression model along with several boosting methods. There are mainly three types of decision trees: classification and regression trees (CART), C4.5, and C5.0 [13]. Among these decision trees, the CART is very similar to C4.5, yet it supports both categorical and continuous variables. Therefore CART is chosen to fit the dataset and estimate the electricity saving potential in this study. Furthermore, the authors used boosting algorithms such as Ada Boost and Random Forest to improve the performance of decision tree regression models. Both of the algorithms build multiple decision trees through iterations and take the average of the predicted value. Ada Boost is short for adaptive boost, which iterates the training process to build multiple decision trees and modifies the training data during each iteration and gives higher weight to the poorly modeled part [14]. Random forest algorithm, in addition to randomly selecting segmentations of the training data with replacement using the bootstrap method, also randomly selects the attributes when fitting the model.

3.3.2 Model Selection Criteria

One of the major advantages of the decision tree algorithm is that it is easier to interpret the result and can provide logic statements of the model [13][15]. However, it is also very easy to get over-fitted. In this study, the authors used four criteria, bias^2, variance, mean square error, and R^2, together to prune the model to avoid both over-fitting and under-fitting and meanwhile, aiming for adequately good prediction performance. Denoting N as the sample size of the training data, $\{f(1), f(2), \ldots, f(N)\}$ are the predicted values over the training data. The expected predicted value of the fitted model $f(x)$ is shown with $\overline{f(x)}$ (see Equation 1). Bias^2 captures the systematic error of the model (see Equation 2) [16]. When a model has a big bias^2 value, it indicates that the model is under-fitted, whereas big variance indicates the model is over fitted (see Equation 3).

$$\overline{f(x)} = 1/N \sum_{x=1}^{N} f(x) \quad (1)$$

$$Bias^2\left(f(x)\right) = \left(\overline{f(x)} - f(x)\right)^2 \quad (2)$$

$$Variance\left(f(x)\right) = E\left[\left(\overline{f(x)} - f(x)\right)^2\right] \quad (3)$$

The mean squared error (MSE) is composed of Bias^2 and Variance (see Equation 4), and measures the average squares of the errors, where Y denotes the observed data. Meanwhile, R^2 captures the capability of the model in explaining the observed data (see Equation 5).

$$MSE = 1/N \sum_{i=1}^{N} (f(i) - Y_i)^2 \quad (4)$$

$$R^2 = 1 - \left(\sum_{i=1}^{N} (f(i) - Y_i)^2 \Big/ \sum_{i=1}^{N} (Y_i - \bar{Y})^2 \right) \quad (5)$$

In Figure 2, the simplified relationship between variance, bias^2, and mean square error is demonstrated. As the complexity of the model increases, the Bias^2 decreases while the variance increases. There is an optimal point in the middle, where the variance meets with the Bias^2, and the mean square error is the lowest.

In this study, the authors visualized all four criteria to prune the models. For decision tree models, the authors iterated the depth of the tree from 1 to 10 to fit the models. For AdaBoost and Random Forest models, two parameters were included to iterate, the depth of the tree and the number of the tree estimators, both from 1 to 10. The optimal choice of the parameters was determined by the authors by visualizing the criteria, and the parameters with a lower bias, variance, MSE and higher R^2 were chosen. At last, the optimal models for each model were fitted and evaluated based on the average R^2 value among the cross-validation of the complete dataset.

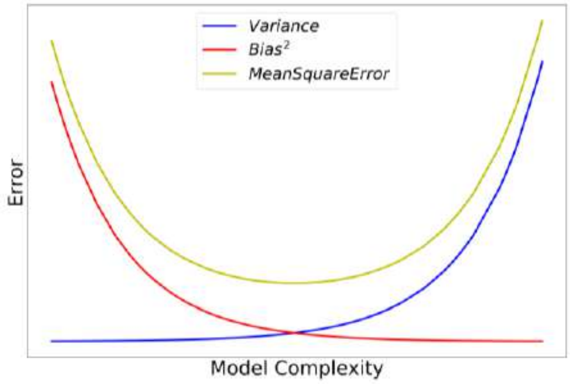

Figure 2. Simplified relationship between Bias^2, Variance, and MSE

4 Implementation of the Framework on a Case Study

4.1 Overview

The framework was tested on a case study of 19 campus buildings (including offices, academic buildings, and dorms) that participated in DR programs in 2016. There were six events that happened in 2016. During the events, data such as weather and electricity meter data was collected from different sources to quantify the saving potential of the buildings.

4.2 DR Dataset Pre-processing

The authors examined the 116 DR protocol statements for nineteen buildings manually to extract the DR attribute-pairs to fit the models. Table 1 listed three examples of the extracted attribute-pairs. As shown in Table 1, there are eight attributes identified from the protocol statements. However, not every protocol

Table 1. Three Examples of the Attribute-Pairs Extracted from the DR Protocols

Building ID	Building_ type	HVAC_ action	HVAC_ quantity	Light_ action	Light_ quantity	Fan_ action	Fan_ quantity	Elevator_ quantity
Building1	Office	Shut Off	4	Shut Off	5	Reduce Power	40%	1
Building2	Dorm	Shut Off	1	Shut Off	27	Shut Off	5	1
Building3	Office	Reduce Power	40%	Shut Off	4	None	-1	2

includes all the attributes, and such cases were reflected as none in the dataset. For example, the DR protocol for Building 3 in Table 1 does not contain any instruction for Fans. Therefore, the authors put 'None' as the Fan_action and '-1' as the Fan_quantity.

In addition to the attribute-pairs extracted from the DR protocol statements, the authors also collected the weather condition data, DR profile data, and electricity meter data during the event (based on event times from DR profiles). The description of all the datasets is shown in Table 2. The datasets are integrated with each other by merging keys. For example, the DR attribute-pairs were merged to the DR profiles by linking the dataset based on the building ID. The integrated dataset was pre-processed using forward filling method, which means that the missing value is filled with the nearest previous data.

Table 2. Description of the Datasets

Datasets	Variables	Merging Key
DR Attributes Pairs	Building_type, HVAC_action, HVAC_attribute, Light_action, Light_attribute, Fan_action, Fan_attribute, Elevator_attribute	Building ID
Weather Data	Weather Condition, Temperature, Humidity, Wind Speed	Date-time
DR Profiles	Baseline, Enrollment	Building ID
Electricity Meter Data	Electricity Consumption	Date-time; Building ID

4.3 Quantifying Saving Potential in Buildings

4.3.1 Decision Tree

With the integrated dataset from the previous section, the authors fitted the decision tree models and pruned it by iterating the depth of the trees from 1 to 10. Figure 4 demonstrates the results of the MSE, R^2, Variance, and Bias^2 of the decision trees with different depths. As shown in Figure 3, MSE and Bias^2 decrease when the depth of the tree increases, whereas R^2 and Variance increase when the depth of the tree increases. When the depth of the tree is four, Bias drops drastically with relatively low variance and MSE, and with a fairly good R^2. Therefore, the depth of the decision tree is determined as four, meaning that in this case, the model can provide sufficient capability in estimating the saving potential and not suffering over-fitting and under-fitting issues.

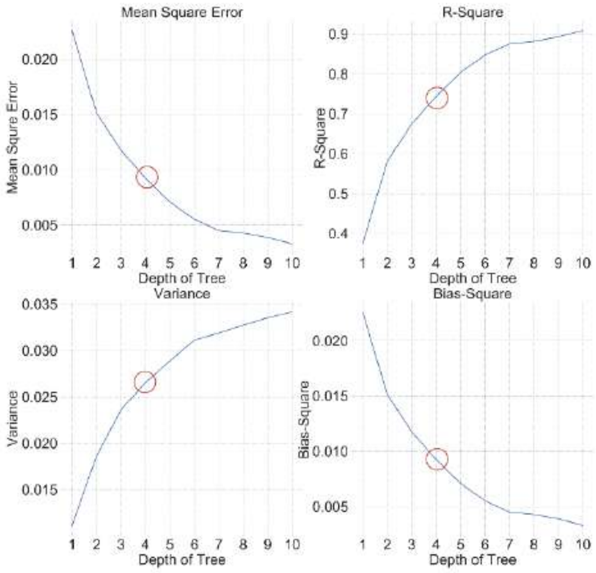

Figure 3. Comparison of MSE, R^2, Variance, and Bias^2 of the Decision Trees with Different Depth of the Trees

4.3.2 Ada Boosting

To improve the performance, the authors implemented Ada Boosting decision trees and pruned the parameters by iterating both the depth of the trees and number of the tree estimators from 1 to 10. The heat map of the four criteria is shown in Figure 4 with blue indicating a small value and red indicating a large value. As shown in Figure 2 and Figure 4, variance and bias^2 are negatively correlated. Hence the boxes with the color in middle range of the sidebar are selected as candidates. Furthermore, among the candidate boxes, the authors chose the parameters based on the R^2 and Occam's razor law, which means that the square with a higher R^2 and less depth of tree and number of estimators will be chosen.

Figure 4 shows that when the depth of the tree is equal to five and the number of tree estimators is four, the MSE, variance, and bias^2 are smaller than the surrounding cells (meaning that the model is better fitted than the surrounding models), along with a relatively high R^2 (meaning that the model is capable of estimating the saving potential of the buildings). Therefore, the pruning process of Ada Boosting results in five as the depth of the tree and four as the number of estimators.

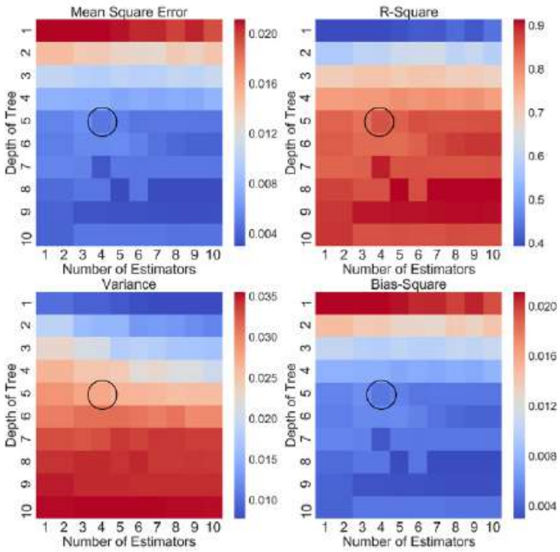

Figure 4. Heat map of MSE, R^2, Variance, and Bias^2 of the Ada Boost of Decision Trees with Different Depth of the Trees and Number of Estimator Trees

4.3.3 Random Forest

In addition to modifying the training sample to improve the performance, random forest fits the trees with different attributes from the integrated training dataset as well. The parameters for the random forest is the same as Ada boosting, the depth of the tree, and the number of tree estimators, and the best parameters are chosen based on the same process as Ada boosting as well. Figure 5 shows the heat map when pruning the random forest models. When the depth of the tree is six, and the number of tree estimators is four, the bias^2, variance, and MSE are all fairly small with a high R^2. Therefore, the best parameters for the random forest model, in this case, are six as the depth of tree and four as the number of estimators.

4.3.4 Comparison of the Models

The authors tested all the pruned models on the datasets using 20 folds cross-validation, which will randomly pick 70% of the data as the training sample to fit the model and 30% of the data as the testing sample to evaluate the performance for 20 times. The pruned parameters and average R^2 from the cross-validation are shown in Table 3. As shown in Table 3, random forest with six as the depth of the tree and four as the number of tree estimators has the best performance in explaining the DR dataset and resulting 0.862 as the R^2, which indicates that the framework has better capability of estimating the true saving potential of the buildings in different types and scales.

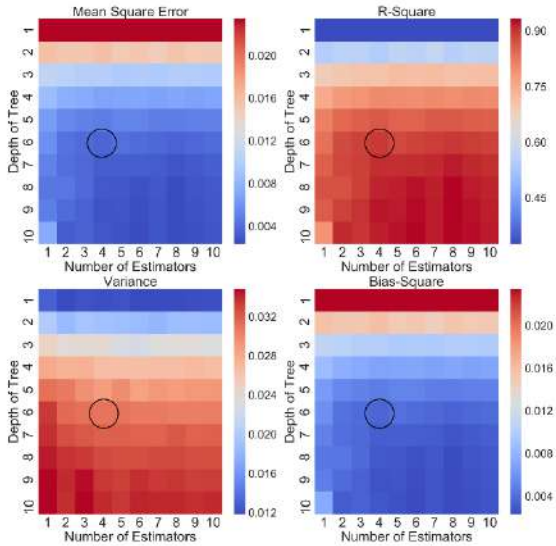

Figure 5. Heat map of MSE, R^2, Variance, and Bias^2 of the Random Forest of Decision Trees with Different Depth of the Trees and Number of Estimator Trees

The comparisons between the estimated electricity saving potential from the random forest model, the enrollment value of the buildings, and the actual curtailment during the DR events are shown in Figure 6. In Figure 6, X-axis represents the actual curtailment (percentage of the baseline) of the buildings, and Y-axis represents the estimated electricity saving potential (percentage of the baseline) during the events (predicted by random forest model or the enrollment value from the DR profile).

Table 3. Parameter and Performance of the Models

Model	Depth of Tree	Number of Trees	R^2
Decision Tree	4	-	0.743
Ada Boosting	5	4	0.828
Random Forest	6	4	0.862

The diagonal black line indicates the case when the actual curtailment is equal to the calculated electricity saving potential. The red dots illustrate the enrollment value from the DR profiles versus the actual curtailment, and the blue dots illustrate the estimated saving potential from the random forest model with respect to the actual curtailment. For the red dots, almost half of them indicates that the enrollment value is smaller than the actual curtailment during the events (the red dots that are at the right of the black line), which indicates over-performance of the buildings (i.e., facility operators signed up for a small enrollment value and resulting in saving more electricity) while half of them indicates that the enrollment value is larger than the actual curtailment (the red dots that are at the left of the black line), which indicates under-performance of the buildings (i.e., facility operators signed up for a large enrollment value and resulting in penalties due to less electricity saving). Meanwhile, the blue dots distribute closely around the black line, which demonstrates the capability of the framework for estimating the electricity saving potential for the studied campus buildings. These cases illustrated the potential of the framework in estimating the saving potential of buildings. By enlarging the training set and including more cases, the framework can have a more promising performance over a group of buildings that share common characteristics.

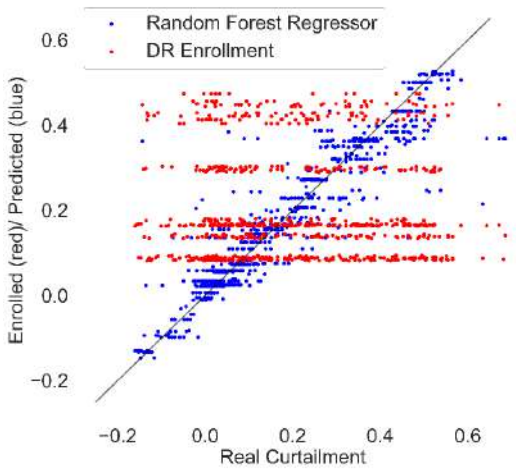

Figure 6. Comparison of MSE, R^2, Variance, and Bias of the Decision Trees with Different Depth of the Tree

4.4 Challenges and Future Work

When implementing the framework on the DR datasets, the authors faced multiple challenges. Firstly, DR protocol statements were not explicitly written, which result in inaccuracy and difficulties when estimating the electricity saving potential of buildings. For example, when a DR protocol statement instructs the facility managers to shut down the AHUs in common areas, it is hard to quantify the saving potential since the quantity of involved equipment remains vague. Secondly, occupancy status in buildings plays an essential role impacting the electricity consumption, which gives inherent complexity in predicting the electricity consumption. Furthermore, occupancy data is rarely available in buildings, and the available occupancy data usually contains a large amount of noise. These situations lead to difficulties when estimating the electricity saving potential considering the uncertainty of the occupancy status.

For future work, the authors plan to include more data to improve the performance of the framework presented in this study. In addition to extracting coarse building and equipment information from DR protocols, the authors intend to include Building Information Models (BIMs) to provide building and equipment configuration information to reduce the vagueness in DR protocol statements. Furthermore, the authors aim to collect DR related equipment sensor readings from building automation systems, which will provide much more details about the equipment behaviors during event times.

5 Conclusion

In this study, the authors presented a data-driven framework to estimate the electricity saving potential of buildings. The framework developed in this study fills the gap in the previous studies by providing a granular building-level data-driven approach to estimate the electricity saving potential for buildings by integrating various data sources containing data for DR events. By implementing the framework on 19 campus buildings that vary in type and scale, the authors demonstrated the capability of it in estimating the saving potential of buildings during DR events. The results from the case study indicate that the building owners and facility operators can benefit from the accurately determined saving potential by avoiding penalties and making the most out of the DR programs. The framework is extensible by integrating more equipment sensor data from BAS and BIM in the future to further improvement of the performance.

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Gaussian Markov Random Fields for Localizing Reinforcing Bars in Concrete Infrastructure

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Abstract -

Sensor technologies play a significant role in monitoring the health conditions of urban sewer assets. Currently, the concrete sewer systems are undergoing corrosion due to bacterial activities on the concrete surfaces. Therefore, water utilities use predictive models to estimate the corrosion by using observations such as relative humidity or surface moisture conditions. Surface moisture conditions can be estimated by electrical resistivity based moisture sensing. However, the measurements of such sensors are influenced by the proximal presence of reinforcing bars. To mitigate such effects, the moisture sensor needs to be optimally oriented on the concrete surface. This paper focuses on developing a machine learning model for localizing the reinforcing bars inside the concrete through non-invasive measurements. This work utilizes a resistivity meter that works based on the Wenner technique to obtain electrical measurements on the concrete sample by taking measurements at different angles. Then, the measured data is fed to a Gaussian Markov Random Fields based spatial prediction model. The spatial prediction outcome of the proposed model demonstrated the feasibility of localizing the reinforcing bars with reasonable accuracy for the measurements taken at different angles. This information is vital for decision-making while deploying the moisture sensors in sewer systems.

Keywords -

Concrete sewer; Electrical resistivity; Gaussian Markov Random Fields; Localizing; Non-invasive; Reinforcing bars; Spatial prediction; Wenner technique.

1 Introduction

Recently, robotic systems are largely viewed by scientists as a promising tool to navigate, explore and measure environmental health of hostile areas [1]. One such area is an urban sewer system, where long-term direct human exposure can cause occupational health hazards [2]. Exploiting robotic inspections in such infrastructures not only requires hi-tech robots but also advanced sensing technologies in order to provide credible information about the sewer assets. In this context, this work focuses on utilizing the sensor data and provide meaningful information for pertinent decision-making.

The underground sewer pipes are deteriorating mainly due to microbial induced concrete corrosion [3, 4]. This raises concerns among water utilities around the globe as the sewer asset rehabilitation costs are at an estimated annual value of over $100 millions [5, 6]. Presently, water utilities use data-driven machine learning models for estimating corrosion [7]. In such models, surface moisture conditions of the concrete sewers can be used as an observation for improved prediction [8, 9]. So, a new robust sensing technology was developed by us in collaboration with four water utilities in Australia. This technology estimates surface moisture levels based on non-invasive electrical resistivity measurements.

The technology was deployed and tested in a sewer pipe belonging to Sydney Water in Sydney, Australia. This evaluation demonstrated sensing feasibility under aggressive sewer conditions and capabilities for long-term moisture monitoring operations. However, the sensor measurements can be influenced by the reinforcing bars (rebars) inside the concrete and hence requiring onsite calibration. Therefore, the research problem is to determine the location and orientation of rebar embedded in concrete by using the same sensor rather than having to rely on expensive sensors such as ground penetratin radars. This allows appropriate localization of sensor installations to improve the reliability of moisture estimations.

In this paper, we propose a discretely indexed Gaussian Markov Random Fields (GMRFs) based data-driven machine learning model for spatially localizing the rebar embedded in concrete using electrical resistivity measurements. The proposed machine learning method is a computationally efficient alternative to the non-parametric Gaussian Process (GP) based models. In this work, we employ resistivity meter to perform non-invasive measurements of electrical resistivity variation on the concrete sample by utilizing four probe Wenner technique. The measurements were taken at different spatial location of the concrete sample by placing the resistivity meter on the concrete surface at different angles with respect to the rebar. Then, the measured data obtained from each angle is fed to the

GMRF model for experimental investigations.

The remainder of the paper is structured as follows: Section 2 elucidates the sensing technique and procedures followed for data collection. Section 3 formulates the theoretical considerations for spatial prediction. Section 4 presents the experimental results with analysis. Section 5 discusses the limitations of the work. Finally, Section 6 concludes the proposed work with future prospects.

2 Electrical Resistivity Measurements

An electrical resistivity meter was developed in the laboratory to measure surface electrical resistivity variations on the concrete. This device performs non-invasive measurements based on the Wenner technique [10], which uses four electrodes with an equal spacing distance between them. The two outer electrodes inject electrical current into the concrete material whereas the two inner electrodes measure the electrical potential differences. Then, the electrical resistivity of the concrete on the surface of interest can be determined by using Equation 1:

$$\rho = 2\pi a\Big(\frac{V}{I}\Big) \tag{1}$$

where ρ is the electrical resistivity of the concrete denoted in terms of kΩcm, $a = 40$mm is the spacing between the two electrodes, V is the electrical voltage signal measured by the inner two electrodes and I is the electrical current injected by the outer two electrodes.

The developed device is compact and works on the open-source electronic prototyping platform (Arduino Nano). It was evaluated on the benchmark scale and it produced measurements as desired. More information on the development of this resistivity meter is available in [11].

A concrete of thickness: 10 cm, width: 35 cm and length: 35 cm was made with a rebar having width: 1.2 cm, height: 1.2 cm and length: 30 cm was embedded into the concrete material at a 2 cm depth from the top surface of the concrete. This concrete was divided into several cells to perform measurements in those cells. Totally, the concrete was partitioned into 49 cells and each cell had a dimension of 4cm^2. The rebar runs through the column 4 of the (7×7) partitions. Electrical resistivity measurements in each cell were obtained by placing the inner two electrodes of the sensor at different angles. For each angle, two sets of data were taken in each cell.

3 Modelling for Spatial Prediction

3.1 Gaussian Markov Random Fields

GMRFs are a discretely indexed Gaussian Fields, which can be achieved through the observations of random variables in the spatial process [12]. It incorporates Gaussian Processes and also satisfies Markovian property [13]. This makes GMRFs a computationally efficient alternative to GP [14].

Let $s = (s_1, s_2, s_3, ..., s_n)^T$ with $s \sim \mathcal{N}(\mu, Q^{-1})$ referring to GMRFs given by the mean μ and a symmetric and positive definite precision matrix Q that represents the convex polytope in $\mathbb{R}^d$ ($\mathbb{R}$ denotes real numbers), and an inverse of the GP covariance matrix, $\sum$ [12, 15]. So, the density of s will be of the mathematical form as given in Equation 2:

$$p(s) = (2\pi)^{-\frac{n}{2}}\Big(det(Q)\Big)^{\frac{1}{2}} exp\Bigg\{-\frac{1}{2}(s-\mu)^T Q(s-\mu)\Bigg\} \tag{2}$$

The salient feature of the Markovian property is that the full conditional distribution of s_i $(1 \le i \le n)$ is only dependent on the elements set of the neighbourhood structure of the process and it is given by Equation 3

$$p(s_i|s_{-i}) = p(s_i|s_{Ni}) \tag{3}$$

where s_{-i} represents the elements in s apart from the element s_i, and s_{Ni} denotes the neighbourhood elements of s_i. Therefore, it is established that in the case of given neighbourhood elements, s_i element is independent on all other elements in s with the exception of the element s_{Ni}, which defines the conditional independence as $s_i \perp s_{-i,Ni}|s_{Ni}$ ($\perp$ denotes the independence of two variables) for $1 \le i \le n$. According to [12], μ is not related to pairwise conditional independence properties of s and therefore, afore stated characteristic is limited to the precision matrix Q. Generally, if s_i and s_j are conditionally independent, $s_i \perp s_{-j}|s_{-i,j}$ is equivalent to $Q_{ij} = 0$. This condition give rise to $Q_{ij} \neq 0$ when $j \in \{i, N_i\}$ and deduce the sparsity of Q that results significantly in computation performance.

3.2 Spatial Field Model by way of GMRFs

Let the finite set of spatially observed locations be $\psi = (\psi_1^T, \psi_2^T, \psi_3^T, ..., \psi_n^T)^T$. Each spatially observed location in ψ comprise of one electrical resistivity measurement data and consider $x(\psi) = (x(\psi_1), x(\psi_2), x(\psi_3), ..., x(\psi_n))^T$ as the vector of measurements in the spatial field [12]. In this work, the model utilized is similar to [15, 14], which is a summation of a large scale component, a random field and an identically distributed noise. The model is mathematically defined in Equation 4:

$$x(\psi) = \zeta(\psi)\beta + s(\psi) + \epsilon(\psi) \tag{4}$$

where $\zeta(\psi)\beta = \mathbb{E}(x(\psi))$ is the expectation of $(x(\psi))$ and $\mathbb{E}(\cdot)$ defines the expectation operator. $\zeta(\psi)$ is the covariates determined at spatial location ψ and β is the vector of mean parameters. s is a GMRFs with a n zero mean vector and a $n \times n$ precision matrix Q. $\epsilon(\psi)$ is the measurement noise with $\mu = 0$ and a known covariance matrix $\sigma_\epsilon^2 I_\epsilon$ at spatial locations ψ_i $(1 \leq i \leq n)$, where σ_ϵ^2 is assumed to be known and I_ϵ is the identity matrix, $n \times n$.

As in [16], the GMRF can precisely work as a GP when the continuous domain stochastic partial differential equations (SPDE) possess a solution with Matern covariance function [12], which is mathematically given by Equation 5:

$$cov(\gamma) = \frac{\sigma^2}{\Gamma(v)2^{v-1}}(\kappa\gamma)^v K_v(\kappa\gamma) \tag{5}$$

where γ indicates the Euclidean distance between the spatial locations, $\gamma = \|v_i - v_j\|$. The term σ^2 denotes the marginal variance and the term κ implies spatial parameters with v as the Matern smoothness and K_v represents the modified Bessel function [12]. The term $\zeta(\psi)\beta$, in this case denotes the mean function in the context of GP [17, 18].

3.3 Sensor Data Modelled by GMRFs Using SPDE Approach

The SPDE approach formulated by [19] demonstrates computational effectiveness while used in the spatial process. This approach incorporates finite element method [20] to focus the SPDE onto a basis representation, which includes piece-wise linear basis functions described by a triangulation that pertains to the interested regions [12]. Assuming that the spatial process $s(p)$ is observed at N locations where $p = (p_1^T, p_2^T, p_3^T, ..., p_n^T)^T$, then the initial vertices of the triangle are set at those spatial locations. Further, in order to achieve spatial prediction, more vertices of the triangles are added to realize a large triangulation.

The GMRF model is developed on the basis function representation for the given triangulation of the domain Q [12]. Therefore, $s(p)$ is given as in Equation 6:

$$s(p) = \sum_{i=1}^{n} f_i(p) w_i \tag{6}$$

where $\{f_i(p)\}$ denotes the basis functions that are piece-wise linear on each triangle [12]. In the i^{th} vertex of the mesh, $f_i(p)$ of the functions $\{f_i(p)\}$ is 1, and 0 for all other vertices. The term $\{w_i\}$ denotes the Gaussian distributed weight. At each triangle vertex i, the value of the spatial field is given by $\{w_i\}$ [12]. Thus, the SPDE approach incorporating finite element method establishes the link between the GP and GMRFs with feasible computation efficacy. The precision matrix Q of size $n \times n$ is determined by computing the Equation 7:

$$Q = \tau^2(\kappa^4 D + 2\kappa^2 H + HD^{-1}H) \tag{7}$$

where τ controls the variance, D and H are the $n \times n$ matrices with $D_{ij} = \langle f_i, f_j \rangle$ and $H_{ij} = \langle \Delta f_i, \Delta f_j \rangle$.

The total number of triangulation vertices defines the dimension of Q in the region of interest. Thus, Q can be seen as a function of κ and τ. Lets define the hyper-parameter vector as $\Phi = (\log(\tau), \log(\kappa))$. Now, it can be said that the sparse property of Q is embraced by the GMRFs representation built by the linear basis functions. The inherent random field at the n vertices of the triangulation is defined by GMRFs with μ as

$$s|\Phi \sim \mathcal{N}(\mu, Q^{-1}) \tag{8}$$

In the interest of mapping between the basis function representation located at n vertex of the triangulation and random field at resistivity meter locations having N dimension, let us consider the projector matrix as B, whose size is $N \times n$. B projects the modelled inherent random field at the vertices of the triangulation to the data locations.

In reference to the spatial field model presented in the preceding section, the measurements at N locations of the spatial field can be given by Equation 9:

$$x|s, \Phi, \beta, \sigma_\epsilon^2 \sim \mathcal{N}(\zeta(p)\beta + Bs, \sigma_\epsilon^2 I_N) \tag{9}$$

where $\zeta(p)$ refers to $N \times q$ matrix of covariates, β and Φ are the estimated parameters of the maximum likelihood approach [18], I_N refers the identity matrix $N \times N$.

If all the model parameters are learned, the joint distributions of x and s are calculated by adopting the technique in [21, 12], which is given by Equation 10:

$$s|x, \Phi, \beta, \sigma_\epsilon^2, B \sim \mathcal{N}\left(\begin{bmatrix} 0 \\ \zeta(p)\beta \end{bmatrix}, \begin{bmatrix} Q^{-1} & Q^{-1}B^T \\ B^T Q^{-1} & \sigma_\epsilon^2 I + BQ^{-1}B^T \end{bmatrix} \right) \tag{10}$$

The full conditional distribution of s given by x is also Gaussian with respect to probabilistic theory [12]. By using block-wise inversion approach [22] and the Schur complement, the Gaussian expressed in Equation 10 can be mathematically written as in Equation 11:

$$s|x, \Phi, \beta, \sigma_\epsilon^2, B \sim \mathcal{N}\left(\mu_{s|x}, Q_{s|x}^{-1}\right) \tag{11}$$

where $\mu_{s|x}$ denotes the vector of posterior means and the term $Q_{s|x}$ denotes the posterior Q. They are given as follows:

$$\mu_{s|x} = \zeta(\psi)\beta + Q_{s|x}^{-1}(\sigma_\epsilon^2 I_N)^{-1}(x - \zeta(p)\beta) \tag{12}$$

$$Q_{s|x} = Q + B^T(\sigma_\epsilon^2 I_N)^{-1}B \tag{13}$$

Equation 12 factorizes the sparse matrix $Q_{s|x}$. However, $Q_{s|x}$ is not dependent on the collection of sensor measurements [15, 12].

4 Experimental Results

4.1 GMRFs Spatial Prediction Performance

This section investigates the spatial prediction performance of the GMRFs model. In this regard, this evaluation was carried out by placing the resistivity meter at an angle 90° and three sets of data were taken in the 49 partitions. Among the 49 partitions, 20 were used for training the GMRFs model and 29 were used for testing. The spatial prediction results for the three different datasets are shown in Figure 1, Figure 2 and Figure 3.

In order to evaluate the spatial prediction performance efficacy of the GMRFs model, Mean Absolute Error (MAE) and Root Mean Square Error (RMSE) were used as metrics, which was computed based on the data of measured values and the predicted values. Table 1 tabulates the computed metric values for the three different datasets, where it can be observed that the MAE and RMSE are reasonably low and therefore, the results indicate that the GMRFs model can be utilized for localizing the rebar.

4.2 GMRFs Spatial Predictions for Measurements Obtained from Different Angles

This section presents the results of the GMRFs predictions for localizing the rebar based on non-invasive

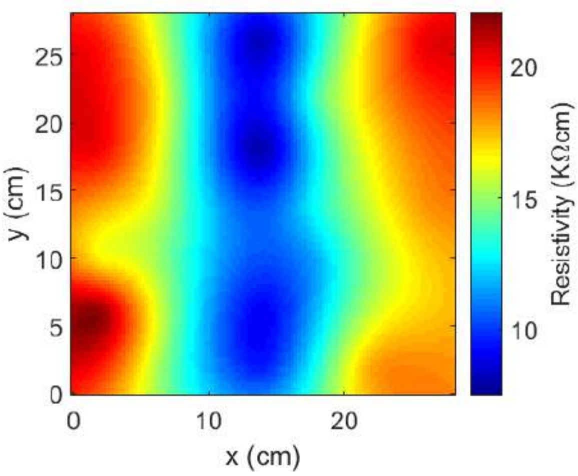

Figure 1. Dataset-1: Spatial prediction using GMRFs by taking resistivity measurements at 90°.

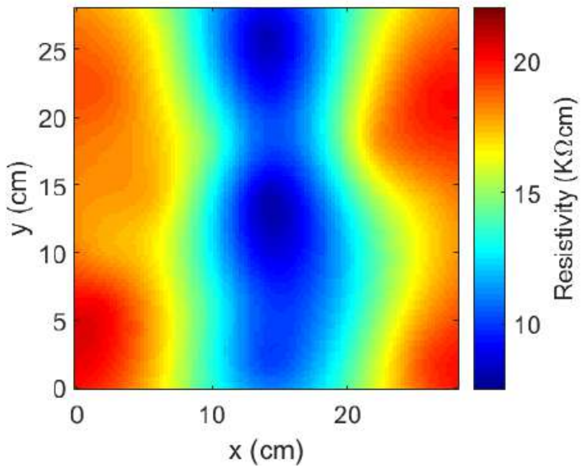

Figure 2. Dataset-2: Spatial prediction using GMRFs by taking resistivity measurements at 90°.

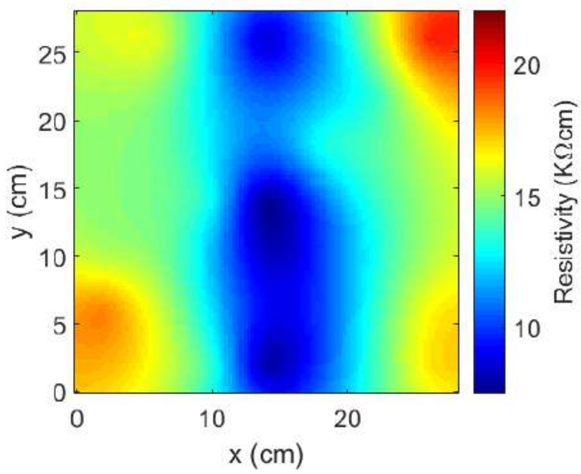

Figure 3. Dataset-3: Spatial prediction using GMRFs by taking resistivity measurements at 90°.

Table 1. GMRFs Spatial Prediction Performance

Datasets	MAE (kΩcm)	RMSE (kΩcm)
Dataset-1	0.50	1.69
Dataset-2	0.61	1.60
Dataset-3	0.28	1.37

electrical resistivity measurements. The measurements were taken by placing the resistivity meter at different angles such as 0°, 30°, 45°, 60° and 90°. The angle 0° is perpendicular to the rebar whereas the angle 90° is parallel to the rebar.

Figure 4 shows the spatial prediction for the measurements taken at an angle 0°, where it can be observed that area of low resistivity denotes the presence of rebar. Similarly, Figure 5 shows the spatial prediction for the measurements taken at an angle 30°, Figure 6 shows the spatial prediction for the measurements taken at an angle 45°, Figure 7 shows the spatial prediction for the measurements taken at an angle 60° and Figure 8 shows the spatial prediction for the measurements taken at an angle 90°.

From the figures showing the spatial prediction using GMRFs, the low resistivity area represents the influence of the rebar located inside the concrete. It can be said that the measurements taken at different angles such as 0°, 30°, 45°, 60° and 90° can be utilized to locate the rebar embedded in the concrete through GMRFs based spatial prediction model. This information of rebar placement can be used for optimal moisture sensor installations. However, it can be observed from the Figure 4 that the measurements taken at the angle 0° has less rebar influence compared to other angles.

5 Discussion

In the reported work, we performed electrical resistivity measurements on the concrete that has a rebar at 2 cm depth from the top concrete surface. In order to locate the rebar inside the concrete, whose rebar is placed at different depths lower than 2 cm, modifications need to be done in the sensing technique by changing the

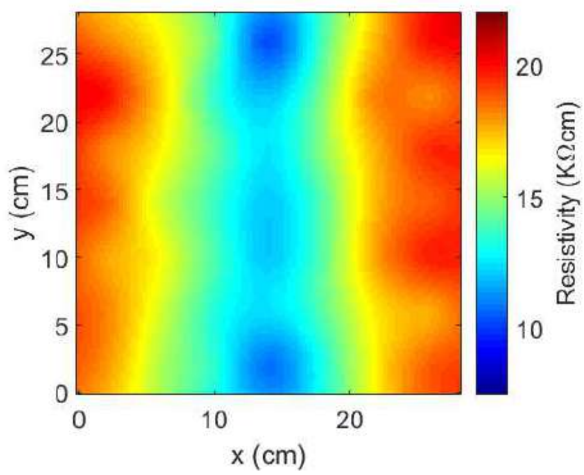

Figure 4. GMRFs prediction at 0° measurements.

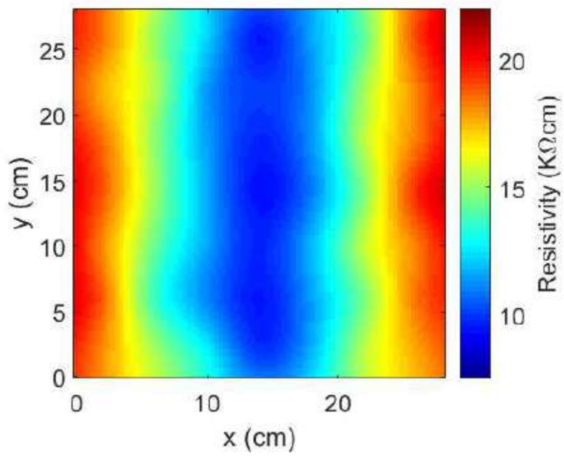

Figure 5. GMRFs prediction at 30° measurements.

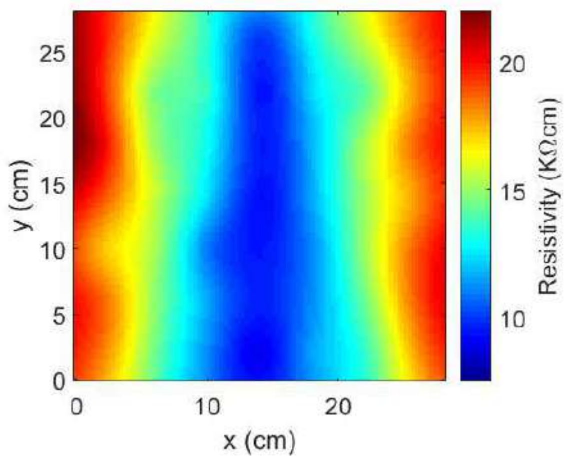

Figure 6. GMRFs prediction at 45° measurements.

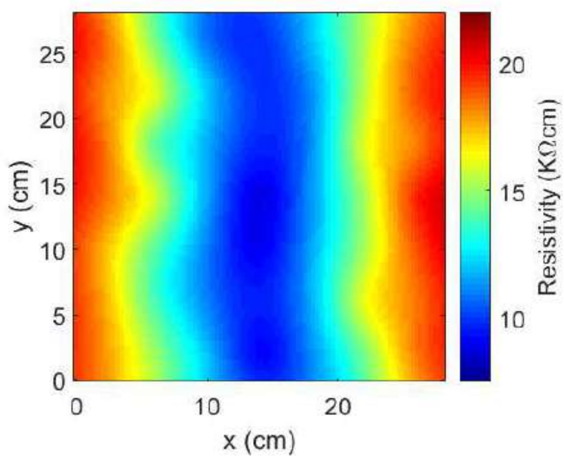

Figure 7. GMRFs prediction at 60° measurements.

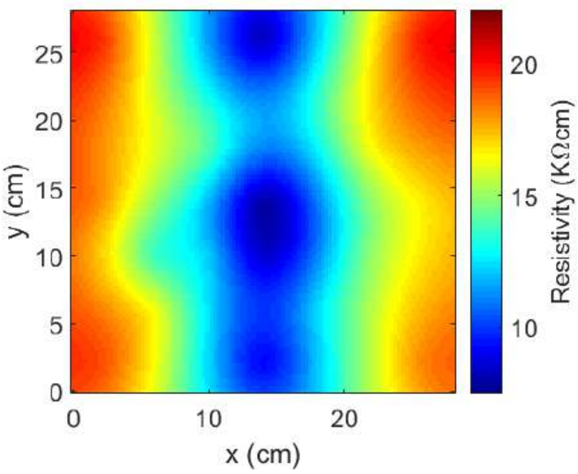

Figure 8. GMRFs prediction at 90° measurements.

operating frequency. Presently, the device used in this work is set to perform measurements with 40 Hertz. However, it is possible to change the frequency of the device based on the application. Also, the rebars that are located near the measuring surface of the concrete only has influence during moisture measurements for 40 Hertz. Higher the operating frequency higher is the penetration depth of electrical signals into the concrete.

With the operating frequency of 40 Hertz, given the unknown conditions of the rebar at sewer pipes, the electrical resistivity measurements taken at different angles through GMRFs spatial prediction model can shed light on the rebar location. Therefore, this information is vital to place the electrical resistivity meter for surface moisture estimation in sewer systems.

6 Conclusions

This paper proposed a machine learning model using GMRFs for localizing the rebar in concrete infrastructures. In this context, the work reported has led to the following three major contributions:

- We experimentally demonstrated that non-invasive electrical resistivity measurements based on Wenner technique has influence to the embedded rebar of the concrete and henceforth, the measured data can be utilized to determine the rebar location.

- The proposed GMRFs model for spatial prediction based on electrical resistivity measurements has produced satisfactory results and the statistical evaluation results computed from three different datasets demonstrate that the spatial prediction performance of the GMRF model is reasonably accurate and can be used for localizing the rebar.

- GMRFs spatial prediction based on the measurements at different angles such as 0°, 30°, 45°, 60° and 90° demonstrated that rebar can be identified irrespective of measurement angles. However, there was less influence of rebar when the measurements were taken perpendicular to the rebar.

Overall, the proposed work can improve the way surface moisture conditions are quantified inside the concrete sewer systems. In the future, the reported work will be extended to perform measurements on larger concrete having rebar meshes. Then, in-situ evaluation will be conducted within the Sydney based municipal sewer system. Eventually, the field results will be reported in the appropriate journal.

Acknowledgments

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Influence of Upper Body with Dual Arms on Posture Control of Independently Driven Quadruped Crawler Robot

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Abstract

Independently Driven Quadruped Crawler Robot(IDQCR) can rescue survivors rapidly in case of disaster situations. In order to prevent rollover, the IDQCR must level out the operator cabin to overcome rough terrain and do posture control when gripper is carrying heavy things of the robot. In this paper, we define a mathematical model based on differential kinematics for posture control and discuss the influence of the posture control to upper body of IDQCR on. In order to verify the proposed mathematical model, we simulated with DAFUL and MATLAB/Simulink, which can analyze dynamics.

Keywords –

Rollover; Influence of Upper Body; Independently Driven Quadruped Crawler; Posture Control; Disaster Response Robot; Wheel-legged System;

1 Introduction

Globally, occurrence frequencies of disasters such as conflagration and earthquake are increasing gradually [1]. When huge disasters occur, survivors are possibly under collapsed debris and rescue is not easy when a fire occurs. The existing survivor rescue systems needs plenty of rescue time because of various variables and additional collapse can make the situation worse[2].

For this reason, it is necessary to develop the robot for rescue and the robot must be able to travel on rough terrain. As a requirement of robots for the disaster, the ability to overcome the roughness, ease of operation and promptness must be satisfied.

Firstly, the ability to overcome obstacles allows four independent legs to freely pass obstacles by attaching a crawler that can easily overcome obstacles.

Secondly, the ease of operation is that the existing excavators have to control the four legs directly by the driver, but IDQCR is easy to control the joints and crawler speed of each leg automatically according to the terrain.

Thirdly, in the event of a disaster such as a large-scale earthquake or a fire, other heavy equipment or vehicles can't be operated properly due to collapsed debris, but the IDQCR can be quickly put into the field.

Various systems for safe operation for preventing rollover in the disaster environment have been proposed [3-6]. The DARPA Robotics Challenge, the symposium to perform missions in disaster situations, is being studied mainly in humanoid robots [7]. In addition, control methods for improving the driving systems of military robots have been studied, but research on the control techniques applied to the driving systems of large robots such as IDQCR has not been conducted [8].

Previous studies have concentrated on posture control considering only the lower body of the robot [9]. In this paper, we study the effect of the robot on the posture control by integrating the lower body and the upper body of the robot when overcoming the rough terrain. We propose a mathematical model for the posture control of the IDQCR driving system and verify the results by simulation considering the weight of the robot upper body. We entered the weight for each part of the upper body and tried to demonstrate the posture control by simulating the pose of stretching the two arms, which are the worst situation.

2 Introduction for Posture Control System of Disaster Response Robot

Fig. 1 shows the appearance of Independently Driven Quadruped Crawler Robot (IDQCR).

Four independent leg mechanisms can make the operator cabin horizontal when driving or working on rough terrain, with a crawler to easily overcome obstacles.

The legs mechanism independently drives the four hydraulic cylinders attached to the chassis to implement the up and down movements of the robot. The four hydraulic cylinders attached to the inside of the legs mechanism adjust the distance between the legs.

Fig. 2, the four hydraulic cylinders attached to the chassis are related to the driving system and show the relation with the posture control.

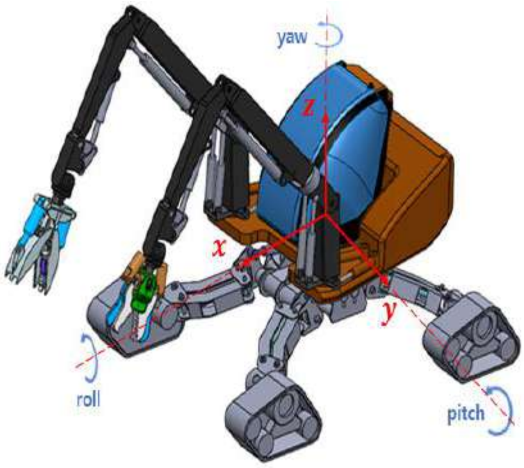

Figure 1. Independently Driven Quadruped Crawler Robot with integrated lower and upper body

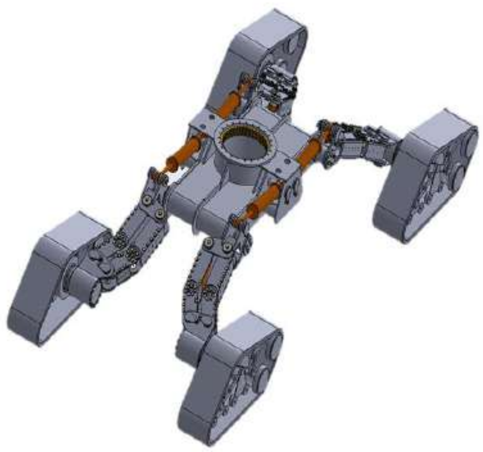

Figure 2. Independently Driven Quadruped Crawler system for posture control

The posture control of the driving system is related to up and down movement, roll and pitch motion of the robot. the posture control of the working system uses the four hydraulic cylinders inside the leg mechanism to expand the area of the support polygon [10].

The upper part of the robot consists of cabin, chassis, arm, 8 hydraulic cylinders and 2 grippers. The eight hydraulic cylinders are designed to have four degrees of freedom for each arm of IDQCR.

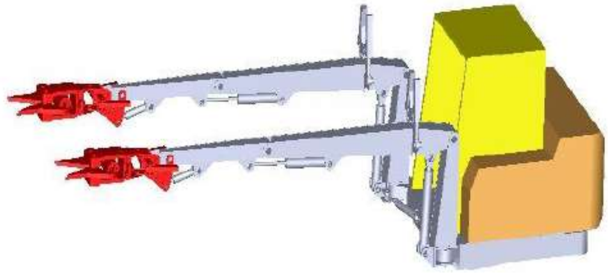

Figure 3. The worst posture of upper body posture of IDQCR

Fig. 3, the most worst posture of the upper body posture of IDQCR is the posture in which the two arms are stretched straight. If there is no rollover in that posture, there is no rollover.

3 Posture Control of Disaster Response Robot

3.1 Coordinate Frame for Robot

Prior to setting differential kinematics model, the setting of coordinate system must be preceded. Figure. 4 shows the schematic diagram of the system. {A} is global coordinate. The origin of {B} is located in the centre of mass of IDQCR in the driving system. z_B is an unit vector in the direction of outer product with y_B and x_B. y_B is an unit vector in the left direction of the robot and x_B is an unit vector in the front direction of the robot.

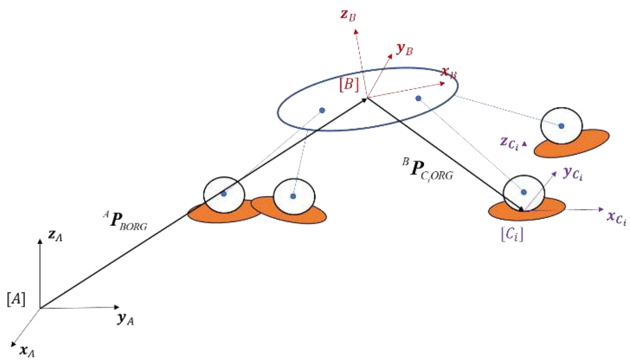

Figure 4. The schematic diagram of the system

3.2 Differential Kinematic Model of Robot

With respect to the coordinate system{A}, the velocity of the origin of frame $\{C_i\}$ is denoted by ${}^{A}V_{C_iORG}$ and can be obtained by the following equation (1).

$$ {}^{A}V_{C_iORG} = {}^{A}V_{BORG} + {}^{A}\Omega_B \times {}^{A}_{B}R\, {}^{B}P_{C_iORG} + {}^{A}_{B}R\, {}^{B}V_{C_iORG} \quad (1) $$

${}^{A}V_{BORG}$ is a linear velocity of the origin of {B} relative to frame {A} and ${}^{A}\Omega_B$ is the angular velocity of frame {B} relative to frame {A}. ${}^{A}_{B}R$ is the rotation matrix of {B} relative to frame {A}. ${}^{B}P_{C_iORG}$ is the position vector of the coordinate system $\{C_i\}$ relative to frame {B}. ${}^{B}V_{C_iORG}$ is linear velocity of the origin of frame $\{C_i\}$ relative to frame {B}. ${}^{B}V_{C_iORG}$ can be expressed as the product of the Jacobian matrix J_i and the joint angular velocity of the leg and the sprocket $\dot{q}_i = [\dot{\alpha}_i\ \dot{\beta}_i]$ of the crawler. Assuming that there is no slip between the crawler and the ground, ${}^{A}V_{C_iORG} = 0$ and then equation (2) can be derived.

$$ {}^{C_i}({}^{A}V_{C_iORG}) = L_i\dot{X} + J_i^*\dot{q}_i = 0 \quad (2) $$

3.3 Jacobian Matrix

$J_i^*\dot{q}_i$ of equation (2) is divided into two velocity components as equation (3).

$$ J_i^*\dot{q}_i = {}^{C_i}({}^{B}V_{\dot{\alpha}_i}) + {}^{C_i}({}^{B}V_{\dot{\beta}_i}) \quad (3) $$

${}^{B}V_{\dot{\alpha}_i}$ is a component related to the joint velocity $\dot{\alpha}_i$ of ${}^{B}V_{C_iORG}$ and ${}^{B}V_{\dot{\beta}_i}$ is a component related to the joint angular velocity $\dot{\beta}_i$ of crawler sprocket of ${}^{B}V_{C_iORG}$. ${}^{C_i}({}^{B}V_{\dot{\alpha}_i})$ and ${}^{C_i}({}^{B}V_{\dot{\beta}_i})$ can be obtained by the following equations (4) and (5).

$$ J_i^*\dot{q}_i = {}^{C_i}_{B}R\, J_{\dot{\alpha}_i}(\dot{\alpha}_i) + \dot{\beta}_i(-r\ 0\ 0)^T \quad (4) $$

$$ J_i^*\dot{q}_i = [{}^{C_i}_{B}R \begin{bmatrix} -l sin\alpha_i \\ 0 \\ -l cos\alpha_i \end{bmatrix} \begin{bmatrix} -r \\ 0 \\ 0 \end{bmatrix}] \begin{bmatrix} \dot{\alpha}_i \\ \dot{\beta}_i \end{bmatrix} \quad (5) $$

$J_{\dot{\alpha}_i}$ is a Jacobian matrix of ${}^{B}V_{\dot{\alpha}_i}$, r is a radius of sprocket and l is the link parameter between the joint and the crawler sprocket.

3.4 Domain between the Joint and the Crawler Sprocket.

$\dot{X} = [{}^{B}({}^{A}\dot{V}_{BORG})^T\ \ {}^{B}({}^{A}\Omega_B)^T]^T$ is a 6×1 matrix that consists of the linear velocity vector and angular velocity vector. Let ${}^{B}({}^{A}V_{BORG}) = [v_x\ v_y\ v_z]^T$ and ${}^{B}({}^{A}\Omega_B) = [w_x\ w_y\ w_z]^T$.

Then, $\dot{X} = [v_x\ v_y\ v_z\ w_x\ w_y\ w_z]^T$. We need to change the control parameter domain from $\dot{X} = [v_x\ v_y\ v_z\ w_x\ w_y\ w_z]^T$ to $\dot{H} = [v_x\ v_y\ \dot{z}_{avg}\ \dot{\phi}\ \dot{\theta}\ \dot{\psi}]^T$. Where $z_{avg} = \sum_i^k z_i$. z_i is value of ${}^{B}P_{C_iORG}$ in z_B direction and k is the number of legs. $\dot{\phi}$ is the roll angle rate, $\dot{\theta}$ is the pitch angle rate and $\dot{\psi}$ is the yaw angle rate. Figure. 5 is showing overall notation and coordinate.

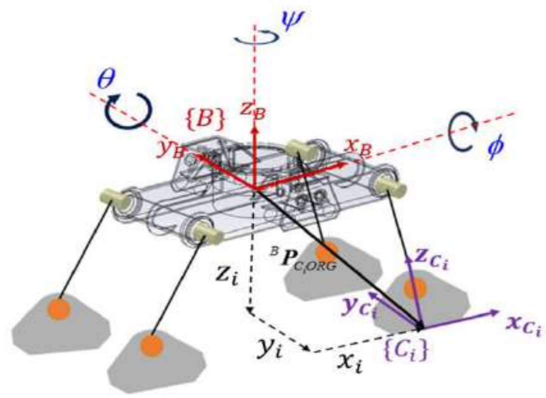

Figure 5. The description of the mentioned notation

A relationship between v_z and $\dot{z}_{avg}$ is equation (6).

$$ v_z = -\dot{z}_{avg} + w_y x_{avg} - w_x y_{avg} \quad (6) $$

Where $x_{avg} = \sum_i^k x_i$ and $y_{avg} = \sum_i^k y_i$. x_i and y_i are values of ${}^{B}P_{C_iORG}$ in x_B and y_B direction respectively. Since we want to control $\phi = 0°$ and $\theta = 0°$. $w_y = \dot{\theta}\cos(\phi) + \dot{\psi}\cos(\theta)\sin(\phi) \cong \dot{\theta}\cos(\phi)$ and $y_{avg} = 0$. Then, the equation (6) can be (7).

$$ v_z \cong -\dot{z}_{avg} + \dot{\theta}\cos(\phi) \quad (7) $$

By using the relationship between Euler angle and angular velocity, 'xyz' transformation, a relationship between $\dot{X}$ and $\dot{H}$ can be derived as (8).

$$\begin{bmatrix} v_x \\ v_y \\ v_z \\ \Omega_x \\ \Omega_y \\ \Omega_z \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & -1 & 0 & c_\phi x_{avg} & 0 \\ & & & 1 & 0 & -s_\theta \\ & 0_{3\times3} & & 0 & c_\theta & c_\theta s_\phi \\ & & & 0 & -s_\theta & c_\theta c_\phi \end{bmatrix} \begin{bmatrix} v_x \\ v_y \\ \dot{z}_{avg} \\ \dot{\phi} \\ \dot{\theta} \\ \dot{\psi} \end{bmatrix} \quad (8)$$

Resultingly, rate of crawler and body velocity, in other words relation between task and joint space in this machine can be derived like (9).

$$\dot{q} = -(J^*)^+ \mathrm{LU}\dot{H} \quad (9)$$

U is 6 by 6 matrix in (8). By using this equation (9), CLIK (Closed Loop Inverse Kinematics) algorithm was applied to method about rollover prevent and simulation used it.

4 Influence of Upper Body Posture

In the existing lower body posture control algorithm, the weight of the upper body of the IDQCR and the weight of the object gripped by the gripper are not considered. In order to travel while performing work and posture control, it is necessary to consider the result of influence of the upper body posture and to implement an additional rollover prevention algorithm. We can determine the influence on the rollover in several various posture and determine the worst posture.

4.1 When both arms are driven dependently

We divided the cases where two grippers hold one object in two cases.

4.1.1 Case 1

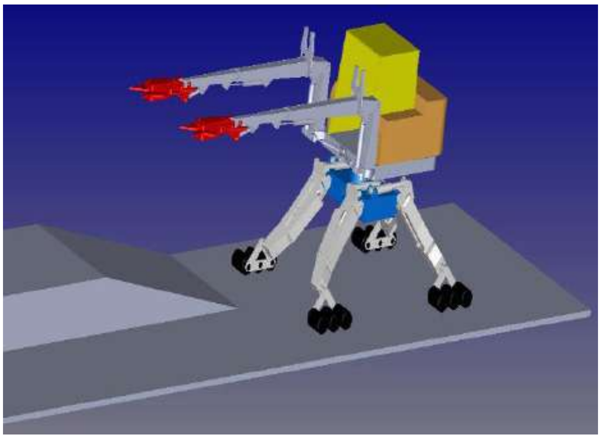

Figure 6. when both arms are stretched straight in the direction of robot's movement

The most basic posture like figure. 6 is when the two arms stretched straight in the direction of the robot's motion. Figure. 7 shows the case where the upper body is rotated 90 degree in the Yaw direction.

4.1.2 Case 2

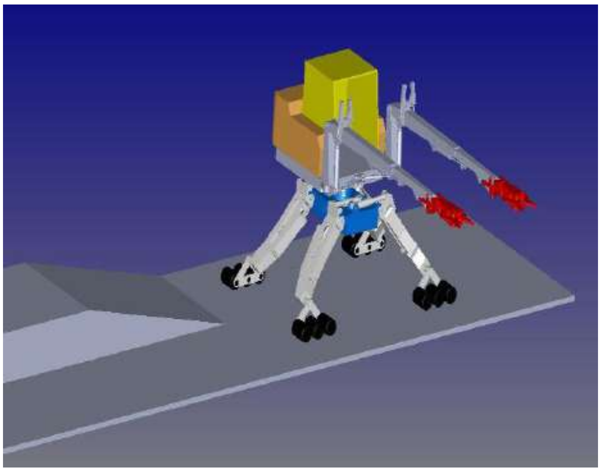

Figure 7. when the upper body is rotated 90° in the Yaw direction.

4.2 When both arms are driven independently

4.2.1 Case 3

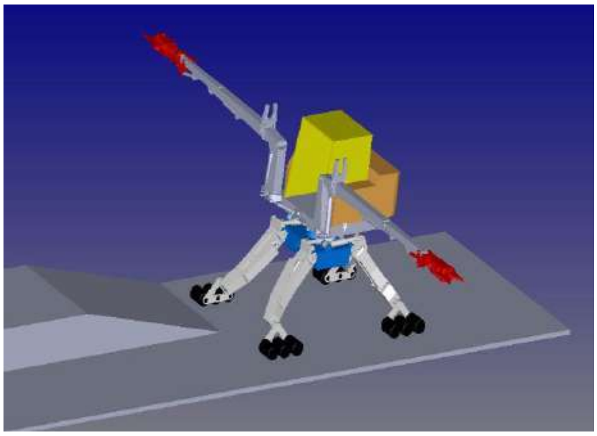

Figure 8. Two grippers hold two objects each

Figure. 8 shows that each grippers hold objects with different weight.

5 Simulation Analysis and Results

In order to verify the proposed mathematical model, we simulated with DAFUL and MATLAB/Simulink, which can analyze dynamics [11]. The simulation conditions are shown in Figure 9, Figure 10, the performance of the proposed model was verified by setting the roll angle to 35 ° and the pitch angle to 25 °.

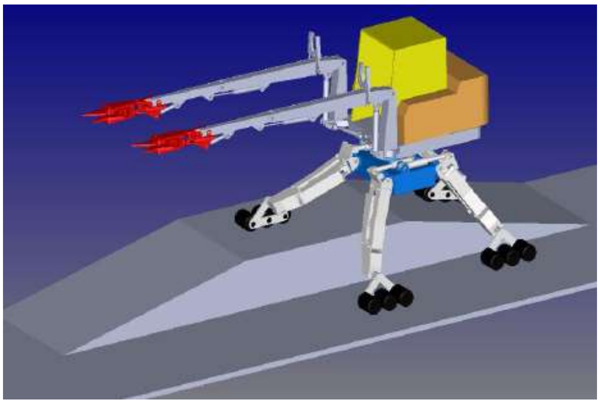

Figure 9. Simulation Condition of Roll angle (35°)

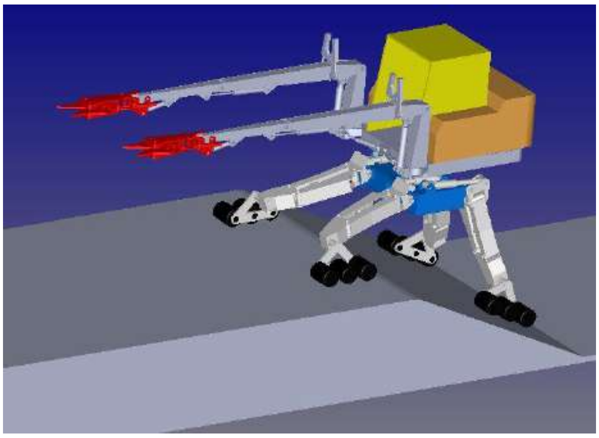

Figure 10. Simulation Condition of Pitch angle (25°)

5.1 Simulation of Roll and Pitch angle

Figure 11 and Figure 12 is the result of the roll angle and pitch angle considering the weight of the upper body of the robot. Figure 11 shows that the robot cannot be rolled over but the cabin is not perfectly horizontal, Figure 12 shows the result of rolled over in the ground-falling period while maintaining the roll angle to 0° in the ground-rising period. In the roll and pitch values analyzed from the mathematical model proposed above, the posture control is perfect for the robot considering only the lower body, but when the robot integrated with the upper body, the robot becomes unstable.

In figure 13 We could confirm the rollover result when simulating the grippers with more than 1.4t objects. An algorithm is needed to find a stable posture when the robot reaches the rollover threshold.

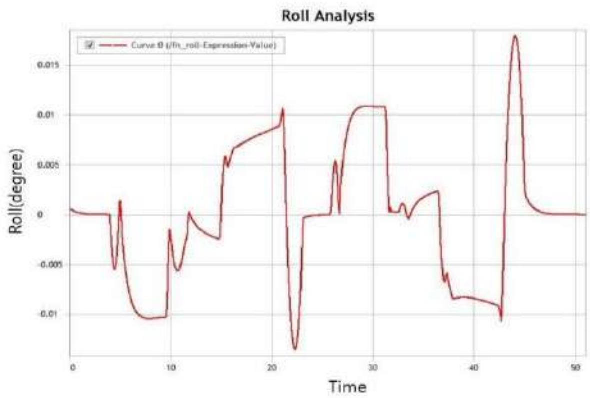

Figure 11. Result of Roll angle

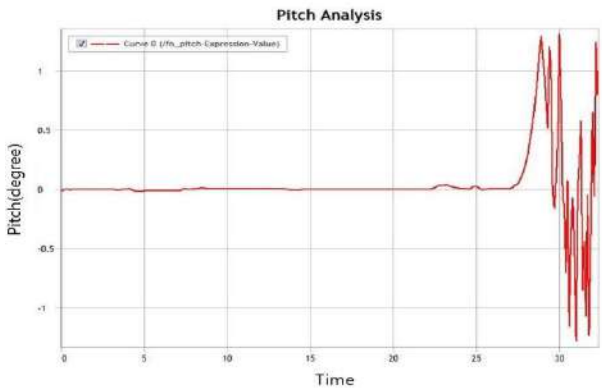

Figure 12. Result of Pitch angle

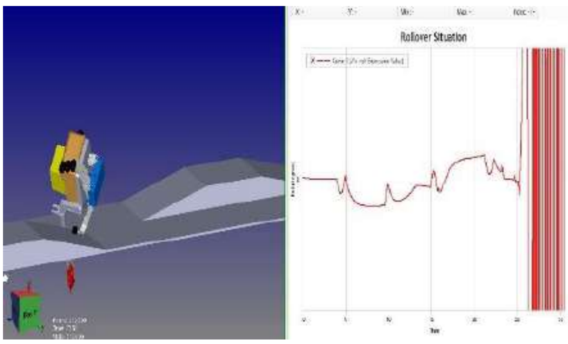

Figure 13. Result of Rollover situation

5.2 Simulation Result of Various Posture

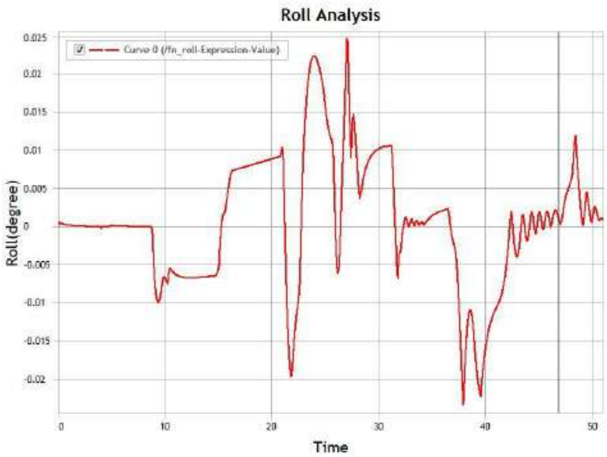

Figure 14. Result of Case 3

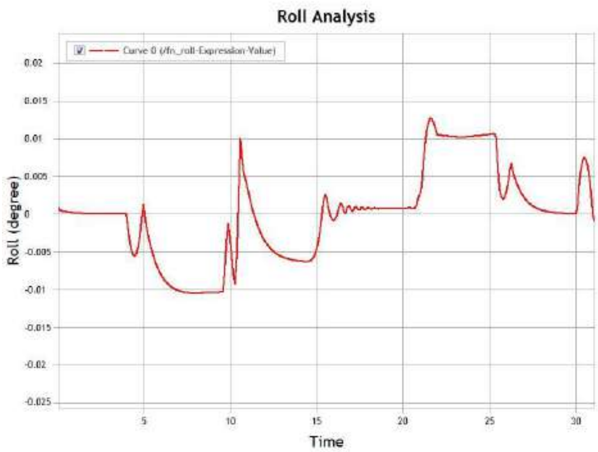

Figure 15. Result of Case 2

Figure 14 is a graph showing the results of Case 3, and Figure 15 is a graph showing the results of Case 2. The graphs in Figures 14 and 15 show that the Roll angle is shaking a lot and we can confirm unstable results.

6 Conclusion and Future Work

In this paper, we propose a mathematical model for the posture control of the IDQCR driving system.
In addition to, the results were confirmed and verified by simulation considering the weight of the upper body of the robot. The proposed mathematical model confirmed that the cabin maintains the horizontal position but does not achieve perfect posture control. It has been confirmed that the rollover occurs when the gripper is weighed more than 1.4t and we confirmed unstable results when simulate various posture. In order to compensate the rollover, an additional algorithm is need to prevent rollover control as well as a posture control algorithm when the overturn limit occurs.

7 Acknowledgement

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Multi-View Matching for Onsite Construction Resources with Combinatorial Optimization

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Abstract

When multiple video cameras are set up to monitor construction activities, onsite construction resources (e.g. equipment and workers) might be captured by two or more cameras at the same time. It becomes important to identify whether the resources captured into separate camera views refer to the same one on the site. Otherwise, the automatic reporting of onsite resources utilization will produce repetive countings. This paper proposes a novel method for matching onsite construction resources in multiple camera views. The method relies on the visual features of a construction site and the spatial relationships of the resources on the site as matching cues. It starts with searching potential matching candidates between the camera views following their epipolar constraints. Then, the candidates' local triangular coordinates are calculated to define matching costs. This way, the matching of multiple construction resources between camera views could be solved through combinatorial optimization. The proposed method has been tested to match workers, equipment and traffic cones within the images and videos captured from construction sites. The test results showed that the method could reach an average of 93% matching accuracy.

Keywords

Onsite resources matching; Epipolar geometry; Combinatorial optimization; Multiple camera views

1 Introduction

The recent fast development of digital camera technology made it possible to set up multiple cameras to monitor construction sites [1]. These cameras can capture the detailed information on the utilization of construction resources (e.g. equipment, workforce, and materials), which could help to facilitate several construction management tasks [1]. For example, the working states of construction equipment were analyzed to estimate its productivity [2]. Also, equipment poses could be extracted to improve onsite safety in equipment operations [3].

When there are multiple cameras on a construction site, they typically have overlapping fields of view (FOVs). It is important to match the visual appearances of construction resources captured in the overlapping FOVs to find out which visual appearances refer to the same construction resource onsite. The successful matching is expected to reduce the repetitive counting and identification of construction resources. Also, it is one of essential steps to locate the resources on the site from the triangulation [4]. Moreover, if one resource is heavily occluded in one camera view, it could still be detected and tracked, as long as its occlusion in another camera view is not severe.

So far, several research studies have been proposed to match the visual appearances of generic objects of interest under multiple camera views. For example, Hu et al. [5] relied on a set of feature points through the Scale-Invariant Feature Transform (SIFT) [6, 7], Speeded Up Robust Features (SURF) [8], etc., to describe and match the object visual appearances in different camera views. Cai and Aggarwal [9] facilitated the object matching by referring to the epipolar constraint. According to the epipolar constraint, it was indicated that the projection of an object point in one camera view could generate a line (i.e. the epipolar line) in another camera view on which its corresponding projection must lie [9]. This way, the searching space is narrowed down to a line.

Most of existing generic matching methods have a limited use on construction sites. This is partly because construction video cameras are typicall set up at heights with wide camera baselines and large differences in view orientation. As a result, the construction resources in each camera view appear small with large variations. It could be difficult to find sufficient common object visual feature points for the matching purpose. On the other hand, the use of the epipolar line could not match the resources one to one, although it does help to limit the matching search space. When the visual appearances of multiple similar construction resources lie along the same epipolar line, the matching fails with the sole use of epipolar constraints.

The goal of this paper is to address these limitations by proposing a novel method for matching the visual appearances of construction resources between camera views. The method is built upon the visual features on a construction site, as well as the spatial relationships of the construction resources on the site. Specifically, potential matching candidates between camera views are first found following the epipolar constraints. Then, the local triangular coordinates of the candidates in each camera view are calculated. It is assumed that the same resource in different camera views should have the same local triangular coordinates. This way, the matching of multiple construction resources between two camera views could be solved by minimizing the matching cost through the combinatorial optimization.

The effectiveness of the proposed method has been tested with the images collected from a real construction site. The tests were conducted under different weather and illumination conditions. According to the test results, it was found that the overall matching accuracy could reach 93% (93% for construction workers, 100% for excavators, and 92% for traffic cones separately). Moreover, the proposed method was compared with the research work of Lee et al. [4]. The comparison results indicated that the proposed method could successfully match small-sized construction resources even if their visual appearances in one camera view lie on the same epipolar line.

2 Related Work

So far, numerous generic object matching methods have been created. These methods could be classified into two categories based on their matching cues. The methods in the first category relied on the visual features of the objects in each camera view; and the methods in the second category relied on the spatial relationships of the objects under the camera views.

2.1 Matching with Visual Features

Under the matching with visual features, the visual appearances of an object under different camera views are first characterized by a set of local point or area features [10]. Then, the matching is directly conducted by checking whether the visual appearances in camera views have the same local point or area features. If the same point or area features are found, it indicates that these visual appearances refer to the same object. Otherwise, they belong to different objects.

Examples of point feature detectors and descriptors include SIFT [6, 7], SURF [8], etc. The SIFT features are typically robust to the orientation changes of camera views; however, they might be sparse for matching object visual appearances between camera views. The SURF features could be detected in a faster way; but they are not fully affine invariant [11].

Compared with point features, the area features typically refer to the visual patterns in small, local image windows. Those area-feature based matching methods first find seed points and propagate from these points into small image windows. Then, the cross-correlation of the visual patterns in these windows is conducted for the matching purpose. For example, Pratt [12] used the local image intensities for the cross-correlation; and Rashidi et al. [13] adopted the adaptive color difference.

In general, the area-feature based matching methods could produce dense matching results [14] and are robust to local affine distortions. However, the matching might still fail. This is especially true when distinctive visual patterns could not be found in the local image windows, or when the patterns experienced significant deformations from the image transformations [15].

2.2 Matching with Spatial Relationships

The epipolar geometry is one of the common common spatial relationships that have been investigated in the matching procedure. In the epipolar geometry, if the projection of a three-dimensional (3D) point X on the left view is known, its epipolar line on the right view could be calculated. Morover, the projection of the point X on the right view must be on the line. Such spatial contratint signficnatly reduces the search space in the matching process [16].

Zhang et al. [17] used the Least Median of Squares (LMedS) to find the epipolar geometry between two camera views. The method of Lee et al. [4] then relied on the epipolar geometry to match onsite construction workers captured in two camera views by considering the locations of the workers in the camera views as well as their distances to the corresponding epipoar lines. Their matching recall and precision could reach 71.4% and 98.7%, respectively [4]. Recently, Konstantinou and Brilakis [18] proposed an idea that combined the epipolar geometry with the shift of the workers' centroids and visual features across video frames to improve the matching accuracy.

2.3 Gaps in Body of Knowledge

There are several limitaitons, when adopting the existing methods to match construction resources. First, the video cameras are typically set up at height on construction sites. Their shooting distance to the onsite construction resources (mobile equipment, workers, etc.) is long. As a result, the resources captured in the camera views always appear small, which makes it difficult to find effective point or area visual features to characterize them.

Second, most of existing matching methods based on visual features failed to match construction resources, when they have similar visual appearances. For example, all taffic cones look similar. Therefore, methods based on visual features for matching traffic cones between camera views have errors .

In addition, the matching methods based on spatial relationship might also fail due to the errors introduced in the calculation of the epipolar lines. For example, both methods proposed by Lee et al. [4] and Konstaninou and Brilakis [18] assumed the centroid of the bounding box of a worker as his/her location in one camera view, and determined the corresponding epipolar line in another view. When the worker is partially occluded in the first view, the centroid of the bounding box does not reflect his or her accurate location. As a result, the epipolar line in the second view is deviated to another worker instead, and the matching error is produced.

3 Objective and Proposed Methodology

The main objective of this paper is to propose a novel method for automatically matching onsite construction resources (e.g. mobile equipment, worker, and temporary facility) captured into camera views. The method is expected to be robust to the changes due to dynamic site activities as well as different illumination and weathe conditions. Also, it is common that construction onsite resources experience occlusions in the camera views. The proposed method is required to be able to match the resources even if they are partially occluded.

This paper focuses on matching excavators, workers, and traffic cones on a construction site. They represent three types of onsite resources, i.e. mobile equipment, labor, and temporary facilities. These resources of interest are first identified through the visual detection and/or tracking. However, many detection and tracking methods have been developed in the past, which could be used in this research.. This paper selected the Single Shot multi-box Detection (SSD) detection method [23] and the Kernelized Correlation Filters (KCF) tracking method [24].. However, other methods could be applied as well.

There are two main steps in the proposed method. The first step is to detect and match the visual feature points of the overall construction site under different camera views. The visual feature points help to establish the epipolar geometry within each pair of camera views, so that the potential matching candidates could be found. The second step is to generate a dynamic triangular mesh in each camera view with the visual feature points of the site. The triangular coordinates of the potential matching candidates in the corresponding meshes are calculated. It is assumed that the same resource in different camera views should have the same local triangular coordinates. Therefore, the difference in the triangular coordinates is defined as the matching cost. The successful matching of multiple onsite resources in different camera views should find a minimum sum of matching costs through combinatorial optimization.

The overall framework of the proposed method is illustrated in Figure 1. The following two sections introduce the details of the steps in the framework. It is worth noting that the matching method proposed in this paper does not require that the cameras are of the same type.

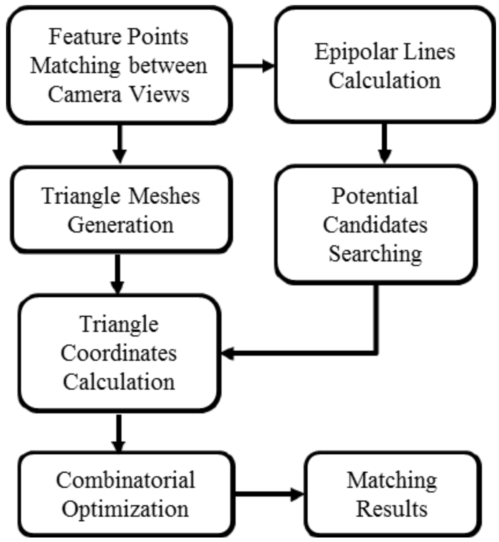

Figure 1: Proposed framework

3.1 Search for Potential Candidates

The purpose of the search for matching candidates is to reduce the matching space and improve the potential matching accuracy. The work here is similar to the previous research study proposed by Lee et al. [4]. Suppose there are two camera views, i.e. CamView1 and CamView2. An initial set of matched feature points in both camera views is first identified with the SIFT detector/descriptor [6, 7]. The selection of this detector/descriptor is mainly due to its robustness to large perspective and/or scale changes [25]. The matched feature points are further refined with the RANdom Sample Consensus (RANSAC) method [26], according to the suggestions from Hartley and Zisserman [27].

The refined feature points are used to generate a 3×3 fundamental matrix. The matrix indicates the hidden epipolar constraint between the two camera views. This way, for each resource of interest in CamView1, its corresponding epipolar line in CamView2 could be determined. The distances of the resources of interest in CamView2 to the epipolar line are calculated. Only those resources with distances equal to or smaller than their size are kept as the potential candidates for matching.

3.2 Pairwise Matching with Combinatorial Optimization

When the potential candaidates are found, the proposed method tries to address the matching problem between camera views with combinatorial optimization. Specifically, suppose there are n resources of interest {O_1, O2, O3, …, O_n} identified in CamView1, and their m matching candidates in CamView2 from the previous step are {C1, C2, C3, …, Cm}. Then, an n by m matrix, M, can be formulated as shown in Eq. 1.

$$M = \begin{bmatrix} M_{11} & \cdots & M_{1m} \\ \vdots & \ddots & \vdots \\ M_{n1} & \cdots & M_{nm} \end{bmatrix} \quad (1)$$

Where the element, M_{ij}, in the matrix indicates the matching cost, if the i[th] resource (Oi) in CamView1 is assumed to match with the j[th] candidate (Cj) in CamView2. The specific matching cost, Mij, is calculated as follows. First, the Delaunay triangulation process [28] is applied upon the correctly matched feature points in CamView1 to generate a triangular mesh (TM1). The mesh (TM1) is further projected to CamView2 to form another triangular mesh (TM2). The local triangle coordinates of each resource in TM1 and each candidate in TM2 are calculated. As for the ith resource (Oi) in CamView1 and the jth candidate (Cj) in CamView2, their matching cost is defined as the difference in terms of their triangle coordinates, as shown in Eq. 2.

$$M_{ij} = \sqrt{(O_{i1} - C_{j1})^2 + (O_{i2} - C_{j2})^2 + (O_{i3} - C_{j3})^2} \quad (2)$$

Where $\{O_{i1}, O_{i2}, O_{i3}\}$ and $\{C_{j1}, C_{j2}, C_{j3}\}$ are the triangle coordinates of the resource (Oi) and the candidate (Cj) in TM1 and TM2 separately. If the candidate (Cj) is not in the list of potetnials candidates for the resource (Oi), their matching cost is then set as +∞.

When the matching costs in the matrix, M, are all determined, the matching between the resources in CamView1 and the candidates in CamView2 is transformed into an assignment problem. Here, the Hungarian algorithm [28] is adopted to find the best assignment with the total minimum matching costs. It is worth noting that M does not have to be a square matrix. The matching could still be made when the number of the objects of interest in CamView1 is not the same as the number of the candidates in CamView2.

4 Implementation and Results

4.1 Implementation

The matching method proposed in this paper has been implemented in Python platform under the support of the OpenCV and Munkres libraries [29, 30]. It was tested on a Microsoft Windows 10 64-bit operating system. The hardware configuration for the tests includes an Intel® Core™ i7-7700HQ CPU (Central Processing Unit) @ 2.80 GHz, a 16 GB memory, and an NVIDIA GeForce GTX 1070 GDDR5 @ 8.0 GB GPU (Graphic Processing Unit).

4.2 Results

The images and videos from real construction sites in Canada were used for the tests. One example is illustrated in Figure 2. On the site, four high definition video cameras were placed to record daily construction activities for a period of 6 months (August, 2015 ~ Feburary, 2016). 51 videos with the total size of 1.3 TBs were collected for analysis. These videos were captured under different environmental conditions (e.g. daytime vs. nighttime; and sunny vs. rainy vs. snowy).

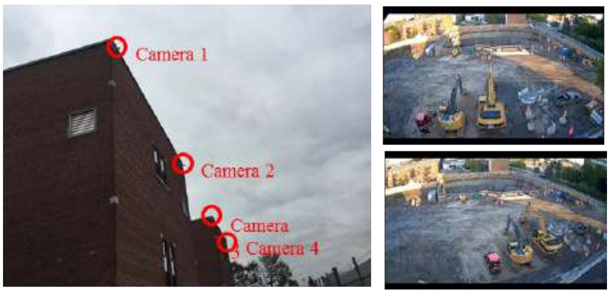

Figure 2: Example of the sites for tests

The videos were used to test the tests of matching workers, excavators and traffic cones. Figure 3 shows the examples of the matching results from the tests. It can be seen that the workers, excavators and traffic cones could be matched between camera views. Also, the matching of the resources is possible even when they experienced occlusions. For example, one excavator is partially occluded by another one in one camera view. The method could still identify the matched excavators in the other camera view. Figure 4 shows the matching examples under different environmental conditions.

Figure 3: Examples of matching workers, excavators, and traffic cones

Figure 4: Examples of testing under different environmental conditons

All matching results have been compiled in Table 1. It could be seen that the average matching accuracy of the proposed method is 93% (construction workers: 93%, excavators: 100%, and traffic cones: 92%). Also, the matching proposed method was compared with the research work of Lee et al. [4]. As shown in Figure 5, the work of Lee et al. [4] could not always successfully match construction resources when they are close to the same epipolar lines and/or partially occluded. The method proposed in this paper addressed such challenges well.

Table 1: Summary of matching results

	Correct Pairs	**Total Pairs**	**Accuracy**
Workers	213	229	93%
Excavators	40	40	100%
Traffic Cones	100	109	92%

Total	353	378	94%

Figure 5: Comparison between Lee et al. [4] (top) and the proposed method (bottom)

4.3 Discussion

According to the test results, it was noted that environmental conditions showed little impacts on the effectiveness of the proposed method. In most cases, the matching accuracy could reach above 90%.

On the other hand, the matching accuracy of the proposed method might be reduced when the size of the resources of interest becomes small. For example, the size of the workers or traffic cones is smaller than the size of the excavators in the tests. That might explain why the matching accuracy for excavators was 100%, while the accuracy rates for matching workers and traffic cones are 93% and 92%, respectively. In addition, the workers and traffic cones could be close to each other in the tests, which also made the matching more challenging.

Another important factor influencing the matching accuracy of the proposed method lies in the camera setup conditions (e.g. the shooting angle between two camera views). The number of common visual feature points detected under each view is reduced when both cameras have a wide view angle. Few feature points will affect the accuracy of the fundamental matrix as well as the generation of the triangular meshes.

5 Conclusions and Future Work

The accurate and robust matching of onsite construction resources of interest under different camera views is still challenging. This paper proposed a novel matching method, which solve the matching problem with combinatorial optimization. Compared with the previous work, the method works even when the resources are close to each other. The method has been tested with the images and videos collected from a real construction site in Canada. The matching was conducted under different lighting and weather conditions. The test results showed that the accuracy rates for matching construction workers, excavators, and traffic cones were 93%, 100%, and 92%, respectively. Overall, the matching accuracy could reach 93%. This paper did not evaluate the relationship between the matching accuracy and the onsite camera setups. Therefore, in the future, the focus will be placed on studying the impacts of the camera setups (e.g. camera distance and shooting angles) on the matching accuracy.

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Parametric BIM Façade Module Development For Diagrid Twisted Structures

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Abstract:

Building Information Modelling (BIM) is an epochal phenomenon in AEC. Most of the developed countries has already adopted BIM by regulations. Biggest projects around the world executing by BIM which provides more effective project management process. Whole construction progress including; feasibility, design, construction and commissioning became digital visualization. Any required analysis can be done via this model template.

In fact, requesting the complex and sophisticated structures' construction is the main catalyst of developing BIM. Mankind start to design and construct cutting-edges and pushing limit structures. Twisted towers are one of the significant instance of like these structures. This study embrace the twisted towers' façade design which has one of the most complex patterns. So it is thought that if such these towers' façade system can be organized and customized limitlessly, most of the façades systems will be solved for the optimum result.

This study aims to reveal a method which can be used for to develop easily alternative façade systems for construction projects even they have very complex design. One of the most complex structures the twisted diagrid systems which are constructed currently around the world was selected. BIM and computational programming have been used to improve the module.

Keywords –
BIM, Building information modelling, parametric design, computational BIM, visual programming, twisted towers.

1 Introduction

Over the last 10 years, diagrid structures have proven to be highly adaptable in structuring a wide range of building types, spans and forms. In most applications, diagrids provide structural support to buildings that are non-rectilinear, adapting well to highly angular buildings and curved forms. [1]

Until the latter half of the 20th century architectural and structural features of such high-rise buildings had remained almost the same with the prismatic box-type structure being the predominant form. Architects started breaking out of this more than century old trend/convention during the later decades of the 20th century [2]. Today's prevalent use of diagrids in tall buildings is due to their structural efficiency and aesthetic potential. For a very tall building, its structural design is generally governed by its lateral stiffness. Compared to conventional orthogonal structures for tall buildings such as framed tubes, diagrid structures carry lateral wind loads much more efficiently by their diagonal members' axial action [3].

Shawn Ursini, says; Advances in construction, engineering and architectural computer programs have enabled this type of architecture to flourish, but it has required a fundamental rethink of tall buildings.

By the way, Eastman et.al [4] define Building Information Modeling (BIM) as a new approach to design, construction, and facility management in which a digital representation of the building process is used to facilitate the exchange and interoperability of information in digital format.

It is no coincidence that the birth of the contemporary diagrid building type came at a time when computer-assisted drawing was hitting its stride. The development of Building Information Modelling (BIM) has been critical to ensuring the successful design and fabrication of highly complex structures [1]Construction of diagrids is more challenging compared to conventional structural systems for tall buildings because the system is relatively new and the joints of diagrid structures are more complicated than those of conventional orthogonal structures [3]. This paper aims to emerge that a proposal module based on parametric BIM which can ensure to make decision easily during diagrid structures design to facade systems of diagrid. This issue is one of the main parts of the skyscrapers cause of their energy consuming. While the most extensive area of the buildings are façades, the design decisions that comprises materials, shapes and geometry are very curious. Similarly with the other parts of the Architectural, Engineering and Construction (AEC) industry façade design can be no longer executed by BIM and parametric modules. The pilot design “Agora Garden” designed by Vincent Collebaut has been chosen as a twisted tower and modelled within Autodesk Revit. It constructed with gardens on the façades’. In this study, its façade design joined to parametric module that built with Dynamo. It has developed as a decision maker which considering environmental effects on the façade.

2 Features & Examples Of Twisted Towers As Diagrid Structures

As diagrid systems twisted towers have become a game changer for AEC. As it has been mentioned above, while structures of diagrid systems accept no fault in computation, it should be designed precisely. Traditional building design methods cannot provide to architects and engineers to carry out the design and construction process for such these building types. The concept of diagrid is not new at all: people have always been intuitively familiar with the inherent stability of triangular structures [8] Placement of diagonals is the oldest and most natural solution in steel structures, and has had widespread applications, receiving great popularity among engineers and architects; however the past architects considered diagonals highly obstructive and usually embedded them within the building interior cores [5] All the contents of construction such as; structural optimization, foundation, spatial decisions can be analyzed via BIM. One of the most curious titles of the project for these types is façade design. Since façade systems have significant roles on energy assumption, building functionality and aesthetic of building design of it is quite sophisticated process. While BIM ensure to design detailed model of the façade systems of the twisted buildings, parametric components ease to reach optimization result which is the useful façade design and material [9].

A high-rise structure where its form is the result of a combination of angled facades on the Z axis is termed as Twisted Tower [2]. Innovative and highly sophisticated digital design tools lends immense capabilities to architects and structural engineers to design highly complex geometrical structures which can be materialised making use of cutting edge technologies, traditional as well as specially developed building materials and highly efficient building practices. Recent decades have seen many high-rise buildings with twisted structures. Most of these have achieved iconic status and have become notable landmarks bringing fame to their locality [1].

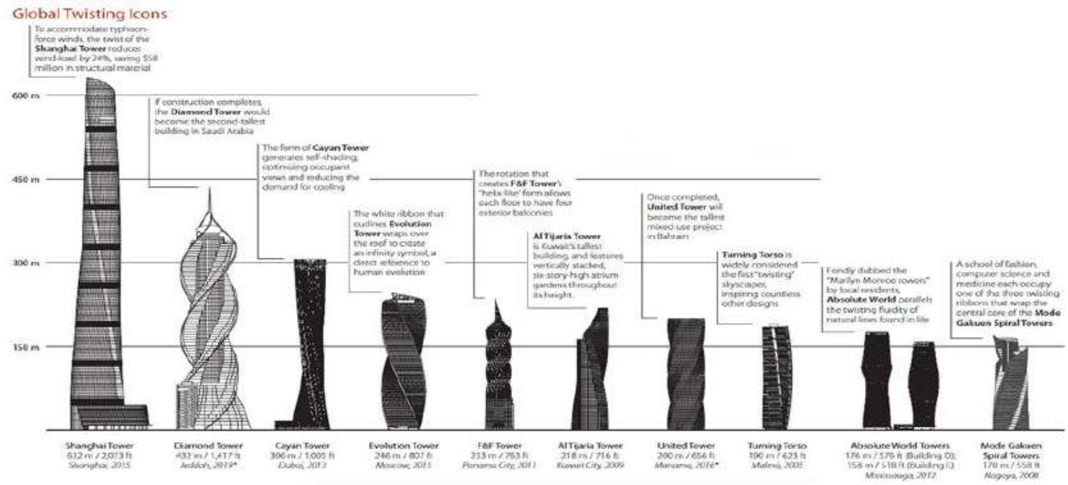

Figure 1. The tallest diagrid twisted towers around the world

A twister is a building with floors that lie horizontally rotated around a vertical axis. This axis usually lies in the centre of the floor plan. Often there is a cylindrical core, around which floor-wings lie. The structural members, mullions and contours all circle helically upward around the rotation axis, resulting in a non-orthogonal superstructure. In a simple Twister all floors are identical and rectangular; they are positioned with a fixed incremental rotation. This type of design can make a building more aerodynamic and energy efficient, leading to an increasing number of twisted tall buildings entering the planning stages throughout the world.

The design for Capital Gate in Abu Dhabi makes a more unobtrusive gesture on the façade regarding the location of the diagrid situated behind the triangular glazing. While the two-storey module size, designed to support the building's 18^0 lean, constitutes one of the smallest modules to date, the member sizes are large and to translate this to the visual appearance of the façade would have been quite overbearing. Instead, a slight colour change at the visible grid is used to acknowledge the pattern of the diagrid structure [10]. In general, these sorts of twisted building forms tend to subdue the reading of the module through the façade.

Figure 2. Famous diagrid structures with façades

3 BIM Model Of The Twisted Tower

Principally in the concept of this study, a selected twisted tower has been the template of the study and it has been modelled as BIM. While selecting the project It is considered that the structure is already completed and opened to use the and the building should have twisted floors and façades together. Some twisted towers have only twisted façades not floors. It is thought that twisted floors with twisted façades give more opportunities for variable joints and so variety design solutions.

3.1 Selected Twisted Tower As a Template

Design of Vincent Callebaut Architecture "Agora Garden" (Figure: 3) has been found proper with the requirements that indicated at the top. Vincent Callebaut defines the tower as : "The 21 storey tower which is currently under construction in the Xinjin District of Taipei City, Taiwan, is directly modeled after a strand of DNA — a double helix twisting 90-degrees from base to top with each level turning by 4.5 degrees.

Figure 3. Selected twisted tower (Agora Garden) model to develop parametric module

According to the architects, this unique form provides solutions to 4 main objectives:

- To be perfectly integrated in the North / South pyramidal profile of the Building Volume along with its East / West rhomboidal profile as well as the North-South reverse pyramid profile.
- To generate a maximum of cascades for suspended open-air gardens, not part of the floor area ratio.
- To offer every resident exceptional panoramic views of the Taipei skyline by multiplying the transversal views, especially towards the very close Taipei 101 tower and the Central Business District."
- To generate from a flexible standardized level a progressive geometry which ensures the privacy of each apartment by avoiding direct visual axes.

3.2 Generating The Digital BIM Model Of The Twisted Tower

The BIM model of the tower was created by using Autodesk Revit. Since the main purpose of this study is optimizing the façade geometry, only the components related with façade was modelled (Figure: 4) The core of the tower as a circle has been placed with parametric properties such as radius. Beside this the vierendeel parts was modelled as floors from ground level to 21st level. The angel of the floor around Z axis changed as

4,5 degree floor by floor. At the end, the first floor has been rotated 90 degree when it reached at 21st level.

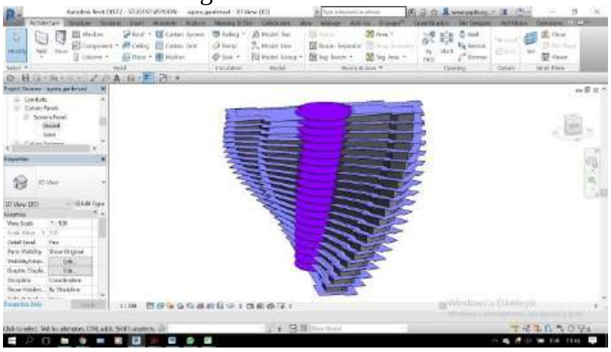

Figure 4. Selected tower's BIM model creation (from Autodesk Revit)

The parametric network was generated by Dynamo (Figure: 5). The rotation of the floors can be customized and the walls placed automatically thanks to parametric network.

The network of floors placement and rotation was established within the visual programming (Figure: 4). The main purpose of the network is to set a template of adjustable rotational floors for BIM. This is not only providing to design twisted structures easily and effectively rather than manual methods also generates to reach the optimal solution of the façade design. It is probably emerge that the angle of the storey floors' rotation required to be changed. The existing project has glass walls for exterior. Owing to its green architecture and design considerations this twisted tower hasn't any curtain wall system or any façades. Despite this status, a parametric façade grid system which enables to adjust via variety of analysis, has been generated (Figure: 5). The grids of façade can be changed by geometry included 3d rotation and translation.

The façade design method was offered with visual parametric programming. Once in Revit interface, mass modelling is used for general façade shape. Since twisted towers generally have curvilinear surface, mass modelling with points should be used for façade. For quite specific façade design mass surface converted as divided surface (Picture :). The countless alternatives can be endeavoured to reach the optimum design even though the shell associated with multiple shapes and amorphous geometries thanks to divided surface. The whole cell of the divided surface might be customizated such as colour, dimension, etc. customization. The "divded surface" node which is in visual programming Dynamo was used for this progress

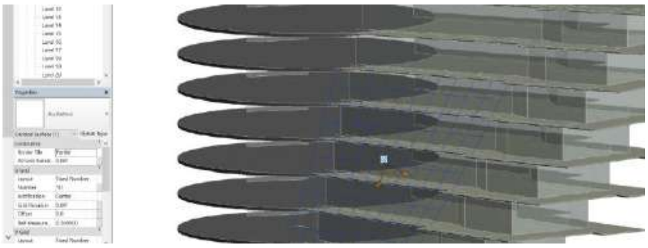

Figure 5. Façade developlent on the BIM model

3.3 Parametric Networks and Features Of The BIM Model

Design stages that applied parametric method are programming, site planning, massing, structure planning, and facade planning. The objectives of the method are project's time efficient, human related advantages (non-determinant decision-making, creativity, pattern recognizing, and advantages by using computers [6]. As mentioned above, the variables of the model has been defined within the parametric network. The panels and mullions of the façade can be changed thanks to this network. The network of the Dynamo loop enables to designers creating many façade alternatives included variety panel dimensions & materials, join types and etc easily for this type of towers. Once, the elements which is composing the surface of the BIM model select via the node of the "select model elements". The floor edges was defined as lines which can be manipulated by their start-end points and by their angles. The storey number of the tower linked to the Dynamo network and it can be tried for any number. Façade surface placed at given storeys and floors' edge.

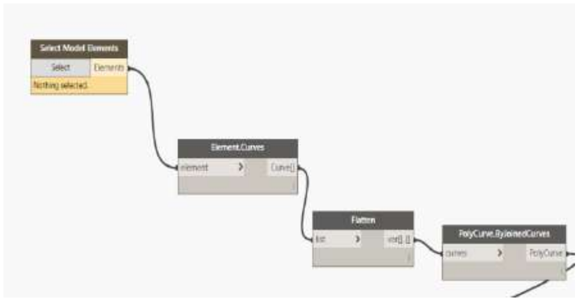

Figure 6. Parametric module development process

The caotic data from the edge lines of the floors arranged with list and list filter nodes. It gives variety opportunities such that any edge of the floor can be unchanged when the others manipulated. The joint component such as rivets and screws can be placed and count even among many alternatives. The grid system enabling to design variety façade options can be placed with any distance from the floors. As adaptive family 3d amorphed panels which dimensions' can be changed via Dynamo nodes generated, it is possible to place a prominent panel system in any geometry on the façade grid system.

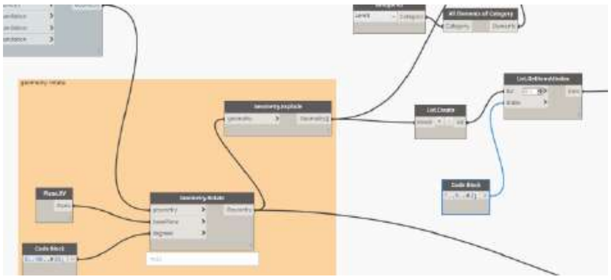

Figure 7. Filtering among multi lines

4 Using the BIM Façade Module As Decision Making Tool

On the instance of the BIM model, multi façade panel geometries, different colour of the façades and the angle of the grids was analysed as per shading and solar lighting. The analysis has been summerized, note that variety types of analysis can be done on the façade systems. Dynamo nodes were used for trying various alternatives to get the optimum solution (Figure. 8).

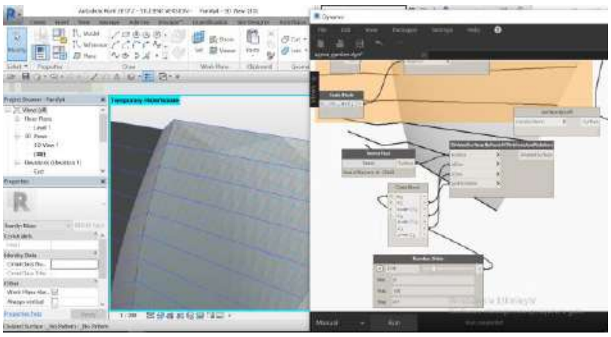

Figure 8 : Fine tuning for optimum façade panel geometry

As mentioned above the façade analysis has been executed on the panel geometry and panel colours. Combinations with the color and geometry of the panel has been connected by the nodes of Dynamo. The colour of the panels has been placed randomly by the "math random" node. It can be inferred from the analysis that how the contrast of colours effect on the interier light and shadow. In addition to this the light and shadow map of the project can be created. The lighting level and shading area was measured depends on the façade combinations. Not only horizontal and vertical grid distance has been connected by the parametric formula but also the angles of the grid lines put into the formula. In addition the mullions' angles and materials might be customized along to the light sourcing and shadow analysis. The network enables to the experts that they make the analysis such as: energy, sunlight, shadow and artificial light.

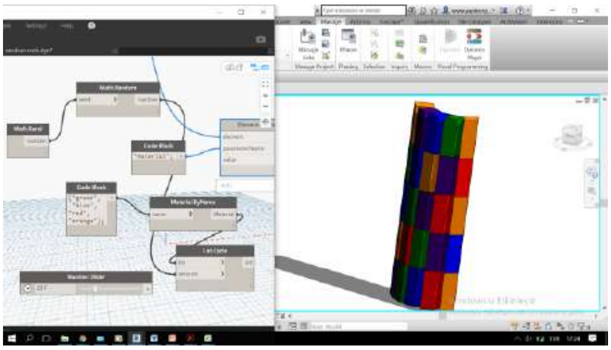

Figure 9. Façade colouring by Dynamo

Twisted geometry provides that more alternatives can be created rather than straight face. If the façade geometry were straight the combination types with geometry & colour would be 10 times less than twisted.

5 Conclusions and Further Studies

Façades are the widest areas of the buildings. They should be analyzed efficiently for energy saving and comfort. Variety alternatives should be tried to reach the most effective solution. In traditional methods only few façade options can be analyzed cause of cost and time especially. If the structure have complex surface, it is much more harder. A BIM based parametric module was generated. This module is unique with regards to specify just for twisted towers. As twisted towers' have rotated floors and curvilinear surfaces in sync, they deserve more efficient façade analysis and most effective selection. Such these modules enable to designers and constructors to reach most efficient solution at the end of so many analysis. The selected twisted façade gives to search more alternatives and it provided to get the best solution as far as possible.

BIM and parametric design getting more curious role in AEC in consequence of seeking energy efficiency buildings whose analysis are complex and cautic. The practical and open source modules should be generated for every unique structures. Additionally, augmented reality (AR) or virtual reality (VR) options which enables to evaluate to the building façade performance to professionals, architects or engineers will be enhanced. Such these modules can be assisted to the analysis developments.

It is thought that the twisted surfaces provides more advanteges to the AEC to construct more sustainable structures and new materials competible with such these shapes will be invented from the nature. Building such these sophisticated buildings and those all analysis are no longer easier than the past thanks to BIM and parametric design tools.

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Motion Data Based Construction Worker Training Support Tool: Case Study of Masonry Work

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Abstract –

Construction work involves a number of repetitive and physically demanding tasks. Exposure to these labor intensive tasks with awkward postures result in an increase in biomechanical risk factors that may lead to work-related musculoskeletal disorders (WMSDs). Thus, it is essential to provide training for apprentice-level workers to adopt safe working postures. Recent advancements in sensing technologies have enabled us to automatically collect body motion data and analyze posture. The present work presents an automated posture assessment method using inertial measurement units (IMUs) allowing for in-depth ergonomic analysis via kinematic data. A case study on masonry work was performed and body motion data from masons with varying experience levels were collected. For the posture analysis, we first investigated the risk of working posture between experience groups using observation-based posture assessment methods (RULA and REBA), then compared the assessment scores between experience groups. Finally, a prototype training tool based on working posture was introduced. The experimental results show that the automated collection and analysis of motion data can provide greater understanding of working postures adopted by workers with different experience levels with the potential to be used as a training tool in apprenticeship programs.

Keywords –

Construction management; Automation; Masonry; Risk assessment method; RULA; REBA; Training tool; Motion capture system

1 Introduction

In the construction industry, workers are frequently exposed to tasks that contribute to work-related musculoskeletal disorders (WMSDs), including overexertion during lifting, repetitive tasks, and awkward postures [1, 2]. Among construction workers, masons are more prone to WMSDs due to frequent lifting and static postures used while handling heavy building materials [3]. In 2010, the masonry trade was found to have the highest rate of overexertion injuries (66.5 per 10,000 full-time equivalent workers) and the second highest rate of back injuries (45.3 per 10,000 full-time equivalent workers) within selected construction subsectors [1]. Furthermore, repetitive tasks have shown to be related to an increase in physical fatigue levels, which can result in greater incidence of accidents and lowered productivity. Hence, it is of great importance to analyze ergonomic risks associated with construction tasks to mitigate the prevalence of WMSDs among construction workers.

Observation-based posture assessment methods have been widely used to identify and monitor potential ergonomic risks associated with WMSDs [4]. These methods include the Rapid Entire Body Assessment (REBA) [5], Rapid Upper Limb Assessment (RULA) [6], and Ovako Working posture Analyzing System (OWAS) [7], which produces risk levels based on input elements such as posture, work duration, and repetition [8]. Traditionally, observation-based assessments require an ergonomist or task analyst to visually assess a worker's posture during an activity in real-time or post-evaluate using a video recording [9]. Body joint angles are the primary input element to describe posture; however, is difficult to obtain precise and reliable input values due to human errors in visual assessments [10].

Recent advancements in motion capture systems have spurred their use in several applications from visual effects in entertainment to biomechanics and sports performance. Motion capture systems based on wearable inertial measurement units (IMUs) can automatically and accurately track motion data. Wearable IMUs are less expensive compared to other motion capture systems, can be used in most site conditions, and do not obstruct the natural motion of wearers. Thus, these wearable IMUs can be used to collect input elements (i.e. body joint angles) with greater accuracy for observation-based assessment methods.

Previous research efforts reported that less experienced workers showed higher lost-workday claims

[1] and significantly lower productivity than experienced workers [11]. Specifically, Alwasel et al. [11] investigated the joint force and moments of masons who were grouped based on experience level, during a bricklaying task. The results showed that joint forces and moments were lowest in the group with the highest level of experience compared to the groups with less experience. Given that the experienced masons adopted safer and more productive methods in their work, it is possible to identify proper, task-specific working postures to develop training tools for inexperienced, apprentice-level workers.

This paper first compares WMSD risk levels of masons with varying levels of experience using existing posture assessment methods (i.e. RULA and REBA). Secondly, a prototype training tool based on working posture is introduced. A case study on masonry work was performed to demonstrate the motion data collection process during a bricklaying task. Based on the motion data, working postures were determined and used as inputs to the RULA and REBA posture assessment methods. Potential issues about the posture assessment methods are discussed.

2 Literature Review

Many ergonomic assessment methods require inputs that describe posture since they are associated with joint force and moment generation contributing to the risk of WMSDs [12, 13]. Posture-based ergonomic assessment methods such as the RULA and REBA posture assessment methods evaluate the stresses on the musculoskeletal system and risk for WMSDs primarily using joint angles with reference to movement planes. RULA and REBA have been commonly applied in the construction industry to study the movement of workers. McGorry and Lin [14] used the RULA method to compare and demonstrate the utility of a proposed methodology that evaluates arm posture and grip strength in tool handling. Kim et al. [15] used the REBA method to estimate the risk of WMSDs in panel erection to improve panel specifications and workplace design. Using the RULA and REBA body part diagrams, a risk score and its prescribed action level for ergonomic intervention can be found. However, since these assessments are traditionally based on visual observations of joint angle, the results are prone to inaccuracies across different observers [10].

Due to the development of sensing technologies, various types of motion sensing systems have been introduced to improve the efficiency and accuracy of posture assessments. Popular among these sensing technologies are vision-based assessments, which use video cameras for object identification and tracking, and inertial measurement units (IMUs), which obtain motion data with accelerometers, gyroscopes, and magnetometers. For example, Ray and Teizer [16] used a Kinect range camera to classify work tasks as ergonomic or non-ergonomic. Alwasel et al. [11] used an IMU-based sensor suit and 3D Static Strength Prediction Program [17] to estimate joint forces and moments in a bricklaying task. Research efforts in WMSDs in the construction industry utilizing sensing technologies, to date, have been focused on posture detection, posture classification, and comparison of working posture to ergonomic standards. However, few studies have examined the differences in working postures adopted by workers with growing levels of experience. In this research, we investigate risk levels associated with working postures adopted by masons of varying levels of expertise using an automated risk assessment tool.

3 Methodology

In Ontario, Canada, the three-year masonry apprenticeship consists of on-site and in-school training. Upon completion, the apprentice can apply to become certified as a journeyman. Forty-five participants were recruited from the Brick and Stone Masonry Apprenticeship Program offered by the Ontario Masonry Training Centre. The experiment was conducted at two institutions: Conestoga College in Waterloo, Ontario, and the Canadian Masonry Design Centre (CMDC) in Mississauga, Ontario. The participants were separated into four cohorts based on years of experience: novice with no experience, apprentice with 1-year experience, apprentice with 3-years of experience, and journeyman with 5 or more years of experience (Table 1).

Table 1. Number of participants

	Novice	1 Year	3 Years	Journeymen	Total
Conestoga	5	4	7	5	21
CMDC	12	5	6	1	24
Total	**17**	**9**	**13**	**6**	**45**

Wireless motion capture suits, MVN Awinda from Xsense [18] and Perception neuron from Noitom Ltd. [19] were used to collect participants' motion data. The suits contain seventeen inertial measurement units (IMUs), and each sensor is composed of a three-axis accelerometer, three-axis gyroscope, and three-axis magnetometer. The suits collected motion data at a 125 Hz sampling frequency. The experiments were recorded using camcorders to label and segment the data in the data processing phase. Prior to the experiment, a calibration session was performed for each participant to ensure conformity between the models generated from the motion data and the participant's body. Each participant was instructed to complete a pre-built lead wall using forty-five concrete masonry units (CMUs), thus each bricklaying task consisted of forty-five individual lifts. Figure 1 shows the experimental setup with the lead wall. The pre-built lead wall was six-courses high and consisted of twenty-seven blocks. The participants completed the wall using CMUs from the second course to the sixth course. The CMU blocks were placed on three pallets approximately 1 meter away from the lead wall. Two panels of mortar were positioned between the three pallets and were continuously supplied by helpers. The CMUs are CSA"A" - Type "A" concrete units and each weigh 16.6 kg with dimensions of 390 x 190 x 100 mm (Canadian Concrete Masonry Producer Association).

Figure 1. Experimental setup.

After the completion of the bricklaying task, motion data from the IMU suits were extracted as Biovision Hierarchy (BVH) type files containing 3D joint orientation over time. Then, joint angles required for the RULA and REBA posture assessment methods were calculated using the International Society of Biomechanics (ISB) recommendations [20, 21]. As shown in Figure 2, a local coordinate system is defined for each body segment using joint centers, then the Euler angles between adjoining segments' coordinate systems were calculated [22].

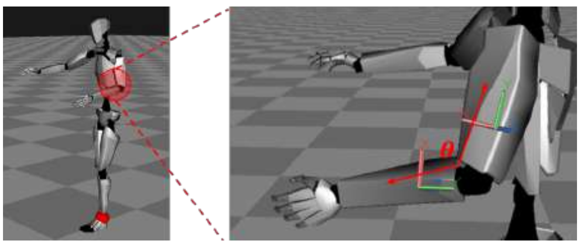

Figure 2. Joint angle based on Local coordinate system

The calculated joint angles were used to assign posture scores in both assessment methods. The RULA and REBA assessment methods consist of two body region sections to obtain a final score representing the risk for MSDs: 1) arm and wrist analysis, 2) neck, trunk, and leg analysis. The posture score according to the segment angle is first obtained, and then the score of each section is calculated considering additional adjustments such as external force and frequency. A final score is assigned by combining the previous two posture scores. The final RULA score ranges from 1 to 7 and final REBA score ranges from 1 to 15, which correspond to four and five risk levels respectively. Table 2 shows the final score range and corresponding risk level.

Table 2. Score range of RULA and REBA

RULA	
Score	Level of MSD risk
1-2	Acceptable posture
3-4	Further investigation, change may be needed
5-6	Further investigation, change soon
7	Investigate and implement change
REBA	
Score	Level of MSD risk
1	Negligible risk, no action required
2-3	Low risk, change may be needed
4-7	Medium risk, further investigation, change soon
8-10	High risk, investigate and implement change
11+	Very high risk, implement change

In this study, both the right- and left-side of body segment angles were obtained, however only the side with the higher score contributed to the final score. Since the wearable IMU suits collected 125 frames of motion data per second, a RULA and REBA score was assigned to each frame. Since each lift varies in duration, the maximum assessment score was selected for each lift. Considering more than 70% of all lift motions were two-handed lifts, the assessment scores were analyzed by selecting only two-handed lifts. Finally, the average final scores of each experience group were used for comparison.

4 Result and Discussion

4.1 Average RULA and REBA scores

Table 3 shows the average RULA and REBA score of four groups with different levels of experience. The overall average score of RULA is 6.95 and of REBA is

10.94, both indicating high risk for MSDs. In the score comparison between experience groups, the average RULA score was highest in the 3-years group, while the average REBA score was the highest in the journeymen group. The novice group showed the lowest score in both assessment tools. It is important to note that the variance of average scores among experience groups were not significant in both assessment tools. Specifically, the difference between the highest score and the lowest score is only 0.11 and 0.35.

Table 3. Average final score of RULA and REBA

Group	**RULA**		**REBA**	
	Average	SD	Average	SD
Novice	6.88	0.39	10.74	0.97
1 Year	6.96	0.22	10.89	0.97
3 Years	6.99	0.11	11.02	0.81
Journeymen	6.98	0.14	11.09	0.78

To build the lead wall, participants placed forty-five CMUs in five courses, from the second course to the sixth course. A detailed risk assessment score by course is shown in Table 4. Both assessment tools showed a lower final score when placing CMUs in the third and fourth courses in all groups. Since the third and fourth course are approximately at hip-height, the result may be due to less back- and arm-bending.

Table 4. Average score of RULA and REBA by course

Groups	**Average RULA score by courses**				
	2	3	4	5	6
Novice	6.94	6.84	6.80	6.89	6.92
1 Year	7.00	6.94	6.90	6.95	7.00
3 Years	7.00	6.99	6.97	7.00	6.99
Journeymen	7.00	7.00	6.92	6.98	7.00
Groups	**Average REBA score by courses**				
	2	3	4	5	6
Novice	10.98	10.62	10.44	10.67	10.99
1 Year	10.72	10.71	10.95	10.93	11.07
3 Years	11.18	10.90	10.90	10.89	11.21
Journeymen	11.07	10.67	10.92	11.22	11.34

The added external load in RULA and REBA is one of the important adjustment factors for the final score. In particular, when an external load greater than 22 lbs (10 kg) is applied, an additional 2 or 3 scores were applied resulting in a higher final score. The CMUs used in this study was 16.6 kg, and both assessment tools showed a very high-risk final score regardless of the various segment angles obtained by the participants. Therefore, in the case of heavy material handling tasks such as masonry work, the practicality of posture assessment methods may be limited since they do not provide significant results to differentiate between experience groups.

4.2 Prototype training tool

Although the average RULA and REBA scores were not able to provide results with significant differences between experience groups, the tools can indicate the risk of each body segment according to the joint angles. Thus, we developed a prototype training tool that provides independent joint scores and adopts the joint angle ranges used in the REBA scoring system since it provides whole body postural risk reflecting both upper- and lower-limbs joint angles. The training tool uses a color-map to reflect risk levels at selected joints. The angle range and risk level indicator is shown in Table 5.

Table 5. REBA Score-based Tool - Risk Level Indicator

Body Segment	Angle (degree)	Score	Risk Level Indicator
Shoulder	0 – 20	1	
	20 – 45	2	
	45 – 90	3	
	> 90	4	
Elbow	60 – 100	1	
	0 – 60 or > 100	2	
Wrist	0 – 15	1	
	> 15	2	
Neck	0 – 10	1	
	10 – 20 or 0 <	2	
Truck	0	1	
	0 – 20 or 0 <	2	
	20 – 60	3	
	> 60	4	
Leg	0	1	
	30 – 60	2	
	> 60	3	

Figure 3 shows a snapshot of the training tool applied to Participant #2 in the journeymen group. As shown in Figure 3, the red color indicates that the back and arm angles are unsafe for the participant. To correct the posture and maintain low risk levels, the participant must reduce the flexion angle of the back and shoulder by bending more at the knees and reduce the flexion angle of the arm by keeping the CMU block closer to the body.

Actual posture **Model in training tool**

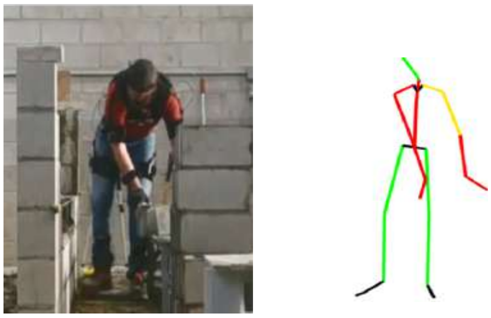

Figure 3. The snapshot of prototype training tool

As demonstrated, the training tool which continuously collects motion data, can inform its user of safe and unsafe working postures for the entire work duration. This allows the user to proactively correct unsafe postures and reduce the risk of WMSDs. The training tool has the potential to be used in apprenticeship programs to establish safe working postures.

5 Conclusion

The practice of safe working postures in construction work help workers maintain good health and productivity levels. Current observation-based posture assessment methods are subject to human error and lack precision. Recent developments of IMUs allow for the continuous collection of motion data which are more reliable for use in posture assessments. In this paper, motion data was collected from forty-five participants with different experience levels ranging from novice to more than 5-years of masonry experience. We analyzed the working postures of the participants while performing a bricklaying task using IMU suits.

Risk levels for WMSDs were determined and compared for each group using posture assessment methods, RULA and REBA. The results showed that the average maximum assessment scores across experience groups for RULA is between 6.88 and 6.99, and REBA is between 10.74 and 11.09. The results of the assessment methods showed that the assessments may not be able to differentiate between the working postures of workers with different levels of experience. Both assessment methods indicated that the risk levels for WMSDs were lowest when the participants were handling CMUs between the knee and hip level. We also presented a prototype training tool that was developed based on joint angle inputs used in the REBA scoring system. The training tool identifies unsafe postures using motion data collected during a work task so that its user can make necessary adjustments.

Future work will compare results obtained from the posture assessment tools presented in this study, with those obtained using biomechanical analysis (e.g., using 3D Static Strength Prediction Program). The biomechanical analysis will be used to determine joint forces and moments generated during the bricklaying task and to develop a biomechanical-based training tool. In addition, studies on work proficiency and productivity using training methods will be conducted.

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Radio-frequency identification based process management for production line balancing

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Abstract –

The widespread application of offsite facilities has encouraged the construction industry to make use of manufacturing approaches to develop efficient production systems. To fully realize the advantages of offsite construction, management must be able to effectively schedule production activities to increase productivity and improve time efficiency. This necessitates a tool capable of dynamically responding to real-time production data throughout the process. Radio-frequency identification (RFID) has proven to be a useful technology to provide real-time location data for products moving through a production line and is often used as part of a reporting tool; however, the information provided by RFID also allows for proactive scheduling, which facilitates production line balancing. Maintaining a balanced production line in a variability-prone process requires the end-user to possess knowledge of the production line and the schedule and be able to effectively communicate the production requirements to employees on the production floor. Contextual information, obtained from RFID and measured against job information and production time data, can be delivered to production floor supervisors in real-time in order to enable timely and informed decision-making on the plant floor. This paper introduces a framework for effective production line balancing using data collected by RFID to dynamically update the production schedule and provide more data to help drive better decisions from production floor supervisors.

Keywords –

Offsite Construction; Virtual Manufacturing; Production Line Balancing; Dynamic Scheduling; RFID; Radio-Frequency Identification; Visual Process Management

1 Introduction

A balanced production line is vital in offsite construction manufacturing, given that it decreases wait time and increases the productivity of the entire line. The aim of production line balancing is to divide the necessary tasks into a minimum number of workstations to optimize the total production cycle time [1]. Production line balancing can be considered a Lean tool and is often implemented during the design or setup of a new production line [2]. The line balancing problem has been studied for several years and can be formulated in various ways. One of the original formulations of the problem is the Simple Assembly Line Balancing Problem (SALBP) [3], where tasks are assigned to workstations and precedence relationships are defined. Tasks are then assigned to stations based on the precedence relationships while the takt time, or line cycle time, is used as a constraint to limit station times, thus minimizing the total number of required stations [4]. One of the primary limitations of SALBP solutions is that the inputs and constraints are considered static, while a production line is usually a dynamic operation. Continuous improvement initiatives, constant management input on the production line, and customizable products are examples of inputs that result in an increasingly dynamic problem. Jaikumar and Bohn [5] recognize that the "knowledge, learning, problem solving, and contingencies" introduced to the process by both the production line workers and the management team play a key role in the balancing of the production line.

Maintaining effective communication between management and production line workers is extremely important to ensure that the final product is built to the desired quality, and in the desired time. Production managers must communicate the requirements for supply chain, labor balancing, and production requirements. In order to make these decisions, the production managers require information from the production line, the desired schedule, and the inventory supply chain. The study by Heilala et al. [6] underscores the value of employing simulation with actual data to provide production managers with the information they require to identify potential problems and react to them appropriately. The use of real data and simulation can reduce the time required for information collection by the production manager and allow for effective decisions to be made in less time. Decision support tools, including Gantt charts and scheduling software, aid production managers in making decisions about the schedule and operation of the production line, and also provide an improved method of communicating the findings to production line workers; however, success with decision support systems requires that information be received from other systems, which is difficult to implement [7]. Gantt [8] himself recognized early on that having management specify tasks for workers to accomplish will increase productivity, and the effect will be even greater if any issues are foreseen and managed by the supervisor.

Radio-frequency identification (RFID) is widely used by industry to track components in the production line. Literature proposes the use of RFID technology in tracking precast concrete pieces [9], material delivery vehicles, and construction workers onsite [10]. The basic premise behind RFID systems is similar to barcode technology, but the RFID system stores the data (identification number, code, other object-related information) in tags making it retrievable by specialized readers. Depending on their power source, tags can be recognized as passive or active [10], where passive tags depend on the reader to operate and have shorter read ranges, and active tags use internal batteries for their power supply, which makes their read ranges significantly higher, they have a limited lifetime of 5-10 years and are more expensive due to their local power source. Overall, the specifications of RFID include their power source, read range, read rate, frequency and data storage capacity, and operational life time and cost [9].
Because of the RFID reader's ability to communicate with several tags at the same time, the contents of elements loaded into a manufacturing facility can be captured [11]. While RFID gates are used at pre-designed locations to identify the arrival dates of material to the station, the primary task includes reporting the identification information to the system for further processing [12]. According to Song et al. [13], implementing RFID technology at laydown yards and portal gates paves the way for time savings in material identification, increasing accuracy and shortening time for establishing information on material availability at the plant for further project planning and resource allocation.

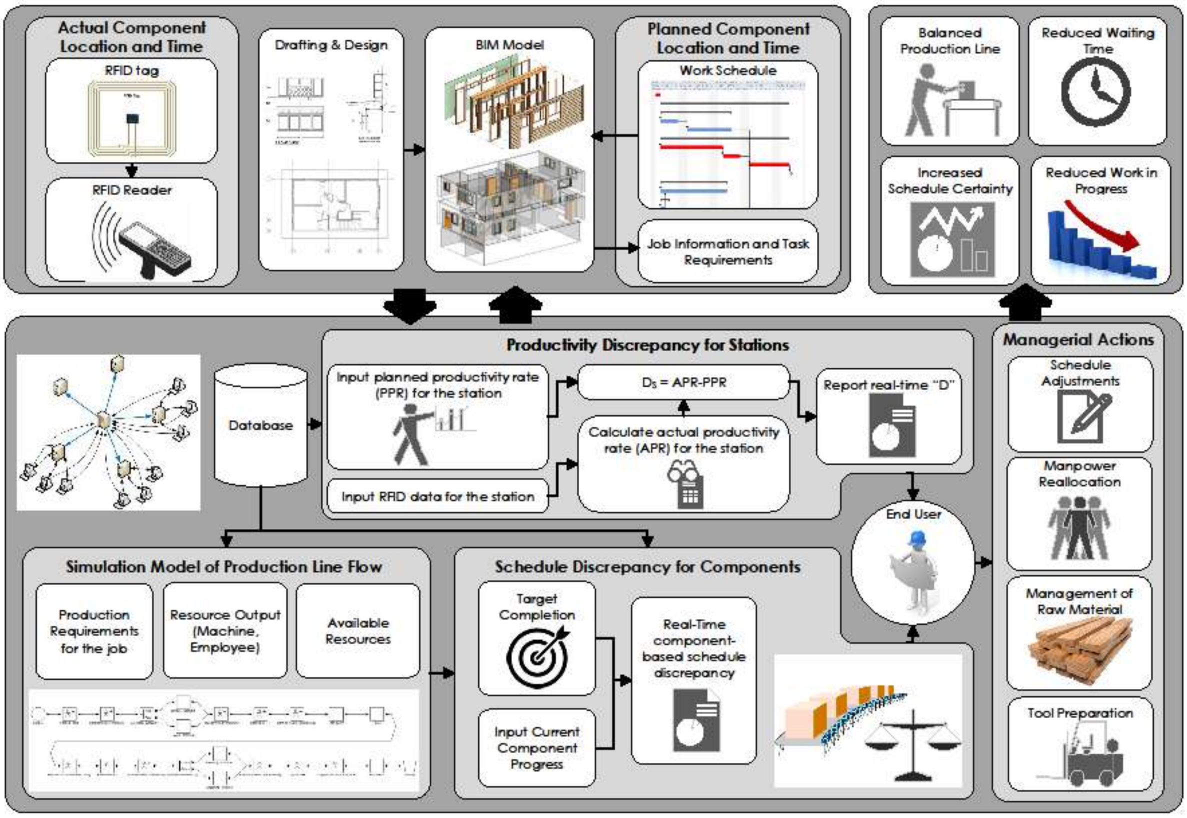

Figure 1. Overview of proposed framework

2 Motivation

A pull system is preferable in a manufacturing setting given that it reduces the work in progress in the facility. Operating a pull system requires knowledge of when each component needs to be completed and how long it will take. This knowledge is usually gained by production managers through years of experience, which leaves the production vulnerable to errors and sudden variations, such as changes in staff. Managers are aided in decision making through reporting, scheduling, and production tracking carried out with the use of RFID data, estimators, and planning departments; however, there is a significant time discrepancy between when information becomes available, when it can be analyzed by the corresponding department, and when it is communicated to the production manager, who only then can make adjustments on the plant floor.

The framework proposed in this paper aims to reduce the time to evaluate and present decision makers with relevant data, allow for the integration of the current plant state into the plan, and to ensure a pull system by planning production progress based on the delivery time for each component.

3 Proposed Framework

The proposed framework utilizes building information modeling (BIM), radio-frequency identification (RFID), and the known work schedule to provide information to production managers or other decision makers in a production facility with reduced delay and necessary manpower. This information will be used to allow the production manager to make more effective, educated decisions while on the plant floor. Figure 1 presents the proposed framework, which is discussed in more detail in the following sections.

3.1 Actual Component Location and Time

The RFID system feeds the last known location of production components to the database. The level of detail for the RFID location is dependent on the number and location of RFID readers in the plant. While the RFID system cannot locate the exact coordinates of any component in the plant, it is able to track the current station each component is in, when it arrives at the station, and how long it has been at the station. This data is used to set the starting point for the simulation model based on the true current state of production in the plant. Using RFID data to determine the current state of the plant reduces the time required for plant managers to collect information about the plant through pure observation.

3.2 Planned Component Location and Time

The information for the planned component location and time is gathered from the work schedule, which will detail the required completion dates for each job; and, the job information and task requirements, together with input from drafting and design and the BIM model, will determine the expected time for the processing of each task in the production line.

3.3 Productivity Discrepancy for Stations

The productivity discrepancy within each station (D_S) refers to the difference between the planned productivity rate (PPR) and the actual productivity rate (APR) for the station. This measure is useful to the end user as it will help to quickly identify the performance of each station compared to that which is expected. These metrics will be available to the end user through a visualization system that enables quick identification of the relative performance of the departments.

3.4 Simulation Model of Production Line Flow

Operating a pull system requires knowledge of the processing time of each station in order to ensure that components will be pulled through the system in a manner that minimizes idle and wait times. The simulation model will use the required completion date for each project along with the BIM model, job information, and task requirements from the database, which will enable the calculation of processing times for each job at each station based on the characteristics specific to each job. The simulation model will then determine how the jobs will run through the production line and interact with one another in order to identify where in the production line each job should currently be in order to meet the required deadline (or as near to it as possible). The simulation model is resource-dependent and built to illustrate the actual case in the plant, including required equipment and its availability, utilization of manpower resources and their limitations, and sequence of production activities required to complete each job.

3.5 Schedule Discrepancy for Components

From the information in the database and the output of the simulation model, the difference between where each component of each job is in the production line and where it should be can be calculated. This discrepancy is important and distinct from the productivity discrepancy of the stations because, even if all stations are meeting or exceeding their target productivity, certain components may be behind the projected schedule that would allow them to be completed by their required completion time.

3.6 Managerial Actions

The information provided to the end user (production manager) will allow for better knowledge regarding the current state of and requirements for production in the plant. The production manager will then be able to make schedule adjustments, such as pulling a component that is ahead of schedule off of the line to allow a component that is behind schedule to accelerate, reallocating manpower to different stations to balance station productivity and requirements based on job types, managing raw material to ensure that there is no wait time or idle time, and preparing tools for certain jobs that are upcoming in the schedule.

4 Proposed Implementation

4.1 Visualization System

To ensure that the end user has consistent access to the production statistics, it is preferred to have a visualization system that can be brought into the production area. This can include the use of tablets or smartphones by the production manager, for which a sketch of the proposed interface is presented in Figure 2. Here, a red bar in the station productivity area (left of view) indicates that a station's productivity is lower than expected, while a green bar indicates the station's productivity is meeting or exceeding that which is planned.

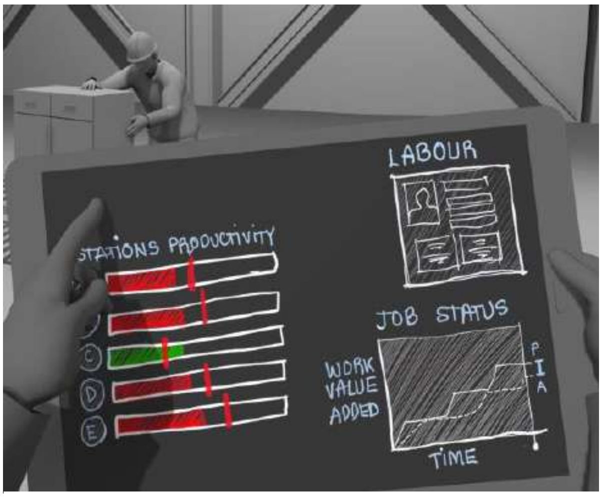

Figure 2. Tablet data display

4.2 Cabinet Manufacturer Case Study

To illustrate some scenarios where the proposed framework would improve on current plant operations, the case of a cabinet manufacturer is described. Change orders, defects and rework, and schedule adjustments all occur in a manufacturing facility and often require production managers to make immediate decisions while on the plant floor. At the time of these decisions, the only information available to the production manager involves statistics and updates gathered at previous meetings or by the manager through current production reporting tools, which often have a significant delay, as well as any information gathered throughout the day by means of observation. This leads to the possibility that the production manager is forced to make decisions based on incomplete information, or that decisions need to be delayed while the required information is gathered. A typical layout for a cabinet manufacturing facility is presented in Figure 3.

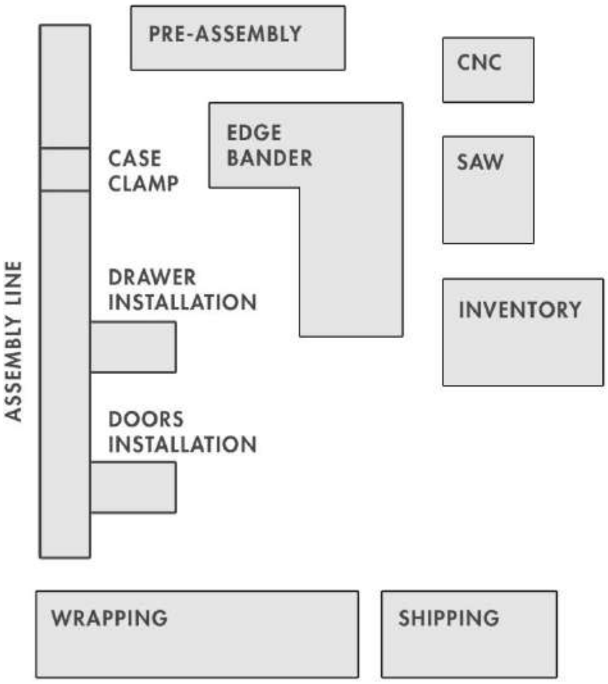

Figure 3. Typical cabinet manufacturer plant layout

One example of a common change that often requires intervention on the plant floor by the production manager is a change in delivery date or schedule change due to material shortage. Most of the cabinets manufactured at the case study facility are designed to be installed in new houses. The date on which the cabinets are needed is dependent on the construction schedule of the house, which can be highly variable. Since the case study plant works closely with partner homebuilders, they have access to construction information and can use this to update the project completion dates to help ensure they are operating a pull system. With the implementation of the proposed system, production managers would be able to track components on a real-time basis, see the outcome of a schedule change on the production line, and be able to make decisions to allow jobs to be processed based on their corresponding deadlines. For example, if one customer of the case study plant is not prepared for the delivery of their cabinets, finishing these cabinets will not benefit the manufacturing plant, as they will then have to store the completed product until it can be delivered. With a daily production of about 200 cabinet boxes per day, and 6-7 boxes fitting on each skid (which covers an area of 1.2 m^2), 31 skids are filled each day. Since the plant only ships orders three days per week, a floor area of 74.4 m^2 is required to store completed jobs between shipping dates. Storing additional finished product reduces the available storage area and reduces production effort available for urgent jobs. The production manager can make changes based on the priorities apparent to them from the information available through the proposed framework to ensure that the production facility maintains a pull system and that wasted storage space is reduced. Also, by the means of the proposed framework, managers would be able to schedule based on the current shipping date of jobs and the estimated production time. The estimated production time remaining is calculated based on the data obtained from RFID and production estimates based on the job characteristics gathered from the BIM model.

The production manager will also be able to monitor the day-to-day production of each station and use this to make labor adjustments to balance the production line. Creating a balanced production line with a variable product such as cabinets is difficult since, with current systems, it is difficult for the production manager to receive continuous details about the plant operations. With the proposed system, the expected workload of each station could be calculated based on job characteristics from the BIM model, and the actual performance relative to the schedule would be consistently available based on the data obtained from RFID, as seen in Figure 2. The production manager could use this information to identify training requirements, to monitor labor efficiency, and to reallocate workers in the plant to ensure each station is keeping up with the schedule. In the case study plant, the pre-assembly area requires the most manual labor and triggers the next activities on the line; therefore, this area has a significant impact on the output of the production line. With the use of the proposed system, the level of productivity at this station would be represented by a red bar, indicating to the production manager that a decision must be made to help increase the productivity at this station. The production manager could then make an educated decision to reallocate workers from another station presenting a green bar (indicating that station is exceeding the planned productivity) to help balance the line. The manager could also decide to implement training for the workers in the pre-assembly area, or to recommend other improvements based on their experience and observations.

Finally, the proposed framework can help to identify and deal with the adverse impacts of rework. For the production manager, being able to instantly show the location of all job components by using the proposed system with up-to-date RFID data, track the job completion progress, or locate a BIM model based on the station being viewed and the job that is currently at that station greatly reduces the time required for valuable information to be located compared to traditional systems. For example, if the case study plant receives a report from a customer about a missing component in the package delivered to their site, the production manager will have instant access to the RFID data for that job and is able to quickly locate the last location at which that component was scanned to help identify the issue.

5 Opportunities and Challenges of Proposed Framework

The proposed framework is intended to address the need to maintain crew work continuity in a construction manufacturing setting. Various interruptions to production line flow, such as plant shutdown, equipment maintenance, employee turnover, variations in productivity, and rework, make it difficult to effectively balance the production line and consistently meet the plant schedule. The proposed framework provides opportunities for improved accessibility of tracking data, efficient communication, real-time schedule monitoring, and innovative data visualization. Figure 2 and Figure 4 present conceptual illustrations of the system from the point of view of the end user.

Common scheduling techniques tend to be complicated to visualize and they lack the means to display the productivity of activities. For example, consider a plant with a productivity rate of 5 jobs per day, where each job consists of 20 units (i.e., 100 units/day); if each includes 6 sequential activities, this would produce a 600-activity network, which may be relatively complicated to schedule and visualize. With the proposed framework, tracking data is easily accessed by the production manager using the system. As illustrated in Figure 2, the production manager can use the system to see the relative station productivities, as well as the more detailed statistics relevant to a selected station or job.

The proposed system will decrease the time required for a production manager to view data required for making effective management decisions, but will still require them to be able to identify the particular job or location they want to see and navigate through the user interface to find the required data.

In the future, this system could be improved through the use of AR as a tool to help the production manager visualize the information; however, current AR technology requires some improvement to ensure that the safety and maneuverability of the manager using the system can be maintained.

5.1 Future Visualization Improvements

The visualization solution would ideally match the complexity of the data presented to the user while considering elements of user experience (UX) specific to factory environments. For instance, safety is a major concern on construction sites and in manufacturing facilities. Computer equipment such as a tablet must be relatively rugged compared to standard office equipment and may require protection from environmental elements such as dust proof enclosures to protect from saw dust. Depending on the manufacturing facilities, these types of considerations must be accounted for. The simplest solution would be to use existing technologies such as tablets and smartphones. Graphs and charts would present the user with context-sensitive data. At the time of writing this paper, 2D data visualization technologies and techniques are mature and relatively user friendly to implement. In his study, Tufte provides guidelines for visualization of complex data [22], making this solution highly feasible; however, it is not without its challenges. Most importantly, tablet screens can distract the user from their environment and could lead to safety issues.

A preferable solution would be to implement augmented reality elements in the visualization. Such a system would ideally use a head mounted display, such as Google Glass or Microsoft Hololens, to overlay the data over the factory view of the user. This would allow the user to move around the factory environment without having their hands occupied and without having their attention diverted back and forth to a screen—a distraction that could be a safety hazard. Furthermore, overlaying data on a real-life scene could enable more effective and contextual data visualization. For instance, 3D CAD models could be overlaid on existing components. This could be coupled with data which describes the length of time needed to complete the operation in the current station, the length of time required for all remaining production for the specific component, or additional information about the job. Figure 4 illustrates how an AR system of this kind would appear to the user.

Detailed implementation of this kind would be contingent on the development of improved technologies that can track the locations of factory elements in real time and with a high degree of location accuracy. As more elements are tracked more data is collected in real time and is run through the simulation. The implementation of a system such as this is also dependent on the development and integration of an AR system that can update quickly enough to satisfy the needs of the proposed framework and allow the system to move wirelessly throughout the plant.

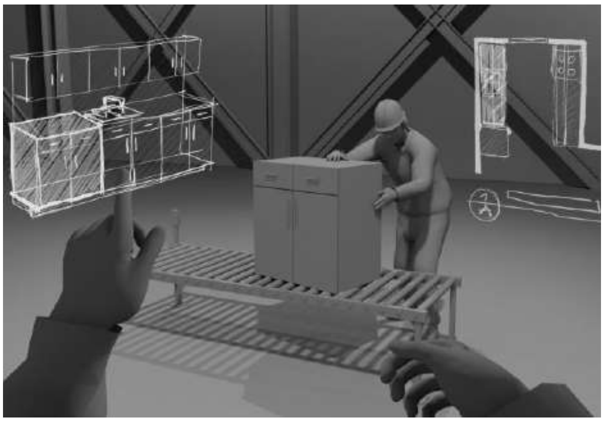

Figure 4. AR overlay of BIM model

6 Conclusion

An effective manufacturing facility requires efficient data exchange between the office and the production line, which enables production managers to make decisions based on the most current information available. The framework proposed in this paper enables the automation of the data exchange and its presentation to the production manager.

The present study integrates the RFID system into the scheduling process and presents the results to the production floor manager. Implementation of the proposed framework provides increased access to tracking data, reduces waste in the communication process, increases the scheduling certainty, and innovatively presents real-time production data to the end user.

Data is currently presented to the user through hand-held devices, such as tablets of smartphones, but could be transferred to AR systems in the future to allow for hands-free viewing, and to enable the user to remain mindful of their surroundings. This transfer should only occur if the system allows for wireless movement throughout the production facility and enables the user to maintain a natural field of view for safety reasons.

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Designing LiDAR-equipped UAV Platform for Structural Inspection

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Abstract –

Efficient inspection and maintenance of bridges are vital for improving safety and sustainability of infrastructure systems. Recently, Light Detection and Ranging (LiDAR) scanners are used for detecting surface defects. The LiDAR scanner can be mounted on an Unmanned Aerial Vehicle (UAV), which provides easier accessibility to most parts of the structure and can fly close to the structure. There are two types of mobile LiDAR scanners: 2D and 3D. A 2D scanner is more affordable, but it can only scan points on a plane. However, a 2D scanner can be transferred into 3D scanner by rotating the scanner using a servo motor. This paper aims to design a platform for LiDAR-equipped UAV for structural inspection using an affordable 2D scanner. First, the requirements and other design considerations are introduced. Then, the design details and the hardware and software integration steps of the LiDAR-equipped UAV platform are discussed. The initial test of the platform showed that it can provide acceptable accuracy for detecting large defects.

Keywords –

LiDAR; UAV; Structural Inspection

1 Introduction

Efficient inspection and maintenance of bridges and other structures are vital for improving safety and sustainability of infrastructure systems. Traditionally, visual inspection using non-equipped eyes and manual measurements are used for detecting surface defects, which may lead to subjective results. This approach is time-consuming and unsafe, especially for inspecting the inaccessible elements of a bridge [1].

Recently, 3D Light Detection and Ranging (LiDAR) scanners [2] and cameras [3] are used for detecting surface defects (e.g. cracks) using computer vision methods. In general, LiDAR technology is more expensive than cameras, and defect detection results may miss some edge points. However, it is a promising method, not only for detecting the location and size of the defects but also for computing their depth and volume [4, 5]. Also, unlike digital images, the generated point clouds are not affected by lighting, and their analysis does not require supplementary information [6].

The LiDAR scanner can be mounted on a tripod [1] (i.e. terrestrial scanning) or on an Unmanned Aerial Vehicle (UAV) [7, 8] (i.e. aerial scanning). Although terrestrial scanning provides high stability for the scanner and less vibration, it is not time efficient. The aerial scanning provides easier accessibility to most parts of the structure and can fly close to the structure. Consequently, higher coverage of the inspected surfaces and more accurate results can be achieved.

In addition, the LiDAR-equipped UAV eliminates the inspectors' falling risks encountered in the traditional inspection method. The risk of damages caused by the UAV is low because of its size, weight, and controllability [10]. The Special Flight Operation Certification (SFOC), required by the Canadian Aviation Regulations, includes the plan of operation respecting specific safety rules, such as the distance between the operators and UAV, keeping people away from the flight site, and flying the UAV in the Line of View (LoV) [11].

LiDAR-equipped UAVs are used in different applications such as surveying [12], inspection [13], navigation [14], and agriculture [15]. There are two types of mobile LiDAR scanners: two dimensional (2D) and three dimensional (3D). A 2D scanner is more affordable, but it can only scan points on a plane, while a 3D scanner can capture the point cloud of the surrounding space, which makes the data more accurate. However, a 2D scanner can be transferred into 3D scanner by rotating the scanner using a servo motor [16] or by moving the scanner on a robot/UAV while collecting the point cloud [17]. The accurate rotational positions of the servo or the Simultaneous Localization And Mapping (SLAM) algorithm can be used to register the collected data. For example, in the research of Winkvist et al. [17] and Bachrach et al. [14], a 2D

LiDAR is mounted on the top of a UAV, and SLAM is used for generating the point cloud taking advantage of the vertical movement of the UAV. In order to increase the Field of View (FoV) of the scanner, in the ARIA project [16] a servo mounted on the UAV is used to rotate the scanner while the UAV is flying, which leads to collecting 3D point clouds for inspection and navigation purposes. However, the details of the platform design for integrating the UAV, the servo and the scanner are not available in the literature.

The objective of this paper is to design a platform for LiDAR-equipped UAV for structural inspection using an affordable 2D scanner. The remaining sections of the paper are as follows: First, the requirements and other design considerations are introduced in Section 2. Section 3 provides the design details and the hardware and software integration steps. Section 4 provides an initial test of the platform. Section 5 provides the conclusion and summary of future work.

(a) MIT RANGE [14]

(b) CMU ARIA [29]

(c) Stormbee [28]

Figure 1. Scanner position on top of UAV in (a) and (b), and under UAV in (c)

2 Design Considerations

In order to have a successful design of the LiDAR-equipped UAV, the following should be considered:

2.1 Objectives

The maximum coverage of the surface of the inspected structure and the minimum cost are the two main objectives of an efficient inspection using the LiDAR-equipped UAV. The main costs of this method are the equipment cost and the flight cost. The flight cost depends on the time of the flight. The full coverage may not be achieved because of the obstacle near the inspected structure, which can limit the visibility of the LiDAR. So, the path planning goal is finding a collision-free path with minimum time-of-flight and maximum coverage.

2.2 Requirements

In order to choose the most appropriate LiDAR-equipped UAV, all the following requirements should be considered with respect to the budget.

(1) Mounting location: Most of the commercially available solutions have the scanner mounted under the UAV because they are designed for surveying purposes (Figure 1(c)). However, for structural inspection purposes, the LiDAR can be mounted either on top (Figure 1(a) and (b)) or under the UAV depending on the location of the inspected area of the structure.

(2) Metrology method: There are two types of metrology methods for LiDAR: Time-of-Flight (ToF) and Phase Shift (PS). ToF is used for long range of measurement with the accuracy of 4-10 mm at 100 m. Unlike ToF, PS is practical for short range of measurement with 2-4 mm at 20 m [1].

(3) Maximum payload: The maximum payload is the weight that the UAV is capable to carry. Therefore, the weight of all carried devices (e.g. scanner, minicomputer, batteries, and GPS) should not exceed this threshold. The payload affects the UAV time of flight because carrying a heavier payload consumes more energy. As the weight of the scanner is one of the major weights in the payload of the UAV, it should be carefully considered. Providing a light and accurate scanner is expensive, and choosing the best option depends on the available budget. Moreover, extra batteries are needed to supply the power for the scanner and other electronic parts attached to the UAV (e.g. servo, microcomputer, etc.).

(4) Size of UAV: The UAV should be big enough to carry the scanner and other equipment, and small enough to fly safely as close as possible to the inspected surface.

2.3 Constraints

There are several constraints which should be considered during the planning.

(1) Minimum and maximum distances: A specific distance range should be considered during inspection based on safety and the characteristics of the scanner. The density of the scanned point cloud decreases with longer distances.

(2) Battery capacity: The battery capacity has effects on the time of flight. As mentioned above, although adding more batteries helps the UAV to fly further, it increases the weight of the system.

(3) Vibration: The vibration of the LiDAR-equipped

UAV during inspection causes errors. A suitable design of a LiDAR-equipped UAV, which includes designing an appropriate engine and body shape, installing dampers, etc., can decrease the vibration [18].
(4) Degrees of Freedom (DoFs): Each UAV has six DoFs: three displacements (x, y, and z) and three rotations (roll, pitch, and yaw). In general, the pitch and roll of the UAV are constrained to keep the UAV in a horizontal position.
(5) LiDAR parameters: The 2D and 3D scanners have one and two FoVs, respectively. The FoV is an important parameter in the visibility analysis. Furthermore, other important parameters of the scanner are the angular resolution ($\Delta\theta$), incidence angle (θ), and beam diameter (Figure). The accuracy of a point cloud is mainly related to the measurement resolution, angular resolution and scanning speed. In the case of the 2D scanner integrated with a servo, the angular resolution and the speed of the servo affect the accuracy of the generated point cloud.

2.4 Other considerations

(1) Safe operation: Mounting additional devices should not change the center of gravity of the UAV because it effects on the stability of the UAV. Also, the additional devices should not interrupt the GPS signals.
(2) Real time: The LiDAR-equipped UAV platform has to collect a large amount of point cloud data to be used in real time for path planning and obstacle detection.

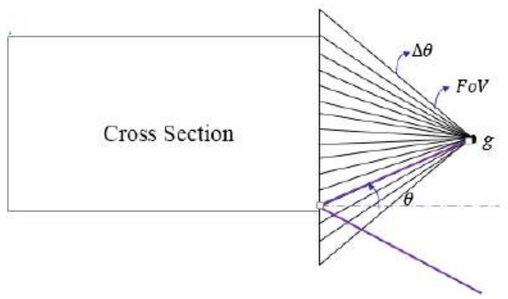


Figure 2. Some specifications of the LiDAR

3 Platform Design

UAV selection

DJI Matrice 100 [19] is used in this platform because it is customizable and has expansion bays to mount the scanner and other devices on top or below the UAV. Also, its radius is less than one meter, which makes it agile and able to enter narrow spaces near the inspection surfaces. The specifications of this UAV are shown in Table 1. The maximum payload is about 1.2 Kg.

Table 1. UAV specifications

Specification	Value
Max takeoff weight	3.60 Kg
Net weight	2.43 Kg
Battery	5700 mAh – 22.8V
Diameter	996 mm
Hovering time (no payload)	28 minutes

LiDAR selection

Hokuyo UTM-30LX 2D laser range finder is used for data collection because of its light weight and affordable price [20]. The specifications of this scanner are shown in Table 2.

Table 2. Scanner specifications [19]

Specification	Value
Detection range	0.1 ~ 30m
Accuracy	±30mm (under 10m)
Horizontal FoV	270º
Angular resolution	0.25º
Scan speed	43,200 points per second
Weight	210 g (without cables)

Servo selection

In order to enable the scanner to generate a 3D point cloud, a servo is used to rotate it. Dynamixel MX-28T is a robotic actuator servo that can control the movement of the scanner with a minimum step of 0.088º, which means the angular resolution of the platform is 0.088º. By rotating the scanner 180º, the vertical FoV of the scanning becomes 360º.

The servo uses an adapter (USB2Dynamixel) to connect to the microcomputer and another adapter (SMPS2Dynamixel) to connect to the battery. Both the servo and the scanner need a 12V power supply.

Microcomputer selection

To control the scanner and the servo, and to collect data from them in real time, DJI MANIFOLD microcomputer is selected in this platform because it is compatible with the UAV [21]. The power for MANIFOLD is supplied directly from the UAV.

Electronic connectors

An isolated voltage regulating board is designed and built to convert the 25V power of UAV's port into 12V. This board makes it possible to run the scanner and servo without adding an extra battery. The weight of the voltage regulating board is 72 g.

Interfacing parts using 3D printing

Although previous research exists about interfacing a servo with 2D LiDAR [22] , the integration with the

UAV requires additional interfaces to control the direction of the scanning. Three different interfacing parts are designed and 3D printed to attach the scanner and the servo to each other and to the UAV. The designed parts are shown in Figure 3. Figures 3 (c) and (d) show the parts for attaching the servo to the UAV in vertical or inclined positions, respectively.

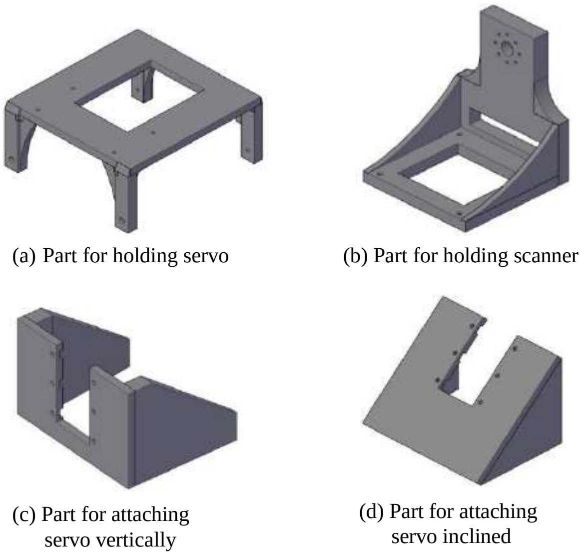


Figure 3. Design of interfacing parts for 3D printing

3.1 Integration

To integrate the components, hardware and software integrations are required. These are discussed in the following sections.

3.1.1 Hardware Integration

Figure 4 shows the integration of the hardware components of the platform. Table 3 shows the summary of hardware specifications and their connectivity to each other. The total weight of the integrated platform is 3.13 Kg, which is less than the maximum takeoff weight of the UAV.

In this platform, the scanner rotates 180º (from -90º to 90º). It stops for 0.1 s when changing direction from clockwise to counterclockwise. This stop causes some errors in the registration process of the point cloud. It is possible to rotate the scanner continuously in one direction by adding a slip-ring between the scanner and the servo to eliminate the rotation of the cables of the scanner. Figure 5 shows the interfacing part for mounting the servo on the UAV vertically or with inclination, and the corresponding configurations of the LiDAR-equipped UAV platform.

3.1.2 Software Integration

Spin Hokuyo Robot Operating System (ROS) software package is installed on the microcomputer to create 3D point clouds in real time [23]. This software works under Ubuntu operating system and contains the code to control the servo and the scanner to generate a 3D point cloud. Spin Hokuyo has five nodes for the following purposes: (1) two nodes (tilt motor and tilt transform) for controlling the servo and assembling point cloud messages; (2) one node (Hokuyo robot filter) to remove unnecessary points that are related to the body of the operating robot. It eliminates all the points inside the radius of 50 centimeters; (3) one node (scan to PCL (Point Cloud Library)) to convert the scanned data into point cloud messages; and (4) one node (PCL assembler client) to combine all the published point cloud messages into one point cloud message. Spin Hokuyo can adjust the initial, start and end positions of the servo and its rotation speed. The SLAM algorithm can be used in the software package to enable the platform to scan during the UAV flight.

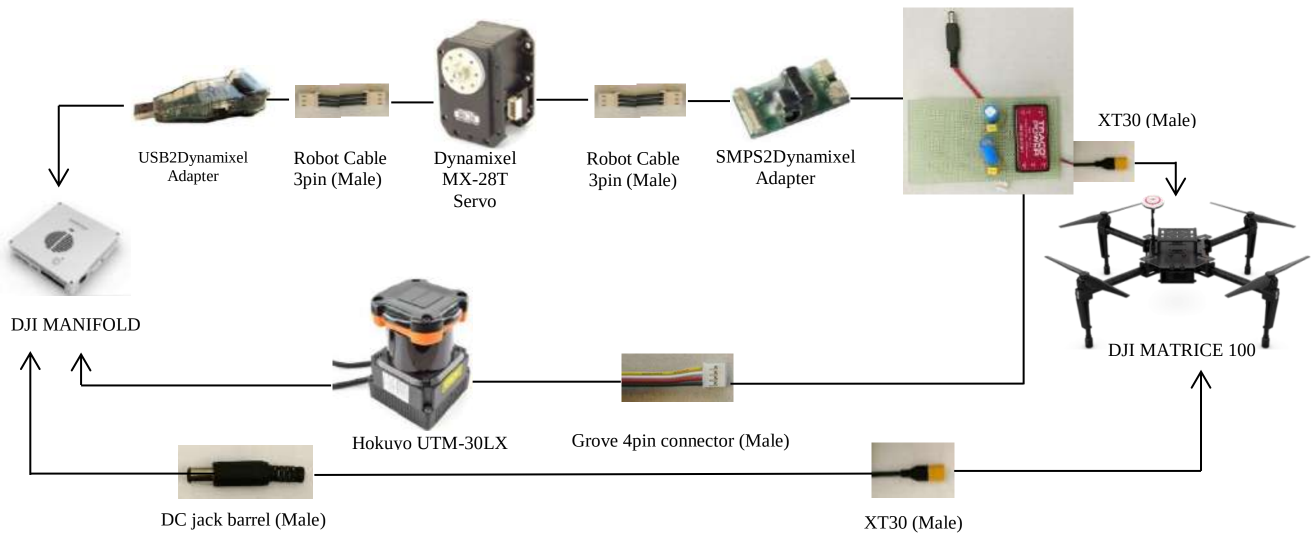


Figure 4. Hardware integration

Table 3. Summary table of hardware components

Component	Function	Voltage (V)	Current (A)	Weight (g)	Attached to
Hokuyo UTM-30LX	Laser Scanning	12	1.0	210	MANIFOLD, Voltage Regulator Board
MANIFOLD	Controlling scanner and Servo	14-26	Up to 10	197	UAV, USB2Dynamixel Adapter, scanner
Dynamixel MX28T	Rotating scanner	12	1.4	72	USB2Dynamixel Adapter, SMPS2Dynamixel Adapter
USB2Dynamixel Adapter	Connect servo to MANIFOLD	N/A	N/A	28	Servo, MANIFOLD
SMPS2Dynamixel Adapter	Power supply for servo	12	1.4	14	Servo, Voltage Regulator Board
Voltage Regulator Board	Regulate the voltage to 12V	9-36	3.3	72	SMPS2Dynamixel Adapter, scanner, UAV
Part for holding servo	Connect servo and scanner to UAV	N/A	N/A	45	UAV, 3D printed servo part
Part for attaching servo vertically	Connect servo to the table part	N/A	N/A	26	Servo, 3D printed table part
Part for attaching servo inclined	Connect servo to the table part	N/A	N/A	29	Servo, 3D printed table part
Part for holding scanner	Connect scanner to servo	N/A	N/A	31	Servo, scanner

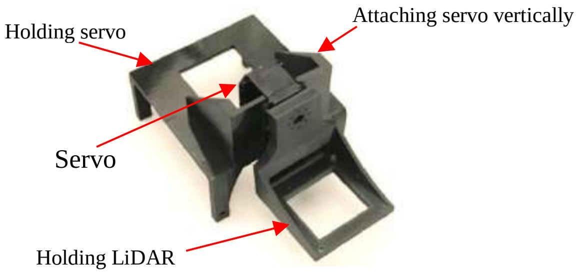
After scanning, the point cloud that is generated by Spin Hokuyo can be visualized in Rviz (ROS 3D visualization tool) [24]. Rosbag package records the output messages of spin Hokuyo and save them as Bag file [25]. There is a node named *Bag to PCL* in PCL-ROS package, which reads the Bag file and converts ROS point cloud messages to PCD (Point Cloud Data) files [26] CloudCompare software can open and visualize PCD point cloud files, and convert them to other point cloud file formats, such as LAS, LAZ and E57 [27].

In this work, Spin Hokuyo is used in a stationary mode for initial testing as explained in Section 4. When integrated with In the case of flying on a UAV, because the GPS signals may not be available when the UAV is flying under a bridge., Therefore, other localization methods can be investigated, such as integrating an onboard Inertial Measurement Unit (IMU) with Visual Odometry (VO), Simultaneous Localization and Mapping (SLAM) algorithms, or Lidar Odometry and Mapping (LOAM) [16].

4 Initial Testing

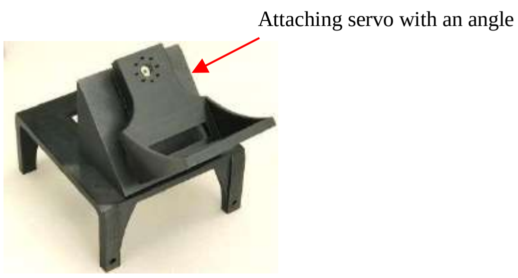
Before moving to outdoor flying tests of the designed platform, the initial test is performed in an indoor environment, and it is limited to testing the LiDAR system (LiDAR, servo, microcomputer, battery, interface elements and connectors) when the drone is stationary. The width, length and height of the room are 4, 7 and 3 m, respectively. The generated point cloud is shown in Figure 6(a). Color distribution of the point cloud is based on elevation. The horizontal and vertical FoVs of the LiDAR system in this test are 270º and 360º, respectively. The LiDAR scans the environment in 2D lines, and each line contains 1,080 points. The number of lines of scanning in a sweep is dependent on the rotation speed of the servo. In this test, the rotation speed was set on 0.5 radians per second. Each sweep is π radians, so, one sweep was taken about 6.28 s to complete. The LiDAR scans 40 lines in a second, so, one sweep should contain about 251 lines and almost 270,000 points. The point cloud shown in Figure 6(a) is generated by 13 sweeps, and contains 3.2 million points. Each sweep has about 250,000 points. Some points are eliminated by the filtering node.

In order to check the accuracy of the collected point cloud, the same space was scanned with a higher accuracy 3D LiDAR scanner (FARO Focus3D) to generate a ground truth point cloud. FARO Focus3D is a 3D laser scanner with the accuracy of 2 mm, which can scan about one million points per second [26][22].

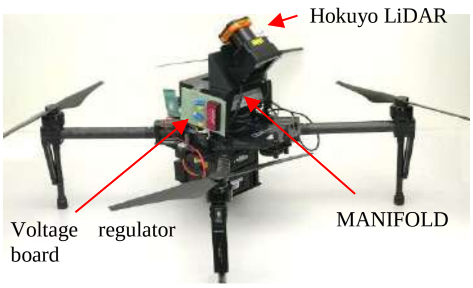


(a) Interfacing part for vertically mounting

(b) Platform with vertial LiDAR

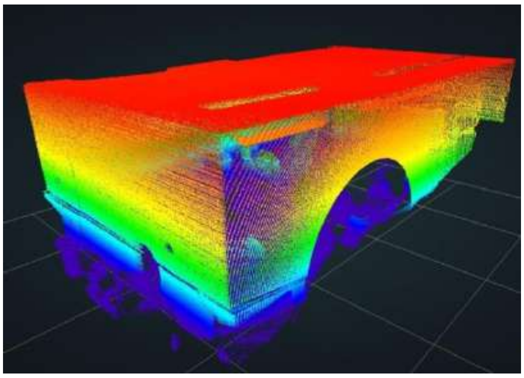


(c) Interfacing part for inclined mounting



(d) Platform with inclined LiDAR

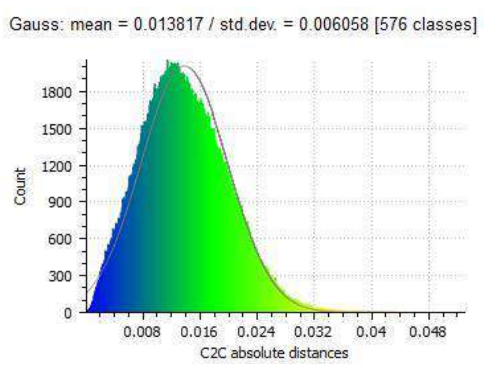
Figure 5. LiDAR-equipped UAV platform



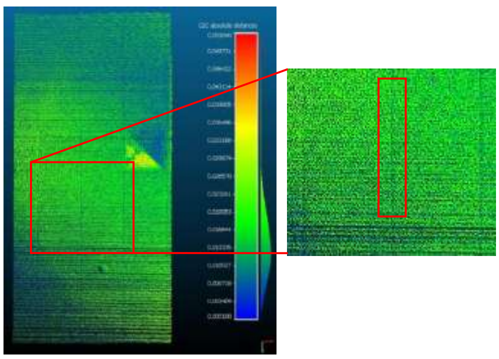
(a) Generated point cloud by the designed platform

(b) Segment of point cloud

(c) Reference segment using FARO



(d) Comparison distance distribution histogram (m)



(e) Compared segment coloured based on distances from the reference segment

Figure 6. Initial testing results

A segment of the ceiling with the dimensions of 2.3 m × 4.7 m is selected (Figure 6(b)) and compared as cloud-to-cloud distance by CloudCompare software, where the distance of each point of the compared cloud is measured to its nearest neighbor in the reference cloud.

The two point clouds were aligned to each other manually in CloudCompare by picking five equivalent point pairs. Each segment contains about 250,000 points. The segment point cloud from FARO (Figure 6(c)) is considered as the reference cloud. The distance distribution histogram of the comparison is shown in Figure 6(d). Gaussian distribution is used in this computation, and the mean of the distribution is 1.4 cm with the standard deviation of 0.6 cm.

As shown in Figure 6(e), the gaps between the drop ceilings tiles of the room are visible. The width of these gaps is about 2 cm, which is greater than the calculated error. Assuming that these gaps are similar in size to some large cracks that could be detected on the actual structure during inspection, the accuracy of the point cloud collected by the platform can be considered enough to detect this size of cracks.

5 Conclusion and future work

In this study, a LiDAR-equipped UAV platform is designed to collect 3D point cloud data using a 2D LiDAR scanner. The design satisfies the main identified requirements and constraints for structural inspection. The platform is realized and tested in an indoor environment in a stationary mode.

Our future work includes: (1) applying the LOAM method integrated with an IMU to register the point cloud when the UAV is flying, and (2) testing the platform in the outdoor environment and defining the size of the defects that can be detected based on the accuracy of the data..

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Research Trend Analysis for Construction Automation

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Abstract –

Automation has been an active research topic in the construction industry for many years to improve the accuracy, reliability, and efficiency of the construction process. This study identifies global research trends in automation in construction during the past 15 years by analyzing papers published in the journal *Automation in Construction*. Text mining, data clustering, and keyword network analysis were applied to identify emerging technologies.

According to the clustering of the most recent three years' research, the main topics fall into seven categories: BIM(building information modeling), optimization, data acquisition, big data and AI, 3-D printing, wearable devices, and others. Over the various regions and periods, the results showed that the research focus has shifted from traditional mechanical automation to construction data acquisition, management, and analysis, introducing a new historical period in construction automation.

Keywords –

***K*-means clustering, Text mining, Keyword network, Trend analysis, Construction automation**

1 Introduction

Construction automation can improve construction quality, work productivity, and safety. Under the trend Industry 4.0, studies of smart construction technologies related to machine learning and the internet of things (IoT) and information and communications technologies (ICT) are currently the focus of active research.

Research trend analysis is essential to securing core source technology through R&D, and it is also essential to assess current technology status and to identify promising research areas for construction automation. Therefore, it is important to assess the current state of technology and to identify promising research fields in construction automation [1–5].

As the primary outcome of basic research, a research paper contains detailed and specific descriptions of the research activities, so papers are rich and valuable data for understanding innovations and changes in technology [6]. Therefore, the use of research data for understanding the status of the technologies of construction automation can be considered as a significant analysis method.

Text mining is a representative, quantitative research method using natural language processing (NLP), and is currently used to extract keywords from large amounts of unstructured data and to derive implications through clustering [7]. In this paper, we apply machine learning based on the *K*-means clustering method to cluster research papers into several groups covering individual research topics. Core technologies by categorical groups are identified through the retrospective analysis method.

Keyword network analysis can be used in various studies, such as coincidence analysis of main keywords, social network analysis, and papers and patents citation analysis. This technique is currently used in various fields, such as social science, physics, and economics [8]. We used keyword network analysis to follow historical trends and to anticipate future patterns of research keywords.

The purpose of this study is to contribute to proactive research and development by comparing and analyzing research papers related to domestic and foreign construction automation technology in depth. Also, keyword-based semantic approach suggested a possibility of effectiveness in the analysis of technological trends, prospects in the construction field.

2 Theoretical Background

2.1 Literature Review

Several studies on trend analysis and prediction using research papers and patents have been conducted for construction automation. Son and Kim identified global trends and issues in automation and robotics technology in the construction industry by analyzing papers published in the proceedings of the International Symposium on Automation and Robotics in Construction (ISARC) [9]. Balaguer and Abderrahim analyzed robotics and automation in construction [10].

However, since 2010, there has been no analysis of trends in construction automation research. This study identify the state-of-the-art research trends in construction automation to reveal promising technologies in the past 15 years.

2.2 Text Mining

Text mining refers to extracting information from unstructured text data in natural languages. It extracts and processes hidden patterns or relationships and finds useful and meaningful information. It is based on NLP. The process of text mining consists of data collection, preprocessing, analysis, and visualization of extracted data.

2.3 TF-IDF

TF-IDF is a weight value for each word used in text mining. It is a statistical weight used to determine the importance of a word in a specific document.

Term frequency (TF) is a value indicating how often the selected word appears in a document. Higher values indicate that the term is more important in the document. If the word is frequently used within a set of documents, it generates a high document frequency. The reciprocal of this value is called the inverse document frequency (IDF). TF-IDF is the product of TF and IDF [11].

The IDF value is determined by the nature of the document family. For example, the word “construction” does not appear very often among general documents, so its IDF value is high and it can be a keyword in documents. However, if the document family is a collection of construction papers, “construction” becomes a cliché, and other words will receive high weight values.

2.3.1 Mathematical Background

The simplest method to calculate the TF is to use the total frequency of the word appearing in the document. If the total frequency of word t in document d is $f(t, d)$, then the simplest TF calculation method is expressed as $TF(t, d) = f(t, d)$.

Another way to calculate the TF value is called increasing frequency, adjusting the word frequency according to the length of the document as follows:

$$\mathrm{tf}(t,d) = 0.5 + 0.5 \cdot \frac{f_{t,d}}{\max\{f_{t',d} : t' \in d\}}$$

IDF indicates how frequently a word appears in an entire document set. It can be obtained by dividing the total number of documents by the number of documents containing the word and then taking the log.

$$\mathrm{idf}(t,D) = \log \frac{N}{|\{d \in D : t \in d\}|}$$

If a word appears frequently in a particular document but only a small number of documents contain the word, the TF-IDF value is high. Therefore, the TF-IDF value is utilized to filter words that are common in all documents. Because the IDF log value is always one or more, the IDF value and the TF-IDF value are always zero or more. As the number of documents containing a certain word increases, the value in the log function becomes closer to one. In this case, the IDF value and the TF-IDF value converge to zero:

$$\mathrm{tfidf}(t,d,D) = \mathrm{tf}(t,d) \times \mathrm{idf}(t,D)$$

2.4 Keyword Network Analysis

To obtain a correlation and historical tracking of keywords, we used keyword network analysis. A keyword network consists of main streams, nodes, and links. A keyword is extracted from the author’s keyword list and indexing keywords provided by *Automation in Construction*. This keyword-based analysis creates several groups of keyword networks with relationships between keywords, and the results afford a sense of the evolution of research trends in construction automation.

2.5 Clustering Method

A clustering method is an analytical technique in which objects are grouped into clusters so that individuals having similar characteristics are grouped together.

In text mining, the extracted keywords are vectorized, and the correlations between documents and words are extracted based on a distance, such as Euclidean distance, cosine similarity, or Manhattan distance between words to perform clustering.

The main purpose of data clustering is to identify the characteristic of each clustered class, and *K*-means clustering, *K*-nearest neighbors clustering, and principal component analysis are the main methods used to cluster the data.

This study used *K*-means clustering after text mining. This method clusters a given data set into *K* classes according to the median values, and it is an efficient method for finding clusters from large amounts of data.

3 Research Analysis

To analyze the research trends in the automation of construction, three main analyses were carried out in this paper. First, the number of papers published over the past 14 years was surveyed to observe global trends in the research and to find quantitative contributions. Second, studies over the past 15 years were divided into five-year periods, to derive the correlation for each research keyword over time through keyword network analysis. Finally, research methods and subjects were extracted and clustered over the past three years to investigate the latest research trends.

3.1 Data Collection

In this study, 1880 research papers were collected, published by *Automation in Construction*, during the period between 2004 and 2018. An R program was used to conduct keyword extraction, preprocessing, frequency acquisition, and *K*-means clustering.

3.2 Relative Research Contributions by Country

Figure 1 quantitatively shows research trends in the world’s automation in the construction area from 2004 to 2017. The graph shows the number of research papers related to construction automation published in each country over those 14 years. The research scope of this paper covers papers published until February 2018; however, the papers published in 2018 were excluded from this analysis to show annual trends.

From 2010 to 2013, a quantitative expansion in research around the overall region is observed, while numbers remained almost steady in the earlier period. The United States’ contribution to the total number of papers has been very dominant overall. However, China showed remarkable growth from 2012 to 2013. This is an indirect indicator that China’s research investment toward automation construction is growing explosively. It has been predicted since the late 2000s that China will become a leading country in future automation research along with the increasing R&D in construction technology [12].

3.3 Keyword Network

To visualize and analyze the trend flow of construction automation over the past 15 years,

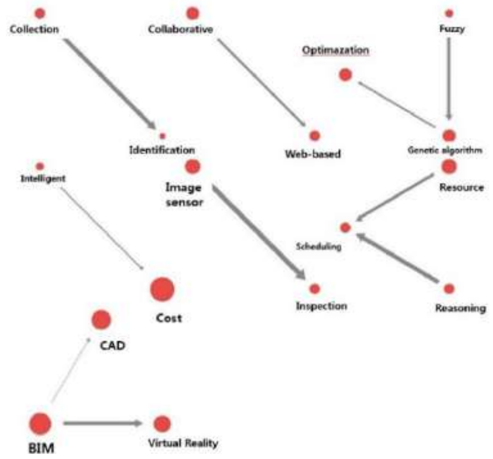

Figure 2. Keyword network, 2004–2008

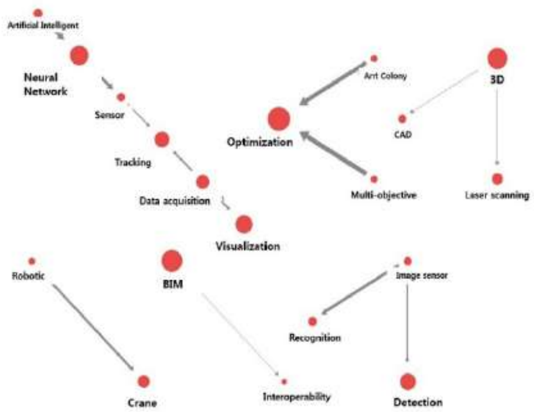

Figure 3. Keyword network, 2009–2013

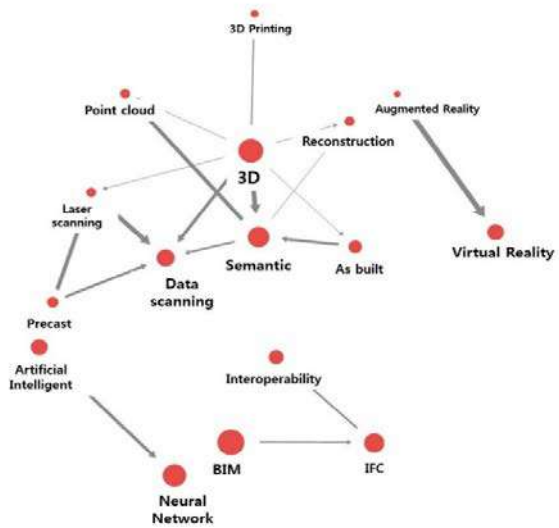

Figure 4. Keyword network, 2014–2018

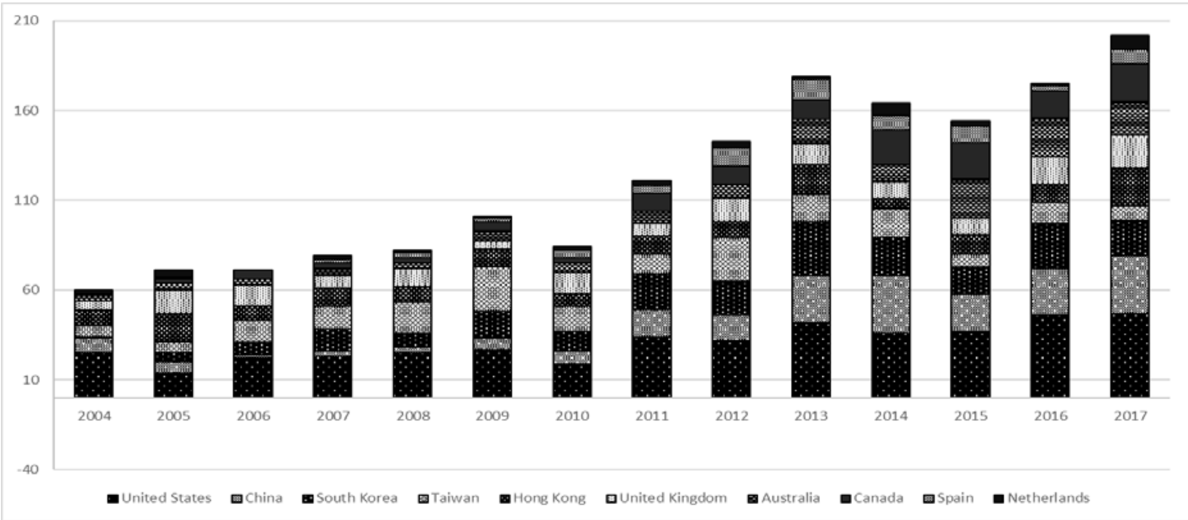

Figure 1. Relative research contributions by country, period 2004–2017

abstracts were gathered in five-year groups, keywords were extracted, and the correlations between keywords are visualized through the following network diagrams. In these diagrams, a larger circle indicates higher frequency and significance of the keyword. The direction of each arrow indicates the dependencies between keywords. A keyword without an arrow link means a separated technical factor keyword.

As shown in Figs. 2–4, research on BIM technology elements is maintained at a high level, and industry foundation classes (IFCs) and interoperability are active research fields. This suggests that the two technologies play important roles both as technology providers and technology adopters in construction automation.

Optimization studies are evolving and proceeding steadily with methodologies such as fuzzy theory, ant colony, genetic algorithm, particle swarm theory, and neural network theory on cost and scheduling, off-site placement, delivery, and simulation.

In the 2014–2018 period, improvements in emerging research areas such as laser scanning and 3-D reconstruction through point-cloud were observed. Further research on the visualization of buildings using drones and conversion between 2-D and 3-D drawing is expected. Real-time detection and tracking of construction equipment and workers with image sensors, augmented reality, virtual reality, and artificial intelligence can be identified as independent technology fields, and these fields are expected to be actively related with construction automation in future.

3.4 Research Trend during the Past Three Years

For research papers in 2015–2017 plus the 113 research papers in early 2018, *K*-means clustering was conducted to extract and analyze the main research topics and keywords for a total of 469 research papers.

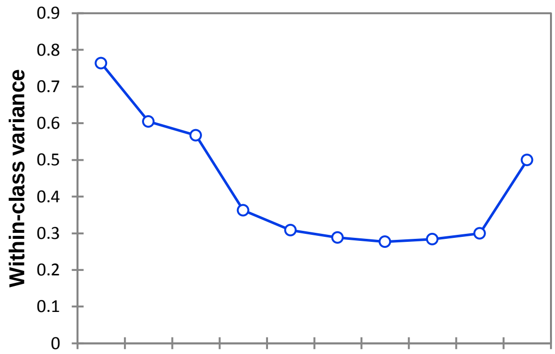

Figure 5. Variance within classes according to the *K*-value in *K*-means clustering

The *K*-value that minimizes the variance of the mean distance for each cluster was selected through repetition. Figure 5 shows the variation of variance according to *K*-value.

The topics and keywords extracted from each group after selecting a *K*-value of 7 are shown in Table 1. The number below the topic title is the number of research papers containing that topic.

Table 1 Extracted topics and keywords of the 2015–2018 group

Topic	Keywords
BIM (110)	CAD, 3D, 4D, management, IFC, data, interoperability, simulation, assessment
Optimization (57)	Algorithm, network, scheduling, layout, multi object, planning, swarm, harmony, genetic, ant

	colony, path
Data acquisition, (56)	Reconstruction, point cloud, detection, image sensing, RTLS, RFID, laser scanning, identification, inspection, monitoring, visualization
Big data, AI (29)	Neural, network, machine learning, energy, IoT, decision, monitoring, surveillance
Wearable devices (13)	Safety, worker, health, device, monitoring, occupational, physiology, sensing, management, hazard, identification
3-D Printing (12)	Fabrication, contour crafting, additive, adhesion, concrete, interlayer, pavement, structural
Other (192)	Energy, decision-making, safety, environment, equipment, earthwork, tunnel, bridge, assembly, mobile, musculoskeletal, prefabricate, excavator, interaction

In the clustering process, six methodology keywords for construction automation were extracted to improve clustering efficiency, and then the scope and objects of the classified categories were analyzed. The topics were divided into seven main categories; BIM, optimization, data acquisition, big data and AI, 3-D printing, wearable devices, and other.

BIM has become a common keyword in most fields, from architecture to civil engineering, and has been actively studied in all fields. Interoperability has been very actively studied to solve the problems of data sharing and consistency through an IFC.

In data acquisition, construction information was acquired through 2-D and 3-D image sensing and laser scanning. Extensive research was conducted on equipment and worker movements through site monitoring, maintenance of buildings through detection of damage sites, and 3-D reconstruction through point clouds.

Optimization has been applied to various fields, such as off-site yard and form placement, crane and lift operation, critical path analysis, and construction material management using different algorithms. Many studies have utilized experimental and evolutionary methods such as artificial intelligence, neural network theory, and big data.

In addition to the BIM and data acquisition topics, because the several technical elements have converged, it was difficult to specify papers as applying only to one research field. For example, laser scanning and BIM technology have been utilized together to analyze construction errors between as-built and as-designed through comparisons [13].

For wearable devices, studies on safety and risk management through real-time tracking were mainly performed by attaching sensors to workers.

There were also 192 papers not belonging to the above topic categories (grouped as “other”), and their keywords throughout the category were mainly related to construction data.

4 Conclusion

Text mining and *K*-means clustering were applied to research papers to analyze research trends and promising technologies for construction automation. The abstracts of 1880 papers published between 2003 and 2018 were analyzed in this study.

The construction industry mainly depends on manpower and is very vulnerable to variations in conditions. Different regional environments mean that no two projects are identical, which increases the dependency on experience and past performance. This leads to great difficulty in accumulating and utilizing well-organized quantitative construction information data.

Our research has discovered the changes in direction and focus of construction automation, from robotics development and machine automation to IT technologies. Construction robot development was very strong during the 1990s and was expected to be still the main research topic in construction automation [10]. However, only 13 robotics-related papers were found in the clustering analysis of the past three years of research. This was a relatively low research status compared with other topics. This implies that construction automation is not only replacing the labor force by adopting new construction methods but also by acquiring, analyzing, processing, and managing construction knowledge data using emerging technologies, such as big data processing, IoT, and artificial intelligence technologies.

A limitation of this research is that this paper gathered only abstract data rather than complete research papers; however, it is important that we used quantitative analysis methods rather than a qualitative method such as the Delphi technique or a survey. It was difficult to verify the characteristics and details of each research case. In addition, unique studies were treated as outliers and assigned to clusters that have less correlation in the clustering process.

By analyzing correlations with a keyword network diagram, current research trends and issues in construction automation were identified. In subsequent research, we expect that by tracking the knowledge transfer process through each paper's influence factor and identifying collaborative research networks based on research institutes and countries, quantitative and qualitative analysis of research flow and development will be possible.

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Reassigning Construction Laborers based on Body Motion Analysis

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Abstract

Construction laborers perform multiple labor intensive and physically demanding tasks, which exposes them to the risk of work related musculoskeletal disorders. When construction laborers sustain these injuries, they are typically reassigned to other tasks. The body motion involved in carrying out the assigned task should have limited use of the affected body part(s). This has implications on the productivity and health of a reassigned laborer. Traditional approach to reassigning laborers are subjective and ignores the effect of the tasks on the affected body part. To address this limitation, an ergonomic analysis framework is proposed to quantify the risk factors associated with body parts during the execution of construction tasks, so as to enable the reassignment of construction laborers to tasks that will impose the least strain on the affected body part. Preliminary results are provided to demonstrate feasibility.

Keywords –

Construction laborers; Work-related musculoskeletal disorders; Reassignment; Wearable technology

1 Introduction

In the construction industry, Work-related musculoskeletal disorders (WMSDs) make up about 37% of injuries experienced by the workers [3]. Of the injured workers, construction laborers are most likely to develop WMSDs because of the physically demanding nature of their tasks. The type of WMSDs usually sustained from these tasks are soreness and pains, carpal tunnel syndrome, sprains, strains and tears, and tendonitis (Figure 1). The most prevalent of these injuries are sprains, strains and tears. Figure 2 shows the rate of occurrence of this injuries amongst laborers in comparison to the overall construction industry. BLS [4] also shows that construction laborers are injured at the rate of 79.5 musculoskeletal disorders (MSDs) per 10,000 workers, while the overall construction industry's musculoskeletal injury rate is 49.2. Thus improving work safety practices of construction laborers is important.

Construction laborers perform a variety of tasks including removing debris and possible hazards, loading and unloading materials, bracing and unbracing scaffolding, digging and backfilling trenches and compacting earth to prepare for construction [5]. When they are injured, their supervisors typically reassign them to less strenuous tasks. This allows the laborer to continue working on the job and prevents the contractor or subcontractor from taking on a lost time injury on their experience modification rate (EMR) safety rating. Reassigning workers to less strenuous task is highly subjective and error-prone, as there is no means of verifying that the worker will be able to assume the postures required for the task. Each of these injuries affect different parts of the body and also restricts the movement of one or more limbs. Table 1 shows the types of MSDs and affected parts of the body. The degree of restriction on the limbs is determined from the postures and each posture is constrained by different muscle loadings, body and joint rotations [2], degree of bent of body parts [8], exposure to vibration and repetitive movements. Thus, to ensure that an injured worker remains on the job, while also being productive, it is important to reassign him to tasks that poses the least risk to the affected body part(s). Construction tasks are characterized by postures that involves multiple risk factors, this poses the following questions: (1) How can we reassign workers to tasks that poses the least risk to their injury, while also ensuring that they are productive? (2) How do we quantify the long term effect of this task on their health? This is important because there is currently no metric for assessing the potential effect the assigned tasks on the affected body part (or existing injuries) and potential of the injured worker to be productive on the reassigned task.

In-spite of the fact that a growing number of workers in the construction industry have WMSD, previous industry and research efforts have been focused on risk assessment [2,6,12,13,15] and prevention of WMSDs [10,14,16]. There have been limited efforts on how to keep injured workers on the job while also maintaining productivity. Furthermore, there have been limited focus on unskilled workers such as construction laborers and helpers.

The objective of this study is to propose an ergonomic analysis framework to (1) quantify the risk factors of postures, body parts and joints of tasks typically performed by construction laborers; (2) reassign injured construction laborers to tasks that will impose the least strain on the affected body part.

Table 1. MSDs and affected body parts [7,11]

MSD	Common affected body parts
Carpal tunnel syndrome	Fingers, hands, wrists
Tendonitis	Shoulder, waist
Soreness and pains	Neck, back, joints
Sprains and Strains	Joints (ankle, knee, elbow, shoulder), neck, lower back

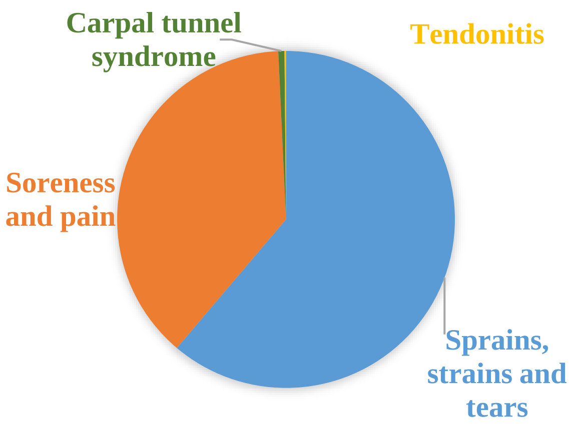

Figure 1. Proportion of occurrence of WMSDs amongst construction laborers

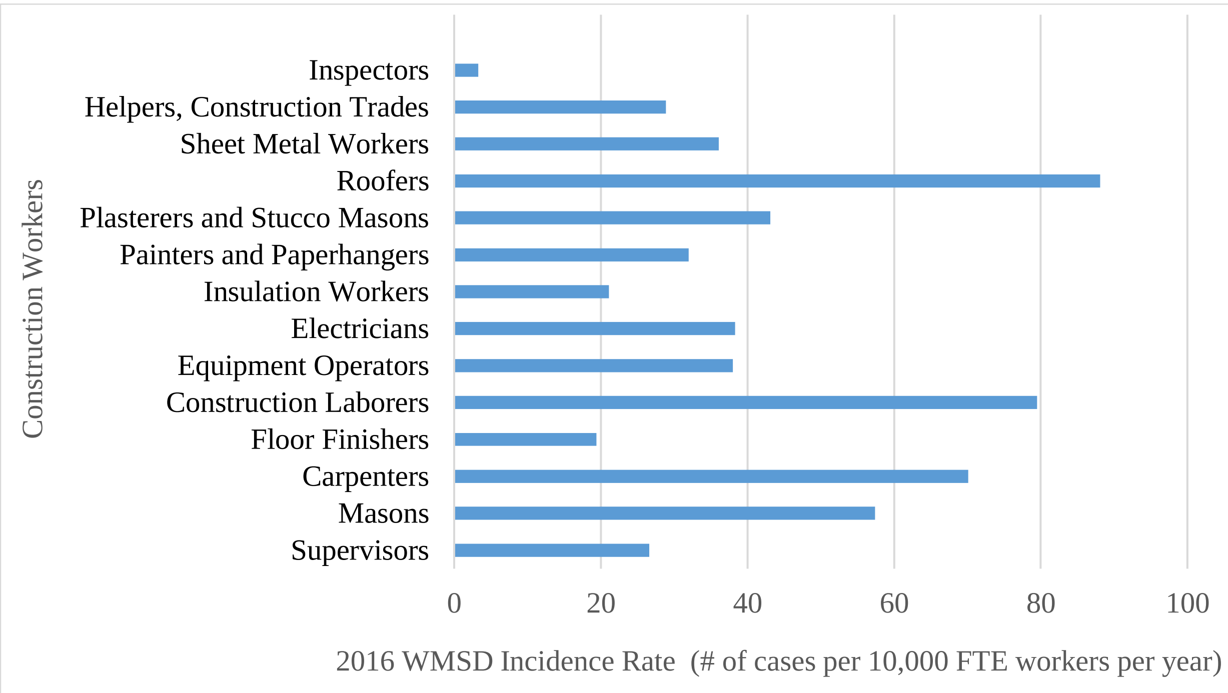

Figure 2. Rate of WMSDs amongst selected construction occupations for 2016

2 Framework for Construction Worker Reassignment

The proposed framework, shown in Figure 3, consists of the following stages: (1) Creating 3D human motion model to imitate tasks that construction laborers typically perform. In addition to this, actual body motion will also be generated from the lab and construction sites using image and component based sensing systems e.g. depth cameras and inertia measurement unit. Since it may not be physically feasible to capture all construction tasks, some of the tasks will be generated in the simulation model and complimented with the physically obtained motions; (2) Import the motion data from the body sensors into the 3D visualization platform; (3) Export the body posture data (from stage 1 and stage 2) from the 3D visualization into a database; (4) Store exported data in a database. The exported data are task, postures, associated body parts and loadings, joint angles and loadings; (5) optimize the data associated with each body part and joints (from stage 4) to predict construction tasks with the least risk to the affected body part; (6) Display suitable the task(s) and ranking(s)/associated effects on the affected part.

Depending on how the human body motion is being generated, the input could be the task process, task schedule, load, work environment and workspace design (i.e. if using the 3D Model) or the input could be the raw data depicting the body motion.

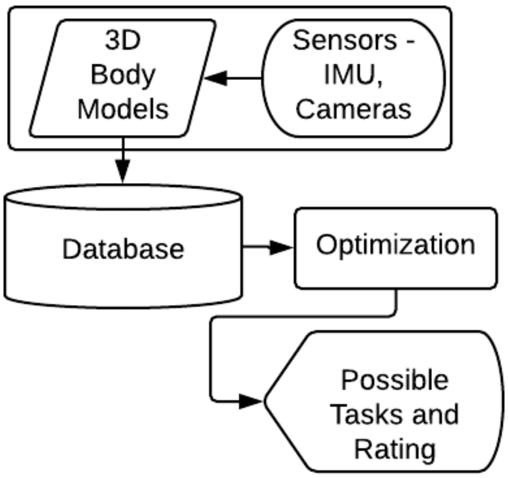

Figure 3. Framework for construction trade reassignment.

3 Preliminary Results

3.1 Sensing System

This study used the Inertia 3DSuit motion capture suit (Figure 4), which is a full body human motion capture system. The suit is based on 3D miniature inertial motion unit (IMU) sensors which includes tri-axial accelerometers, gyroscopes and magnetometers. The suit is equipped with an on-board signal processor and data fusion algorithm which extracts data from the sensors, processes the data and outputs the orientation of the sensors. The suit consists of 18 orientation sensors connected to a mobile bus processing unit which powers and receives data from the sensors via a serial protocol. The received data is wirelessly transmitted to any computer at the rate of 60Hz, to create a body skeleton of the tracked individual.

Figure 4. Inertia 3DSuit infrastructure showing the location of the IMU sensors.

3.2 Case Study

To illustrate the performance of the proposed framework, this case study describes a scenario of a worker who has knee disorder. The site manager has the option of reassigning the worker to one of the following three tasks: stacking wooden boards (Lifting); laying plumbing pipes (Plumbing) and installing lighting systems (Electrical). As part of an initial data collection, we designed an experiment to assess the motions, postures, body parts and joints of a subject while performing all three tasks in a laboratory setting. Prior to commencing the experiment, the computer was connected to a Linksys wireless router so as to aid capturing of motion data. The subject wore the suit and connected it to the wireless router. On calibrating the suit, the subject commenced each of the tasks. For example, while lifting and stacking the boards, the motion was recorded. The motion produced three key repetitive postures – Squatting, walking, and bending (Figure 5). At the end of the task, the recording was stopped and the data was saved. This process was repeated for each of the tasks. The extracted data was analyzed using Biovision software and exported as a .bvh file, which was visualized using Autodesk MotionBuilder. Figure 6 shows a typical bvh file. The posture and joint angles for each task was generated using Autodesk MotionBuilder.

(a) Swatting (b) Walking (c) Bending

Figure 5. Lifting Task Postures

3.3 Results

Table 2 shows the results of the case study discussed in the preceding section. The table shows the angles of the postures and affected joints of the three tasks.

```
HIERARCHY
ROOT Hips
{
    OFFSET 0.000000 0.000000 0.000000
    CHANNELS 6 Xposition Yposition Zposition Zrotation Xrotation Yrotation
    JOINT LeftUpLeg
    {
        OFFSET 7.620000 0.000000 0.000000
        CHANNELS 3 Zrotation Xrotation Yrotation
        JOINT LeftLeg
        {
            OFFSET 0.000000 -44.450001 0.000000
            CHANNELS 3 Zrotation Xrotation Yrotation
            JOINT LeftFoot
            {
                OFFSET 0.000000 -39.369999 0.000000
                CHANNELS 3 Zrotation Xrotation Yrotation
                JOINT LeftFootHeel
                {
                    OFFSET 0.000000 -8.890000 -3.810000
MOTION
Frames: 1540
Frame Time: 0.033345
0.000000 92.709999 0.000000 0.000000 0.000000 0.000000 0.000000 0.000000 0.000000 0
0.000000 93.775620 0.000000 -177.522858 -179.794708 -77.025269 -0.304687 2.126312 9
-0.088638 93.778946 -0.064178 -177.408279 -179.768250 -77.071159 -0.371310 2.141169
-0.164993 93.785400 -0.131210 -177.257370 -179.739853 -77.007706 -0.378414 2.271060
-0.245422 93.788635 -0.200562 -177.131302 -179.732941 -76.936188 -0.391063 2.372070
-0.291595 93.796135 -0.269043 -176.999634 -179.695618 -76.819115 -0.368510 2.490575
-0.314926 93.799065 -0.330246 -176.926605 -179.677399 -76.802353 -0.384335 2.576229
-0.329132 93.813141 -0.381302 -176.818832 -179.590729 -76.704216 -0.305526 2.673508
-0.352280 93.814529 -0.432312 -176.807678 -179.575073 -76.758606 -0.297006 2.688921
-0.380600 93.821915 -0.485306 -176.726578 -179.520920 -76.718971 -0.301624 2.718585
-0.406372 93.827499 -0.541428 -176.660980 -179.489029 -76.642937 -0.272040 2.779530
-0.428696 93.832840 -0.596024 -176.592926 -179.457016 -76.567581 -0.248322 2.837089
-0.452408 93.833824 -0.649384 -176.585220 -179.442215 -76.588425 -0.257118 2.855937
-0.470428 93.835480 -0.708237 -176.602692 -179.411133 -76.648079 -0.269994 2.859571
```

Start of Joint Structure Data
Offset from Parent Joint
Name of Current Joint
Joint Degree of Freedom
Start of motion data
Number of Frames Recorded
Frame Recording Rate (30Hz)
Rotational Data of first 6 channels

Figure 6. Typical bvh file

Table 2. Task, posture, affected joints and angles

		Angles								
		Postures								
		Task 1 - Lifting			Task 2 - Plumbing			Task 3 - Electrical		
Body Parts	**Joints**	**Swatting**	**Bending**	**Walking**	**Swatting**	**Bending**	**Standing**	**Reaching**	**Bending**	**Climbing**
Left Leg	Left Ankle	27.78	22.81	19.41	34.19	13.63	8.04	5.56	8.14	24.86
	left knee	15.72	133.75	17.67	29.05	50.51	63.45	7.21	13.94	56.38
	left hip	99.50	98.13	24.78	86.58	107.62	44.15	10.88	28.58	26.78
Right Leg	Right Ankle	32.64	32.76	11.35	27.98	8.30	9.97	6.27	6.84	9.12
	Right knee	18.40	44.36	18.35	18.78	55.13	13.84	8.26	39.09	14.70
	Right hip	115.09	113.87	10.08	114.2	106.98	14.04	11.49	51.97	40.30
Left hand	Left Shoulder	18.56	30.37	32.40	25.29	57.08	4.48	39.81	24.79	20.58
	Left elbow	25.74	67.86	15.97	77.67	13.25	8.82	72.32	68.55	46.61
	Left wrist	7.23	51.11	65.94	6.26	25.36	10.79	39.66	11.30	17.68
Right hand	Right Shoulder	34.06	35.45	51.27	29.64	60.10	9.47	53.94	23.82	8.27
	Right elbow	57.42	54.43	8.68	34.66	22.79	14.44	114.94	16.23	12.62
	Right wrist	28.94	36.69	5.78	79.57	39.06	34.44	77.42	56.60	50.75
Spine	Upper Spine	9.27	27.22	47.15	34.10	37.20	3.57	23.90	8.10	14.11
	Lower Spine	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Neck	Neck	19.22	7.63	2.99	3.49	20.65	16.81	28.24	34.91	4.89
Hips	Hips	49.87	43.92	18.49	37.18	87.02	6.01	5.003	18.46	37.23
Head	Head	19.22	7.63	17.83	3.49	20.65	16.81	28.24	34.91	4.89

The preliminary data consists of only the angles at the body joints for 3 tasks, as such, optimization is not required. For the purpose of identifying tasks with the least risk to the knee or that will not aggravate the existing condition of the knee, the angle at the knee will need to be compared for all the tasks. Andrews, et al. [1] identified that the risk of a disorder can be measured in terms of angle made by the affected part of the body i.e. the angle made by the knee in relation to the normal status i.e. when a worker is standing – when there is minimal physical stress on bones and muscles [9]. The larger the angle made by the knee, the higher the risk of injuries. Table 3 shows the risks for different knee flexion angles [1].

Table 3. Suggested sizes for measurement of knee flexion

Ergonomic Risk	Knee Flexion
Low	0^0-30^0
	30^0-60^0
	60^0-90^0
High	$>90^0$

From Table 2, by comparing the angles for the left and right knee, the 'Electrical' task appears to have the least angles and the least risk. However, in relation to Table 3, the risk to the knee of the laborer is still significantly high.

4 Conclusions and Future Work

This paper proposes a framework that uses human body motion analysis to reassign construction laborers. The framework uses body motion captured using 3D motion simulation software and motion sensors to capture tasks typically performed by laborers. The associated motion data of these tasks such as postures, affected body parts and joints, loadings on the body parts and joints, condition of the task environment, will be captured and stored for analysis. For any injured body part, these data will be optimized to predict construction tasks with the least effect on affected body parts. Preliminary work using a proprietary body suit has been presented.

For future work, a taxonomy of body motion of construction laborers for different construction tasks, will be developed.

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Gaming Approach to Designing for Maintainability: A light Fixture Example

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Abstract

Buildings are typically designed to be aesthetically pleasing and cost effective, leaving out maintainability. This is partly because existing tools do not permit the involvement of facility managers or their inputs in the design phase. This has often resulted in the design of buildings with components or systems that cannot be accessed or are too costly to maintain. Such non-functional building components affects the performance and often, satisfaction of building occupants. Maintenance of inaccessible buildings components have also been known to have implications on the safety of facility managers. Therefore, this paper presents an approach that uses a gaming platform to engage facility managers in the design phase, while capturing their knowledge and experience for the purpose of improving existing design tools and platforms. The functionality and usability of the developed approach is demonstrated.

Keywords –

Maintainability; Gaming Engine; Building Information Modeling

1 Introduction

Designing buildings without the perspective of maintenance managers often results in facilities that are either costly to maintain or has components that cannot be accessed. For example, light fixtures that can only be reached with scaffolding, which cannot be brought into the building. This has also been known to have implications on the safety of maintenance personnel e.g. in situations where a scaffolding can be brought into the building and there is no resting platform because the floor has a stair as seen in Figure 1. Such unreachable and unmaintained components leads to facilities with high initial and operating cost, decreased performance and often, reduced satisfaction among building occupants.

If involved in the design process, facility managers (FM) can provide valuable input into building designs, such as the type of components typically needing maintenance and the amount of tolerances/clearance to be provided around the components for accessibility. Although building information models (BIM) are designed to facilitate communication and collaboration between project stakeholders, it still lacks the information, and knowledge required to aid facilities management. Moreover, many facility managers lack the necessary knowledge and skills to interact with BIM [4]. This poses the following questions: How can FMs be engaged in the design process without the need to learn how to use the design tool? How can maintenance knowledge be captured so as to inform future designs?

Gaming engines are increasingly being perceived as useful platforms for design review, knowledge capturing and training. This is clearly evident in the use of serious games in the engineering, education, healthcare and marketing sectors. The success of serious games in any industry sector has been ascribed to its ability to actively engage and immerse users while capturing their thoughts and decisions. Although, the serious games has been actively researched in the architecture, engineering and construction (AEC) education, the link to BIM in the context of facilities management has received limited attention. Integrating BIM and gaming technology offers tremendous benefits for the AEC industry, including improvements to BIM in the area of design review and knowledge capturing for improving existing BIM design tools. Hence, this paper presents a framework for capturing knowledge and experience of FMs for the purpose of improving BIM tools for maintainability.

2 Background

It is increasing being recognized that the design phase provides an opportunity to eliminate waste or inefficiencies attributed to inaccessible/ unmaintainable components before they appear in the constructed facility [1,3]. Current approaches do not permit the involvement of FMs in the design phase. This has led to inefficiencies such as shown in Figure 1. Previous research indicates that there are limited tools and technologies for enhancing the involvement of FMs in the design phase.

Over the years, various researchers have demonstrated the potentials for BIM for enhancing both design and construction processes e.g. clash detection, scheduling, cost estimation, progress monitoring and safety management. However, the use of BIM for the FM phase has received little attention [7]. Recently, Liu and RA Issa [5] developed a tool that uses BIM for checking the accessibility of building components. Although, the tool has some potential for improving building maintenance, the role of FMs is still limited. Furthermore, the developed tool does not incorporate the knowledge of FMs for future designs. Other research works have also developed processes for early involvement of facility managers [6] and owner requirements for building management [2]. In-spite of these efforts, opportunities exist for actively engaging the facility managers in the design review while also capturing their design decisions for enhancing future design tools and platforms.

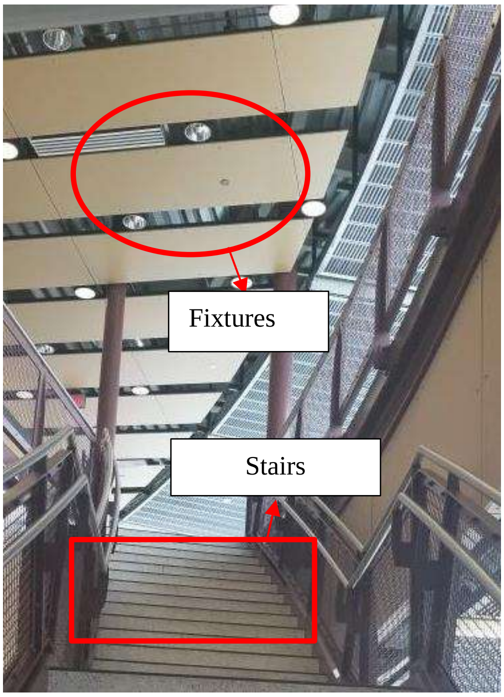

Figure 1. Inaccessible light fixture

3 Research Objectives

Design review decisions from diverse buildings and different facility managers can be continually captured, analyzed and linked to a building information model (BIM) to generate a rule-based building maintenance framework that enables cost effective designs and easier execution of maintenance tasks. Furthermore, data fusion of maintenance rules and component design can create information that once applied, will create knowledge that can improve the design and facility management phase.

The objectives of this work are as follows:

1. Develop a framework that captures and integrates maintenance decisions and rules with BIM. The framework includes a rule-based decision procedure for evaluating designs for maintainability.
2. Implement and verify the framework on a selected case study.

4 Framework

The proposed framework shown in Figure 2, integrates BIM for serious game design, and cloud computing technology, and prototyping a game application. The game is based on Autodesk Revit, Autodesk 3ds max, and Unity3D. Autodesk Revit is used to model the buildings while 3ds max software provides a platform to model, texture the buildings, and import the Revit model into Unity3D. The game was made interactive for design review in Visual studio C#.net using the Unity game development platform. The pseudocode of the developed game is shown in Figure 3.

The first step is to import BIM models into the gaming engine as shown in Figure 2. Since BIM models are developed with different proprietary software, the associated file assets need to be converted to a Unity3D compatible file. To import a Revit model into Unity3D, the model is initially converted to a .fbx format using Autodesk 3ds max. The .fbx file is then copied into a Unity3D project folder, where it can be opened as a Unity3D model.

On importing the design into Unity3D, the FM can select any floor he wishes to review. The FM can also select any floor space by initiating the ‘space’ menu. The building components are categorized into systems e.g. lighting, electrical, mechanical and plumping systems. On selecting any of the components in each of the spaces, the FM is automatically launched to the location of the component. He can query the components using the accessibility criteria of reachability and support. Reachability indicates if the components can be reached using any access equipment e.g. scaffold and scissors lift. On selecting any of the access equipment, the support criteria helps the FM decide if there is a platform to place the equipment. If the FM has an issue with any of the components, he can post comments or decisions regarding affected components. These comments are sent to the architect via SMTP mail server. Google SMTP server is setup to route the mail to the architect. The comments are also stored in a relational database using

OLE DB connection. Microsoft Sql Server (Mssql) was chosen because of its scalability, support SQL syntax, and compatibility with .NET applications.

In the future, it is anticipated that the industry might develop an open database server for storing and sharing facility maintenance decisions. These data can then be linked to a BIM model using an automated rule-based system. The rules will be developed for components to which comments have been posted. The rules will also be coded from the posted decisions of the components. Fusing the maintenance decisions from different facility managers will create valuable information that once updated and applied frequently will become knowledge for building designers. Moreover, the FM can also email the comments to the designer for corrective actions.

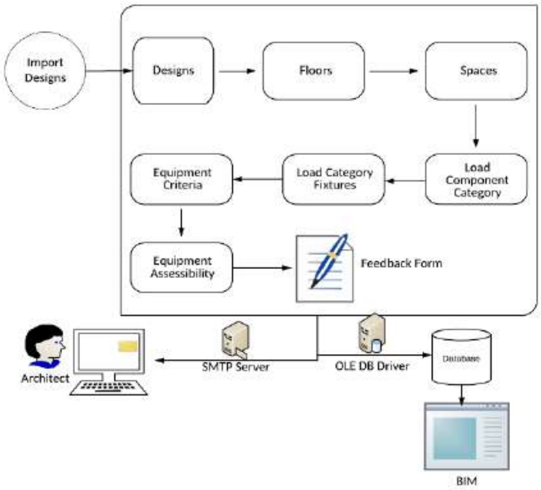

Figure 2. Framework for implementing serious game for design for maintainability

```
For each building in loaded BIM
  For each floor in building
    For each room on the floor
      Select Component
        Select Type of Fixture
          User_position = Fixture.Vector3.transform.position()
          Select Equipment for Accessibility
          Safe distance = T_position – U_position – E_position
          If safe_distance < standard_safe_distance
            Load the Feedback form
            If user select "Close and Exit Option"
              Feedback from is submitted and saved
            Else
              Feedback is stored in Array
          Else
            User can inspect other fixture
```

Figure 3. Pseudocode of developed game

5 Case-Study

The proposed framework was applied to an education building so as to check the accessibility of the light fixtures. A 3D model of an existing educational building was created in Autodesk Revit. The BIM model included different types of mechanical, electrical and lighting components with some inaccessibility issues.

The BIM model was initially loaded into unity 3D using the 'Import Designs' button. On importing the model, an avatar of height 5.8ft is positioned in the model as shown in Figure 4. From the 'Floor' menu, the user selected the first floor. From the first floor, the user was able to access the spaces within the building. On selecting one of the spaces, he was prompted with the option of the type of components. From the 'Component Category', the user can select options from a list of mechanical, electrical, lighting and plumbing components. In this case, the user selected the lighting components. After selection, the user is presented with list of all the light fixtures in the building and he has to choose one of the fixtures.

After making his selection, the avatar was positioned under the fixture using the function: Vector3.transform.position = fixture.transform.position as illustrated in the pseudocode (Figure 5). This relieves the user or FM from the stress of learning the gaming tool. The user was able to define criteria for assessing the fixture using the 'Equipment Criteria' menu. This menu provides two options: Reach and Equipment Accessibility. With the 'Reach' option, the user was provided with options of using a ladder or scissors lift to reach the fixture. A typical stepped ladder has a height ranging from 4ft to 20ft. On selecting any height, the gaming tool adds the height of the avatar (5.8ft), the height of the ladder (20ft). The gaming tool determines the distance between the height of the light fixture and the combined height of the avatar and the ladder. This difference must be lesser or equal to safe reach distance of 0.33ft (4 inches). This is achieved by calling the function: sum(height_of_avatar,height_of_ladder) - fixture.Vector3.y.

If the distance is greater than 4 inches, it means the light fixture cannot be accessed. In this case study, the later was true and a comment was sent to the designer via the interface shown in Figure 6. The comment was communicated to the designer via SMTP mail server.

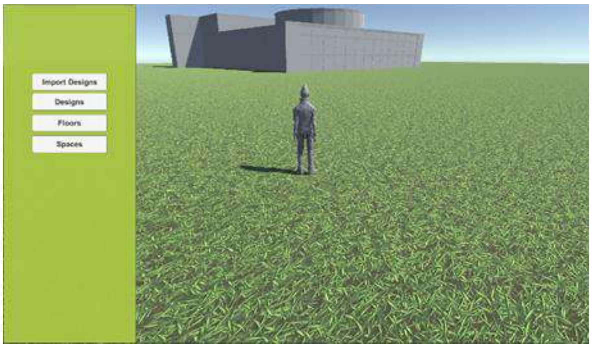

Figure 4. Interface of developed gaming tool

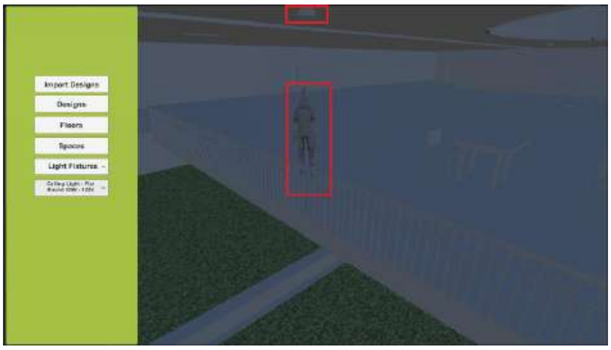

Figure 5. User positioned under the light fixture

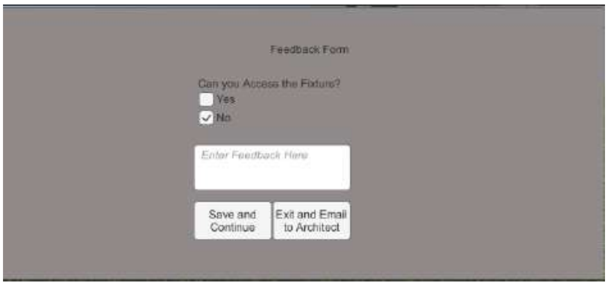

Figure 6. Platform for providing feedback or comments

6 Conclusions and Future Work

This paper presents preliminary results on the framework of a gaming tool for reviewing building designs for maintainability and capturing design decisions for improving existing BIM tools. The developed tool runs on two main platforms: Unity3D and Autodesk Revit. Preliminary results demonstrate the feasibility of using the gaming platform for the design review. The developed automated design review tool shows good capability of practical applications in checking the accessibility of building components and capturing decisions and comments. These comments can be linked to the respective components in BIM and rules can be developed to guide the building design. This offers tremendous opportunity for improving the BIM platforms while also ensuring that the facility management perspective is well represented in building designs.

Future work will focus on developing machine learning algorithms to filter through the comments and develop rules for building components. Research will also focus on the evaluation of the developed tool, development of more case studies, scenarios and best practices to encourage its usefulness.

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Computational workspaces management: a workflow to integrate workspaces dynamic planning with 4D BIM

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Abstract

An effective realization of a building construction project -without incurring in congested site areas or decline of productivity- tightly depends on the construction activities planning process that, should consider and manage site workspaces availabilities. In this context, in the past couple of decades many research efforts have been spent in BIM which represents the process of preparation and use of a computer-generated Building Information Model (BIM) even if effective integrated methodologies and models to assist construction workspaces management are still missing in the field.

This contribution proposes an integrated model that aims to automate the creation of a building digital prototype, BIM-based, in which real site condition, in terms of workspaces allocation, are fully simulated. The outputs of a built-in algorithm to define the on-site workspaces configuration pattern based on the space syntax analysis together with a second one to automatically model workspaces geometries with minimizes input work are presented. Those algorithm are integrated in a coherent construction workspaces management workflow and tested on a simplified BIM of an industrial building, succeeding to allocate and model 611 workspaces required to construct 98 building items the BIM is composed of.

Keywords –

4D BIM; Construction workspace management; Scheduling; computational design.

1 Introduction

Whatever the type of building project under consideration, there is a need to produce a construction schedule that is considered a challenging activity for construction managers due to the number of variables they should consider especially resulting from the dynamic nature of the construction site. Considering its nature, which consist of different activities in limited area, it can be stated that '*workspace*' is the leading factor that is frequently overlooked in construction scheduling. In this sense, researches developed until now are limited in their ability to generate the workspace digital model for all activities of the building project for which workspaces are required. Most of them are focused on static 2D-based workspace models.

A practical motivation is that, since a building project is composed of a huge number activities, it is difficult for construction managers as well as researchers to automatically create at a time the workspace digital model for all the activities, due to the fact that it is a tedious work to generate the workspaces for many activities in the project using a 3D tool.

Riding this problem, the theoretical scope of this study is to automate the creation of a building digital prototype in which all the required workspaces to construct the building objects will be planned and modelled. To achieve this purpose, the use of 4D BIM and computational design will be integrated.

2 Background

2.1 Construction workspace management

Incorporating workspace considerations from the spatial and temporal perspective, in construction planning and scheduling, plays a pivotal role in proactively preventing work-space problems and decline of site productivity. According to [1], construction workspace management includes the following three branches.

1. First, *generation and allocation of workspaces*. In this regard, most of studies such as [2],[3],[4],[5] and [6] support the workspaces modelling by using manual mark-up in a 2D or 3D modelling environment. But, considering the number of required spaces for each construction activity to multiply by the huge number of activities a building project is composed of, design automation in spatial modelling is suggested but still missing in literature.

2. Second, *detection of spatial temporal conflicts*. In this context, three research branches can be identified: (a) detection of physical conflicts between the site workspaces; (b) detection of schedule conflict which means the detection of a temporal overlap between tasks that is mainly taken into account by the models which use traditional representation of the construction process (i.e., Gantt Chart and Network Diagrams); (c) site congestions identification [7] that considers the ratio between the volume of resources occupying a workspace and the volume of the workspace which is available on site for a given activity or a set of activities. Often defined as 'scheduling overlapping ratio' [8].
3. Third, *resolution of identified conflicts*. Regarding this aspect, the methodologies -proposed in literature- reveal the predominant use of mathematical models that, on one hand, are able to manage only a small part of a given building project due to the computational load entrusted to not specific calculation environment (e.g. Matlab), on the other hand require an extremely knowledgeable of the mathematical model itself which cannot be used by construction managers. For these reasons the almost always go unused.

3 Need and justification

Prevailing *activity-oriented* construction scheduling techniques -e.g., Gantt Chart, Network Diagram, Critical Path Method- are not able to consider spatial requirements of activities and for this reason the generated construction schedule is limited in capturing real site conditions. Moreover, more complex techniques -such as Line of Balance- have likewise insufficient ability for workspaces planning because they assume that only one labor crew is able to occupy each work-zone at a time and they lack of a 3-Dimensional representation and planning of spaces as well as spatial conflicts among themselves [9].

More recently, a new research trend of utilizing Building Information Modelling (BIM) and BIM-related technologies to assist construction scheduling is arising. It represents the process of preparation and use of a computer-generated Building Information Model [10], which is data-rich parametric digital representation of a building, from which relevant data, needed to support planning and scheduling of construction activities, could be extracted and used. But, in spite of its growing implementation, the use of BIM to improve construction planning has involved many efforts focusing on its technological aspects (i.e., 4D BIM-based tools) rather than on the integration with site planning models for construction workspaces management.

Therefore, an holistic workspaces planning model -BIM compliant- able to consider, simulate and analyze space availability and demand for each building object, included in a given BIM, is still missing and it could support construction managers in reasoning on the construction schedules that feature specific construction methods and concurrent execution of overlapping activities.

4 Methodology

4.1 Goal and Objectives

For the aforementioned reasons, the overall goal of this research is to define a BIM-based construction planning model that automates the creation of a building digital prototype in which real site condition, in terms of workspaces, are simulated and it should be able to guide an external user (i.e., construction manager) to define the construction sequence that guarantees the non-overlapping condition of the workspaces. In particular, this research makes the following contributions:

- it defines of a construction planning model which acts, logically and technically, on a given Building Information Model (IFC-based);
- it introduces an automated process for geometric planning and modelling of workspaces, within a BIM environment, by means of two built-in algorithm;
- it defines of a tool sets that communicate through an external data-base in which a construction manager introduces his experience in terms of workspaces requirements of construction methods;
- it guides a construction manager in defining the earliest construction sequence -visualized in 4D BIM-based simulation environment- of a given BIM to be processed.

The paper is organized as follows. First, the practical motivation for this research is introduced by using a case study together with the explanation of the working prototype. Next, an overview of the planning model and specifications about its operational framework and its computerization are given. Finally, an evaluation of this approach is provided, followed by a brief discussion of the on-going and future research.

4.2 Motivating case study and working prototype

This section describes a simplified case study that illustrates the practical motivation for this research on which the proposed workflow has been tested. An Information Model of an industrial building, structured according to the IFC-data schema, is the input of this research.

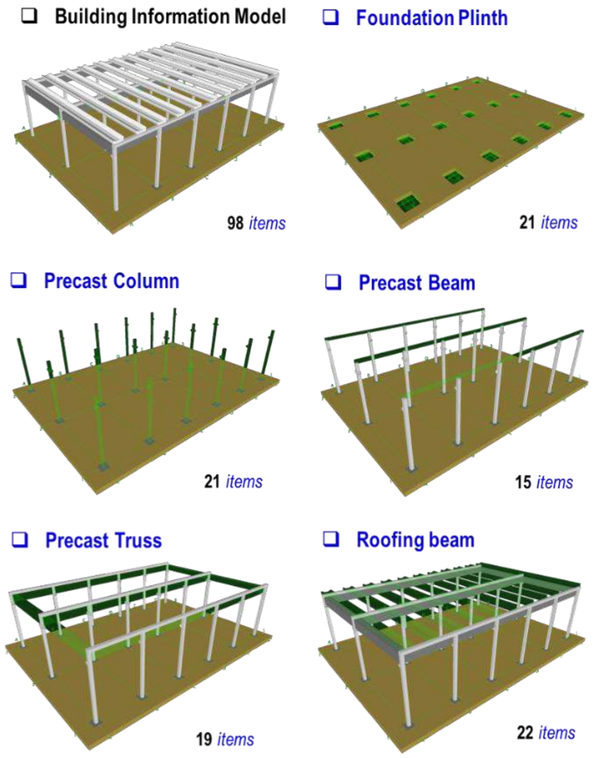


Figure 1. Building Object of the case study

Taking into account its structural subsystem but leaving aside the building finishing, the given BIM is composed of five objects types: (a) Foundation Plinth -eighteen items-; (b) *Precast Column* -eighteen items-; (c) *Precast Beam* -fifteen products-; (d) *Truss* -nineteen items- and (e) *Roofing Beam* -twenty-two elements-. Figure 1 shows the BIM filtered by type of building objects.

Trying to be a construction manager who receives the aforementioned BIM in order to define the optimal construction sequence, the proposed approach seeks to respond to the following open issues:

- Which kind of workspaces are necessary to install those five types of building objects?
- How all those workspaces should be located in site with reference to building object of which they handle the installation?
- Is it possible to automatically generate a workspaces allocation pattern using the construction manager's experience and automatically sculpt geometries of workspaces in a BIM modelling environment?
- Could it be possible to find and simulate a construction sequence by using a 4D BIM which, solving the issues mentioned above, guarantee the non-overlapping condition of workspaces?

It is clear that, to make BIMs useful for construction, all these specific information for construction site must be planned and explicit in the given information model in a way that construction managers can easily work with to better understand and plan their specific schedule which cannot be against to all those condition established in the model itself.

The architecture of the proposed solution to generate the building digital prototype in in which all the required workspaces are planned and simulated is represented in Figure 2.

The architecture shows that the planning process starts with three elements: first of all, a BIM and a structural schedule -due to the fact the latter does not depend on specific consideration but it defines the first scheduling constraints (e.g., plinths before columns, columns before beams, etc.)-; then the experience of the construction manager which is stored within an external database. It works as repository of information relevant to the workspace management process (planning and modelling) according to a predefined structure later specified.

The result is a 4D BIM Model that simulates all the required workspaces allocated in their optimal position that satisfies the conditions specified by the user (Figure 7). The computerization of such a theoretical algorithm will be described in the next paragraphs.

4.3 Problem solving approach and computerization

The proposed design process that reaches the aforementioned objects is composed by a number of operational modules in a coherent data management flow. They are graphically described in Figure 2 and briefly specified step-by-step as follows.

1. **Data extrapolation from the BIM**. Having at our disposal the BIM we are able to extract the following information: *number and types of building objects*, their *local placement on X, Y and Z-axis* (relative to the building grid axis). Those data are stored in an external database.
2. **Workspaces Database preparation**. For each object type a *Construction Method* (CM) is generated in an external database where the user adds a list of workspaces required by the CM itself in terms of *Labor Crew*, *Equipment*, *Hazard*, *Protected and Safety Spaces* according to his experience. For each space the following information are required: *Dimensions*, *Topological Interaction* with the other spaces and *Interaction Value*.
3. **Workspaces planning process**. Defined workspaces properties for each construction

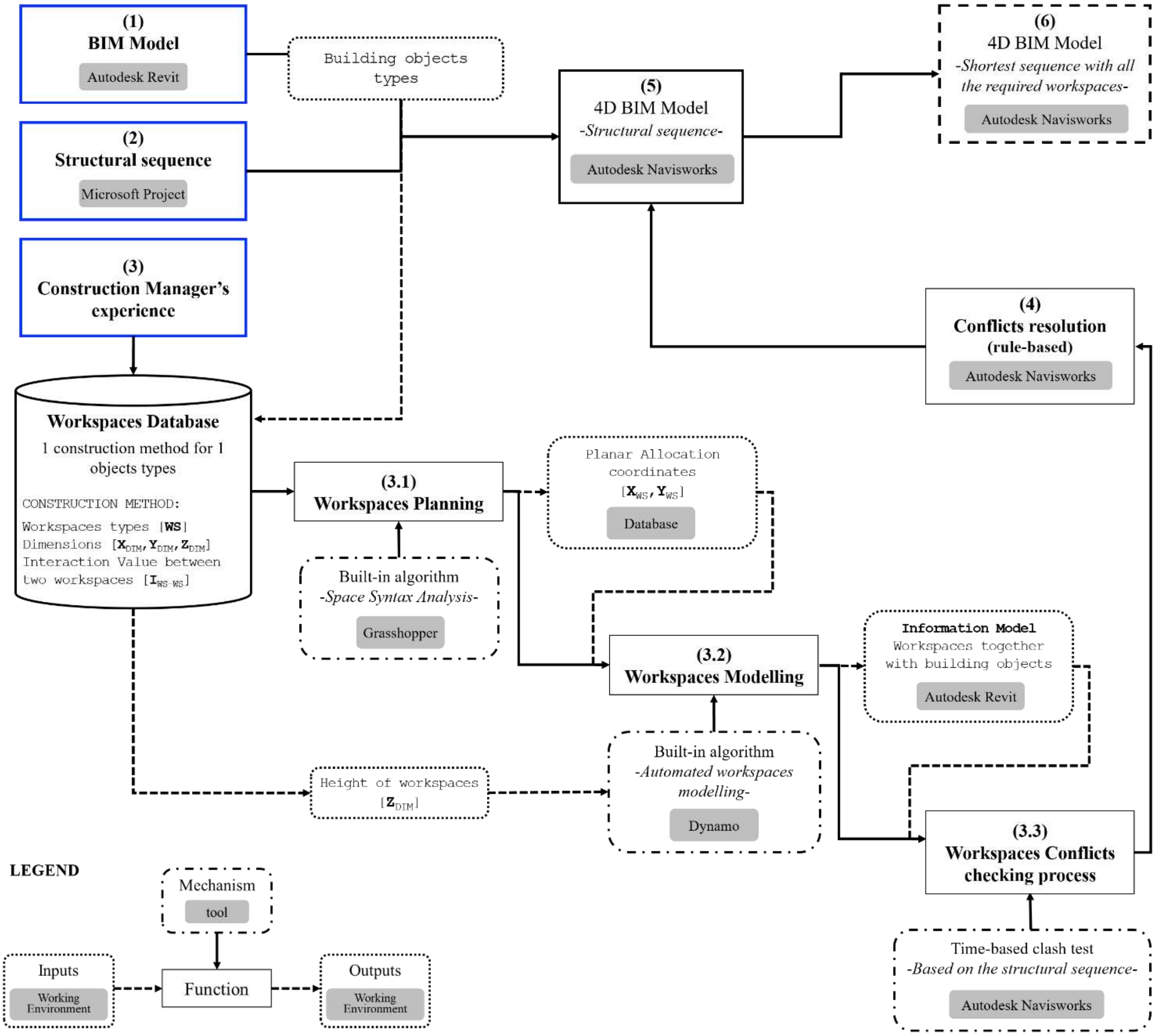


Figure 2. Data management flow to generate the building digital prototype with workspaces in Figure 7

method, it remains to find their optimal layout allocation with reference to the building objects. This is carried out by using a configurational analysis based on *Space Syntax Analysis*. The workspaces configuration pattern is generated in the form of a planar graph by using a bubble diagram which is deduced by Nourian's algorithm [11] and especially customized for our model. It read workspaces information and provides as output the workspaces allocation coordinates for each construction method (Figure 3).

4. **Workspaces modelling process**. Reading the allocation coordinates of workspaces referred to each building objects a Dynamo's script -an algorithm editing environment for computational design linked to a BIM modelling environment- automatically sculpts the geometries. By doing so each building objects is simulated with a cloud around itself that is the non-visible volume in the building needed for execution of works. As depicted in Figure 4 for each construction method and and fully in Figure 7, 611 workspaces have been automatically simulated.

5. **Workspaces conflicts checking process**. The BIM that now includes the building objects and all the needed spaces is loaded in a 4D BIM environment (*Autodesk Navisworks*) to carry out a time-bases clash test on the basis of the structural schedule. By doing so a clash report is extracted, an example in Figure 5, with the pair of conflicted workspaces.

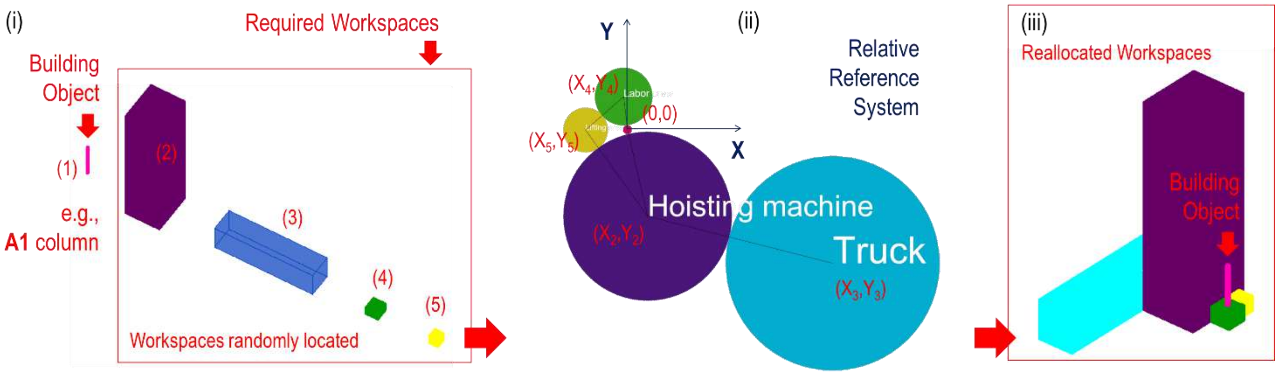


Figure 3.Planning process to find the workspaces allocation pattern around the precast column

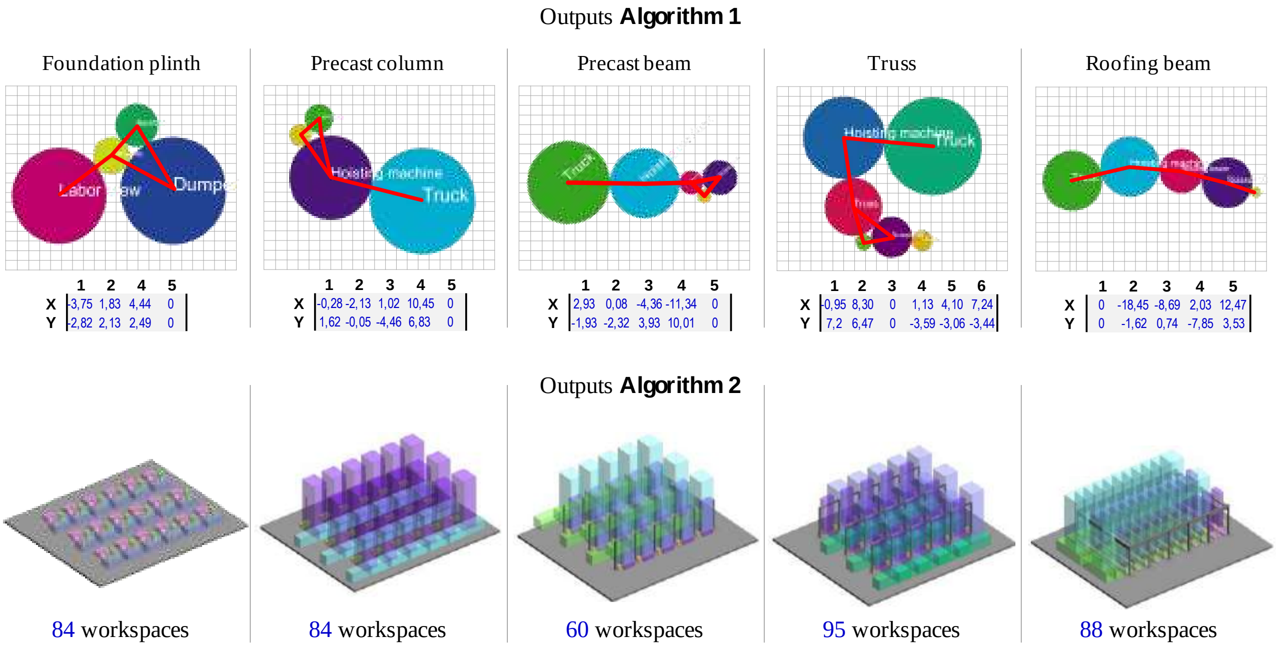


Figure 4. Graphical outputs of the workspaces configuration pattern for the five construction methods

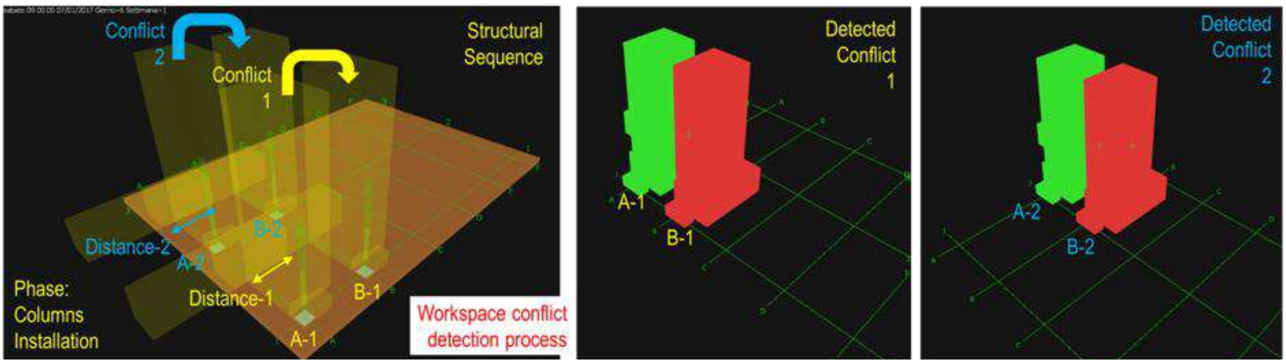


Figure 5. Graphical output of the workspaces conflict detection (*Navisworks Environment*)

In the same environment a scheduling rule is computerized that converts each conflict in a temporal relationship (finish-to-start) among the building objects whose spaces are conflicting.

The generated schedule can be considered the earliest construction sequence in the sense that if one activity will be shifted backwards a workspaces conflict will be detected.

Due to not enough spaces, the proposed workflow as well as the built-in algorithms are basically described in this contribution even if the outputs are presented and a more detailed explanation of the workspaces planning process is presented in the next paragraphs and Figure 6.

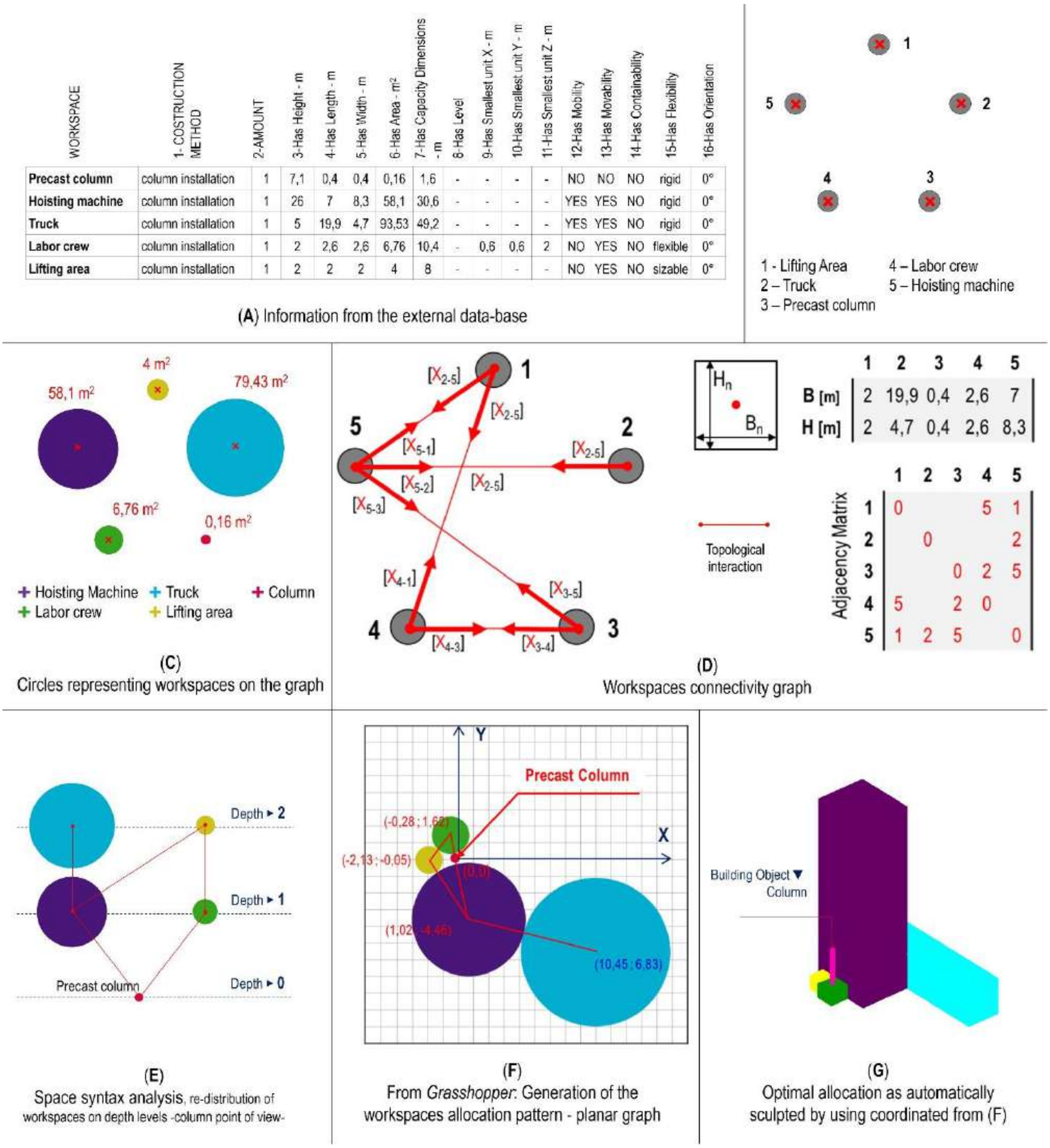
4.3.1 Workspaces planning: algorithm to generate the workspaces spatial allocation patterns

The proposed planning workflow is about going from an abstract graph description of workspaces topological structure and their interactions to find their optimal planar allocation with reference to the building object those spaces are linked. The computerization of such a concept has been possible with a built-in algorithm able to manage a parametric design workflow developed in *Grasshopper©*, (a graphical algorithm editor tightly integrated with a 3-D modelling environment). The proposed one is a customization of the one presented in [11]. It main operating steps are below presented and the graphically visualized in Figure 6 for the construction method of precast column installation.

1. **Workspaces graph representation**. As starting point, a number of randomly located points, representing the barycenter of the workspaces, are generated in a CAD environment by using a first operator. At the same time, two dimension values (*has_Lenght, has_Width*) and the identification numbers (*has_ID*) are imported from the external data-base. At this point, a set of operators, first assign colours to the workspaces to make them more recognizable and then generate one circle around each workspaces' center point. Their dimensions are deduced by the rectangular areas of workspaces as suggested by the user in the data-base itself; they are equal. In this way, a first workspaces map representation is generated. This is carried out for each construction methods included in the given BIM.
2. **Workspaces connectivity graph**. Subsequently, the representation of relationships between workspaces is managed by an operator that draws connections -by using a red line- between those pair of points that have a topological interaction (*has_Topological_Interaction*) set by the user within the data-base. The interaction value can be in a rank from 0 -*no interaction*- to 5 -i*ndispensable interaction*-.
3. **Space Syntax Analysis**. Having generated the connectivity graph, according to the space syntax analysis, an operator re-distributes the workspaces (circles) on deph-levels. A *depth* is the smallest number of syntactic steps (in topological meaning) that are needed to reach one space from another. Therefore, depending on the number of workspaces that each construction methods contains -e.g. five spaces for the column installation- one configuration for each space by using depth levels is generated. It represents the point of view of a labourer getting in position in that workspace on ‘depth-0’. The generated graphs are used for a visual validation from the construction manager (user) who has defined the workspaces requirements in the data-base itself.
4. **Generation of the workspaces allocation pattern**. Once the model is provided with workspaces connectivity values, the algorithm contains a force-directed graph-drawing operator which is able to generate a bubble diagram representing the optimal workspaces allocation pattern based on user-constraints set in the data-base. This function works translating the interaction values between workspaces (*has_Interaction_Value*) in a set of attractive forces. The forces act recursively on the graph vertices, seek a ‘relax’ situation for a graph, and provide the system with a graphical representation of the given solution. The output is a bubble diagram -once again one for each construction method included in the model- compliant with the specified workspaces dimensions and the connectivity values.
5. **Extrapolation of workspaces spatial coordinates**. Once a workspaces configuration pattern is deducted, the spatial allocation coordinates -on the X-axis and Y-axis- from the bubble diagram are extracted and stored in the external database. The model considers those workspaces as located at the same height (Z-axis) of their connected building object.

5 Discussion and future development

The obtained results show how the layout allocations of spaces cannot be considered never fixed but they strictly depend on both the chosen construction method and planning rules. Infact, the space syntax analysis, carried



WORKSPACE	1- COSTRUCTION METHOD	2-AMOUNT	3-Has Height - m	4-Has Length - m	5-Has Width - m	6-Has Area - m²	7-Has Capacity Dimensions - m	8-Has Level	9-Has Smallest unit X - m	10-Has Smallest unit Y - m	11-Has Smallest unit Z - m	12-Has Mobility	13-Has Movability	14-Has Containability	15-Has Flexibility	16-Has Orientation
Precast column	column installation	1	7,1	0,4	0,4	0,16	1,6	-	-	-	-	NO	NO	NO	rigid	0°
Hoisting machine	column installation	1	26	7	8,3	58,1	30,6	-	-	-	-	YES	YES	NO	rigid	0°
Truck	column installation	1	5	19,9	4,7	93,53	49,2	-	-	-	-	YES	YES	NO	rigid	0°
Labor crew	column installation	1	2	2,6	2,6	6,76	10,4	-	0,6	0,6	2	NO	YES	NO	flexible	0°
Lifting area	column installation	1	2	2	2	4	8	-	-	-	-	NO	YES	NO	sizable	0°

	1	2	3	4	5
1	0			5	1
2		0			2
3			0	2	5
4	5		2	0	
5	1	2	5		0

Figure 6. Workspaces planning process: Construction method of precast column installation

out on five different construction methods, demonstrated that even if workspaces had the same dimensions, their layout allocations may be different depending on their relations as well as their interaction values.

Moreover, it demonstrates how important should be the integration of human experiences even in BIM-based scheduling models as well as the pretty unbreakable bond that exists between a construction schedule and the spatial allocation of workspaces and their topological interactions.

The proposed workflow, supported by the two integrated algorithm, was capable to plan and model 611 workspaces by binding the scheduling process to them (Figure 7). The same process would be unsustainable if manually managed or without a holistic and digitized planning process. This requirement increases if we think that if some changes occur (e.g., construction methods, workspaces, building product dimensions, etc.) all the entities should be modelled again. The presented construction scheduling workflow is a part of a wider research project the author are working on that aims to develop an *BIM-based Expert System* supported by an ontology based system architecture (for semantic modelling the construction process knowledge) integrated with a rule-based artificial intelligence (for workspaces management and schedule generation).

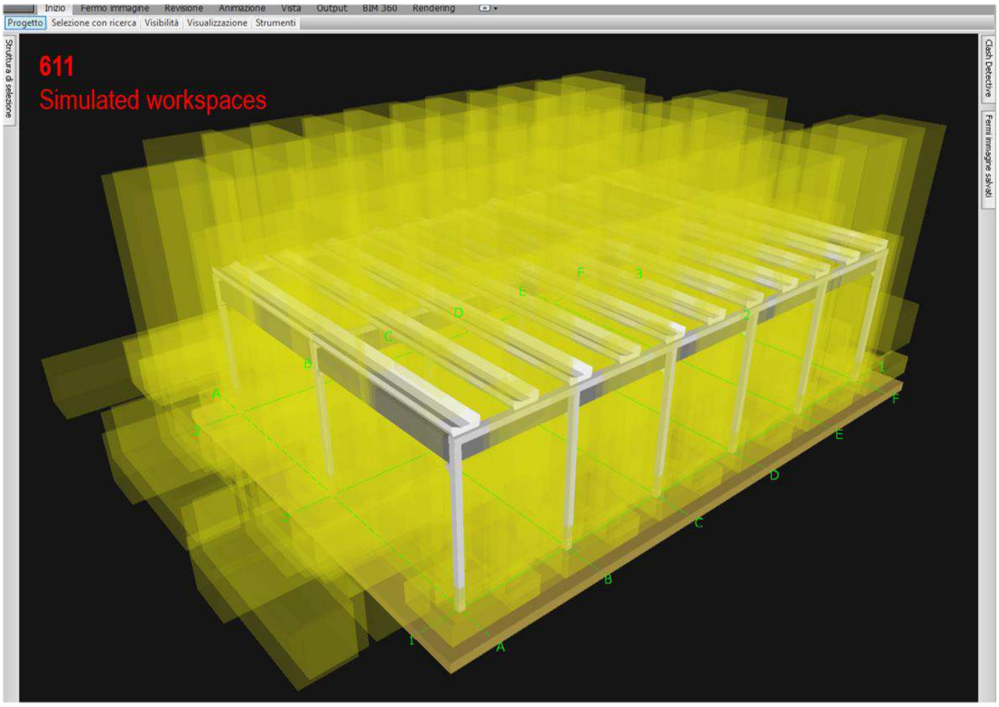


Figure 7. BIM-based site digital prototype with all the required workspaces to construct the building objects

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End-to-end Image-based Indoor Localization for Facility Operation and Management

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Abstract -

Recent research on facility management has focused on leveraging location-based services(LBS) to assist on-demand access to model information and on-site documentation. Researchers highlight that fast and robust indoor localization is of great importance for location-based facility management services, especially considering when using facility management services in a mobile computing context. Despite the importance of location data, most existing facility management systems do not support LBS due to the following reasons: 1) Signal-based indoor localization methods, such as WIFI, RFID, Bluetooth and Ultrasound, require installation of extra infrastructure in a building to support localization, 2) Visual-based indoor localization methods, such as LiDAR and camera, still depend on feature point detection and matching that require heavy computation and can be impacted by environmental conditions. In this paper, the authors present an end-to-end image-based localization framework to support facility operation and management using a convolutional neural network (CNN). The proposed framework contains two modules: mapping and localization. The mapping module takes a set of training images with their pose as input and trains a CNN model for the localization module. The localization module takes a single image and the trained model as input and outputs estimated camera pose (position and view angle). Compared to conventional methods, the proposed end-to-end image-based indoor localization framework does not require any infrastructure installed in a building and can achieve real-time 6-DoF localization that is robust to different lighting conditions and scenes with poor texture. The proposed framework was evaluated on publicly available datasets and the results show that end-to-end imaged-based method can achieve real-time 6-DoF localization with acceptable accuracy and a small map size.

Keywords -

Facility Operation and Management; Image; Indoor Localization; Convolutional Neural Network; Deep Learning

1 Introduction

In this section, the authors give a brief introduction to location-based facility management and the status of current research.

1.1 Background

Locating and tracking people, equipment, and facility components within building supports many novel facility management applications such as asset monitoring [1, 2, 3], infrastructure inspection [4], cross-registration with BIM [5], and field reporting using mobile devices [6]. A location-based facility management system (LB-FMS) has a central geospatial database that stores facility information and allows all possible users to access or potentially change the data conveniently. LB-FMS is expected to streamline building operation activities, such as updating infrastructure status, documenting repair needs, managing work orders and inspection, through automatically linking the data collected by a mobile device at the scene to the facility management model. However, given the location of mobile device only, it's still challenging finding the correspondence at a component level, e.g, linking a window captured at the scene with its corresponding window element in the model. The primary concern that limits component-level registration is the lack of complete pose information (location and view angle). With location information only, there is an infinite number of possible ways to register a facility component to its model due to the freedom of rotation (Figure 1a). In comparison, with complete pose information, the correspondence could be easily established through ray tracing (Figure 1b). The resulting component-level correspondence can reduce the need for manually finding the corresponding component at the scene. In other words, an LB-FMS with complete pose information can be used for automating many of the aforementioned applications.

1.2 Previous Research

Current indoor localization approaches adopted in an LB-FMS can be generally divided into two categories: 1) Signal-based methods and 2) Visual-based methods. Signal-based methods, such as WIFI [7], RFID [8], Bluetooth [9] and Ultrasound [10], estimate locations by comparing recorded signal signatures with signals captured on site. For example, WIFI-based localization leverages the prior known router positions to estimate the signal

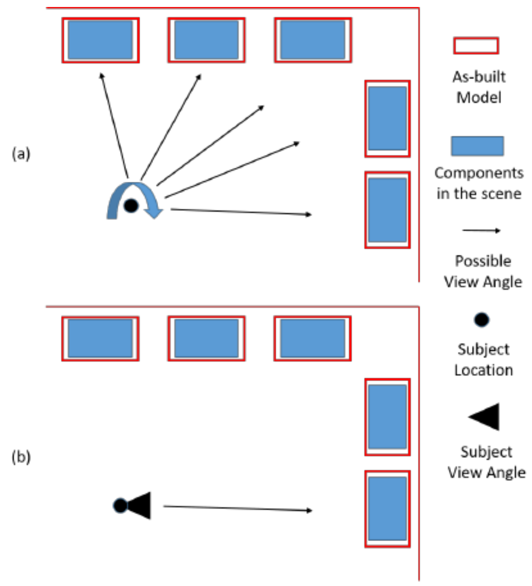

Figure 1. Finding corresponding as-built model for the object in a scene with locations only (a) vs. with poses (b)

strength at different locations within a building. When the client device receives signals from multiple routers, the position can then be estimated using triangulation. Other signal-based methods employ similar mechanisms as well. According to [11], signal-based methods have two primary limitations when applied in facility management applications: 1) They need to have the corresponding infrastructure, such as routers, beacons, RFID tags, or ultrasound receivers, installed in building to facilitate the localization service. 2) They can only output the location (X, Y, Z coordinates) but not the view angle (pitch, yaw, roll angles). Without the view angle information, locating facility components in the as-built model would be more difficult compared to the one with view angle information. Figure 1 demonstrates how pose information can reduce the search space for correspondence.

The visual-based localization methods, especially the image-based ones, are proposed to address the two limitations stated above. First of all, image-based methods do not need extra infrastructure to locate a person. Moreover, image-based localization methods can output location and view angle at the same time, making it much easier to estimate the location of what is being seen in a scene and linking it to what exists in a digital information model (such a 3D building information model). Typical image-based localization methods include image retrieval [12], direct 2D-3D feature matching [13], and end-to-end learning [14]. Image retrieval methods build a spatial database of a facility from geo-referenced images during mapping and retrieve the image that is most similar to the queried image for localization. Since the queried image is not likely to have identical poses (location and view angle) as the images in a database, image retrieval localization can only provide a rough estimation of the pose. Direct 2D-3D matching method reconstructs the 3D model using Structure-from-Motion (SfM) from images, and stores extracted feature points, such as Scale-Invariant Feature Transform (SIFT) in map (Figure 1). During localization, it compares the extracted feature points from the queried image to the ones in the database and estimates the camera pose using epipolar geometry. The localization accuracy can be very accurate (10-20 cm[10]) when feature point matching is successful. However, due to camera intrinsic differences, change of lighting condition and motion blur, direct 2D-3D matching could fail ungracefully even when a small subset of mismatched feature points exist. Another limitation of the 2D-3D matching method is computation complexity. An image usually has 300 to 500 feature points while a map is usually reconstructed from thousands of images. Therefore, locating one image requires finding the best match from millions of feature points which can take several seconds. Hence, existing 2D-3D matching method is also not scalable and might not be applicable for real-time localization needs.

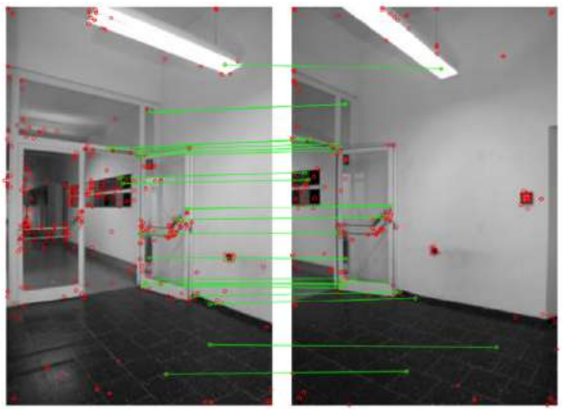

Figure 2. Feature-based Localization using SIFT Matching

Considering these limitations, the authors explored a new approach that learns to automatically extract useful features from images according to the desired objective (in our case, the objective is to minimize localization error), and that uses extracted features to estimate image poses. This approach is being referred to as end-to-end learning-based localization and Section 2 gives a brief introduction to it. Section 3 overviews how the proposed end-to-end image-based localization acts as an important module within a facility management system. Sections 4 and 5 describe the evaluation of the proposed approach with respect to its performance on a publicly available dataset and show the corresponding results obtained.

2 End-to-end Learning-based Localization

Convolutional Neural Network (CNN) [15] was originally proposed to address the image classification problem that can output a discrete label such as door and window given an image as input. CNN also works well in regression problems that require estimating continuous variables such as locations and view angles. In general, CNN is a powerful tool that can automatically learn how to extract useful features with respect to different objectives. End-to-end learning-based localization aims at training a CNN that maps an image to a pose. The localization process consists of two stages: mapping and localization. Basically, in the training (mapping) stage, the system takes a set of training images with ground truth pose and trains a Convolutional Neural Network(CNN) by minimizing the mean squared error(MSE) between the predicted pose and the ground truth pose. In the testing (localization) stage, the trained network takes an image as input and predicts the 6-DoF pose. The problem can be formally written as: given a set of images and their corresponding poses, find a function f that maps the input image $\mathbf{X}$ to its pose $\mathbf{y}$ through $\mathbf{y} = f(\mathbf{X})$ with the lowest localization error. The function f is defined by all the parameters of a CNN.

2.1 CNN Layers

A typical CNN architecture consists of several layers such as convolution, activation, transition, batch normalization (BN), and fully connection (FC). Below is a brief description of the functionality of each kind of layer.

2.1.1 Convolution

Convolution layers play a role of extracting features from input images in CNN. Given an image $\mathbf{X}$ (a tensor with size width × height × color channel), a convolution layer transforms the input by computing linear combination as below:

$$conv(\mathbf{X}) = \mathbf{w}^T\mathbf{x} + \mathbf{b} \tag{1}$$

where $\mathbf{w}$ is the weight vector of a convolution layer, $\mathbf{x}$ is the vector obtained from unrolling the input tensor $\mathbf{X}$, and $\mathbf{b}$ is the bias vector. With different weights, convolution layers are able to extract different features from the input that are useful for achieving the objective.

2.1.2 Activation

Activation layer provides non-linearity between two convolution layers so that the function model is not limited to linear space. A common choice of activation function is Rectified Linear Units(ReLU):

$$ReLU(\mathbf{x}) = max(\mathbf{x}, 0) \tag{2}$$

where $\mathbf{x}$ is the output from last layer.

2.1.3 Transition

Transition layer reduces the input size by averaging. For example, a 2×2 transition layer will average reduce an image with size $56 \times 56 \times 3$ to $28 \times 28 \times 3$. This is used for reducing the number of parameters the system needs to learn.

2.1.4 Batch Normalization

Batch normalization normalizes the input by subtracting its mean from the input and dividing it by the standard deviation. The goal of batch normalization is to improve the generalizability of the model.

2.2 CNN Architecture

In the proposed approach, the authors employ the DenseNet [16] structure for pose regression because of its strong capability of extracting visual features. Depending on the loss function, the extracted features can be used for both classification and regression task. In this problem, we changed the last FC layer to a Sigmoid layer for regression purpose. The adjusted FC layer contains 7 outputs, corresponding to 3 location coordinates(x,y,z) and 4 rotation coordinates(q_1, q_2, q_3, q_4 represented in quaternion format). Table 2.2 shows the DenseNet architecture. Notice that each conv layer listed in the table actually corresponds to a BN-ReLU activation-Conv sequence. The details of each layer can be found in [16].

2.3 Objective

One possible objective is to minimize the mean squared error (MSE) between the predicted pose and the ground truth pose as discussed in [14]. Specifically, denote the ground truth location as a translation vector $\mathbf{t} = [x, y, z]$ and the ground truth view angle as a rotation quaternion $\mathbf{q} = [q_1, q_2, q_3, q_4]$. Notice that the rotation quaternion can be converted back to the axis angle representation. Similarly, denote the predicted location and view angle as $\hat{\mathbf{t}}$ and $\hat{\mathbf{q}}$. The MSE loss of a single image $\mathcal{I}$ to be minimized can be represented as:

$$L(\mathcal{I}) = ||\mathbf{t} - \hat{\mathbf{t}}||_2 + \beta||\frac{\mathbf{q}}{||\mathbf{q}||} - \hat{\mathbf{q}}||_2 \tag{3}$$

where β is a hyperparameter that balances the rotation and translation error.

Table 1. DenseNet Architecture for Localization [16].

Layers	Output Size	DenseNet-121
Convolution	112×112	$7 \times 7 \times 2$ conv
Pooling	56×56	$3 \times 3 \times 2$ max
Dense Block(1)	56×56	$\begin{bmatrix} 1 \times 1 \\ 3 \times 3 \end{bmatrix} \times 6$ conv
Transition Layer(1)	56×56 28×28	1×1 conv $2 \times 2 \times 2$ avg
Dense Block(2)	28×28	$\begin{bmatrix} 1 \times 1 \\ 3 \times 3 \end{bmatrix} \times 12$ conv
Transition Layer(2)	28×28 14×14	1×1 conv $2 \times 2 \times 2$ avg
Dense Block(3)	14×14	$\begin{bmatrix} 1 \times 1 \\ 3 \times 3 \end{bmatrix} \times 24$ conv
Transition Layer(3)	14×14 7×7	1×1 conv $2 \times 2 \times 2$ avg
Dense Block(4)	7×7	$\begin{bmatrix} 1 \times 1 \\ 3 \times 3 \end{bmatrix} \times 16$ conv
Regression Layer	7×7 average pooling 7D fully-connected layer	

An alternative of the objective is to minimize the reprojection error [17]. Denote the ground truth 3D point as P, the reprojected 2D point as p, camera intrinsic (aperture, focal length, etc) as K, and the camera model as a transformation $\mathcal{T}$. The relationship between 3D points and 2D points can be represented as:

$$\begin{aligned} p &= \mathcal{T}_{K,\mathbf{t},\mathbf{q}}(P) \\ &= K[Q|\mathbf{t}]P \end{aligned} \tag{4}$$

where Q is the corresponding rotation matrix of $\mathbf{q}$ and N is the number of known 3D-2D matching pairs. The loss is then defined as:

$$L(\mathcal{I}) = \frac{1}{N} \sum_{P \in \mathcal{P}} \|\mathcal{T}_{K,\hat{\mathbf{t}},\hat{\mathbf{q}}}(P) - \mathcal{T}_{K,\mathbf{t},\mathbf{q}}(P)\|_2 \tag{5}$$

which aims at minimizing the reprojected error between the ground truth pose and the predicted pose. Though the second objective does not need the hyperparameter β, it requires a set of 3D points of the scene as prior, which is usually not available. Therefore, the authors employed the first objective in the proposed approach.

3 Overview of the Proposed Approach

To leverage the end-to-end learning-based localization in facility management, the authors propose an approach that contains four modules: mapping, localization, facility detection, and model update. The pipeline of the proposed approach is shown in Figure 3.

3.1 Mapping

The image-based mapping module takes images and their poses as the primary input but also accepts other

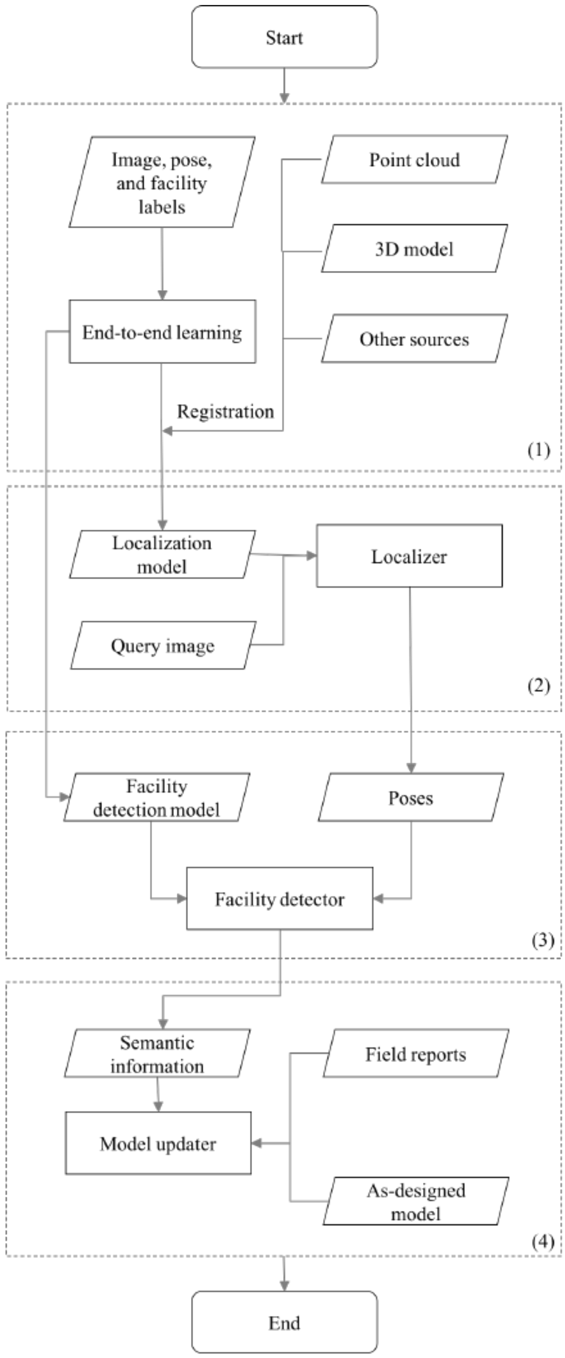

Figure 3. The Proposed Approach with Four Modules: (1) Mapping, (2) Localization, (3) Facility detection, (4) Model update.

data sources such as point cloud, 3D models, and a depth map. The output of the module is a trained network that can predict the camera pose given an image. As stated in Section 2, the goal of mapping is to find a function f with parameters $\mathbf{w}^*$ that minimizes the localization error on the training set:

$$\mathbf{w}^* = \underset{\mathbf{w}}{\operatorname{argmin}} \frac{1}{M} \sum_{i=1}^{M} L(\mathcal{I}_i|\mathbf{w}) \tag{6}$$

where M is the number of images in the training set and $L(\mathcal{I}_i|\mathbf{w})$ is the error of the prediction on the i-th image $\mathcal{I}_i$ given parameters $\mathbf{w}$.

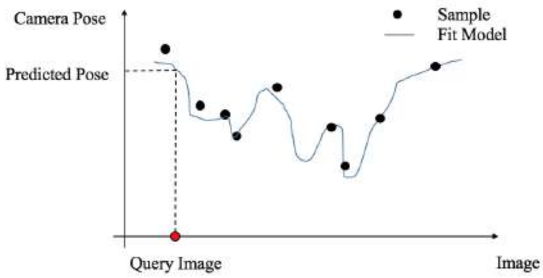

Figure 4. Simplified Representation of Mapping and Localization

Figure 4 shows a simplified representation of a mapping model where the x-axis is the image input, and the y-axis is the camera pose. Since the fitness function is non-linear, there is no closed-form solution of the optimization problem. Therefore, to find the optimal weights $\mathbf{w}^*$, we need to employ optimization methods such as gradient descend to gradually adjust the weights. The basic idea of optimization methods is to start from a random weight and moves along the direction where the loss function goes down. Usually, the data will be randomly split into three parts: a training set, a validation set, and a test set. The model is fit on the training set and usually stops optimization when the loss of validation set reaches the minimum. The test set is used for testing purpose only.

3.2 Localization

The image-based localization module (Part (2) in Figure 3) takes an image and the trained model from the mapping module as input, and outputs the 6-DoF localization result (x, y, z, pitch, yaw, roll) as shown in Figure 4. In the mapping(training) stage, the model is trained to extract features from images that are useful for determining image pose. To understand the mechanism of localization module, we can compare it with the conventional feature-based localization method. In the feature-based localization method, we manually extract the feature point from the image, match the feature point with the ones stored in a database, and estimate the location based on matching as shown in Figure 2. In contrast, end-to-end localization learns to extract relevant features by minimizing localization error. It does not require strict matching. Instead, the trained model tries to estimate the parameter of the function that maps an image to its pose.

Using end-to-end learning-based localization, the localizer does not need to detect feature points from the query image and conduct feature point matching. Instead, the pose is estimated purely by the image itself, which provides two advantages compared to the 2D-3D matching localization method. First, since the weights of the model and the query image have fixed size, the localization time is independent of the map size (Scalability). Second, CNN is able to output accurate pose even with downsized images. For example, to fit the training images into a single GPU with 11 GB of memory, a typical RGB image size used in CNN is $224 \times 224 \times 3$. In the contrast, the feature point detection requires high-resolution images as its input, such as RGB images with size $3000 \times 2000 \times 3$, to improve the feature point matching quality. The computation complexity of end-to-end learning-based localization is much smaller than the one of direct matching localization. Therefore, with proper choice of network architecture and image size, the localizer can provide real-time localization results.

With pose information, if the position of a facility component on an image is known, the component can be linked to a pre-registered as-built model through ray tracing as shown in Figure 5.

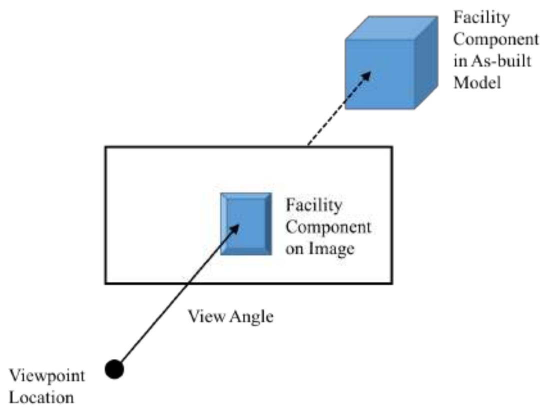

Figure 5. Finding corresponding model for detected facility components on image using pose information

4 Implementation and Experiment

Section 4 discusses the implementation details and presents preliminary results on two publicly available datasets. The authors tested both the proposed method and the state-of-art Structure-from-Motion (SfM) methods using Colmap Library [18] on two datasets and compared their performance.

4.1 Dataset

The authors tested the end-to-end learning-based localization module on two different datasets. The first one is the Navvis dataset [19]. The Navvis testbed is located on the first floor of the main site of Technical University of Munich(TUM) with an indoor track length of 434m. The dataset consists of 3146 high-resolution DSLR images whose size is 3456×5184, point cloud model of the scene, as well as the ground truth camera pose of each image. The ground truth provides the transformation matrix that can be decomposed into locations and view angles. The dataset also provides the camera intrinsic for 3D reprojection. The second dataset is the Baidu IDL indoor localization dataset [20]. The IDL dataset is captured at a mall, containing 682 training images captured from DSLR camera and more than 2000 query images captured from other cameras. In the experiment, the authors randomly split the dataset into three parts: 8/10 for training, 1/10 for validation, and 1/10 for testing. The training set is used for optimizing the parameters of the model, while the validation set is used for determining when to stop training as well as choosing the proper hyperparameter β. Then the authors evaluate the proposed approach on the test set.

4.2 Implementation

4.2.1 Preprocessing

Before training the model, the authors conducted the following preprocessing over the data:

1. Downsize all images to $256 \times 384 \times 3$ to accelerate training and localization. Compared to raw images, our GPU can process 64 compressed images in parallel.

2. Crop the image into four corners and a center using the size $224 \times 224 \times 3$. The authors did the cropping for two reasons. First, it is an effective way of data augmentation that allows the network to have more data for training. Second, the authors used the weights of a pretrained network on ImageNet to initialize the model, images on ImageNet uses the same size as well. Notice that cropping will not change the ground truth pose.

3. Randomly add 10% lighting noise (AlexNet-style PCA lighting noise [21]) to make the model more robust to different lighting conditions.

4. Normalize the image using the mean and standard deviation of ImageNet. Normalization guarantees that the same range of values for each of the inputs to the model, which can effectively prevent ill-conditioned model and accelerate optimization process.

4.2.2 Training

The authors implemented the proposed model using PyTorch. The pretained densenet-121 model from ImageNet is employed as the base net in the experiment. The last layer of DenseNet was replaced by a fully-connected layers that has 7 outputs where the first 3 outputs are x, y, and z, while the last 4 outputs are q_1, q_2, q_3, q_4. As mentioned in section 2.2, the objective function has a hyperparameter β that balances the location and the view angle error. In the experiment, we follow the suggestion in [14] and set the $\beta = 150$ for indoor scenes. The optimization method is Adaptive Moment Estimation(Adam) [22] and set the learning rate as $1e-4$, $\beta_1 = 0.9$, $\beta_2 = 0.999$ using the recommended settings utilized in [22]. The batch size is 64 which uses up to 11 GB of GPU memory. The model was trained on a desktop with Intel i7-7700k CPU, 32G RAM, and a Nvidia 1080Ti GPU.

4.3 Results

The performance of the localization module was evaluated from three perspectives: 1) accuracy, 2) robustness, and 3) efficiency. The average location error is $2.04m$ and the average view angle error is $11.3°$ on Navvis dataset, and $1.02m$ and $4.2°$ on IDL dataset. Figure **??** shows the localization result on Navvis dataset. In comparison, the SfM method failed to reconstruct a 3D model for Navvis dataset due to poor textures of the scene. On IDL dataset, the mean displacement and orientation error of the SfM method are $7.21m$ and $18°$ respectively due to the reconstruction ambiguity. Figure 7 shows the localization result on IDL dataset using SfM (a) and the proposed method (b). As shown in Figure 7, the SfM localization result has an ambiguity issue which is caused by incorrect feature point matching.

Figure 8 shows the translation and orientation error distribution respectively. On the IDL dataset, about 88% of the images has a translation error lower than $2m$. On Navvis dataset, about 93.3% images have a location error lower than $4m$. In comparison, the SfM method failed to reconstruct a 3D model on Navvis dataset and presented an ambiguity issue on IDL dataset. The reconstruction failure was due to the poor texture of the scene and low overlapping between images. In our experiment, the image

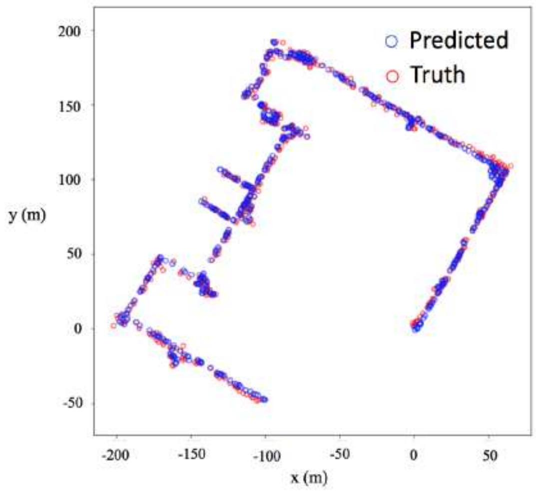

Figure 6. Localization Result using the proposed method on Navvis dataset.

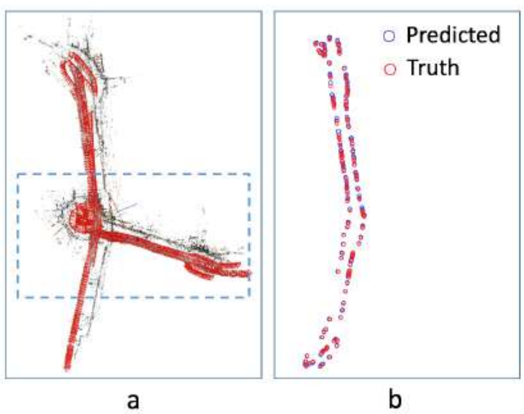

Figure 7. Localization Result from SfM (a) and the proposed method (b) on IDL dataset. The blue rectangle in (a) shows the reconstruction ambiguity.

registration rate on Navvis dataset is about 15%, which is not sufficient for 3D reconstruction. The ambiguity issue comes from the repetitive scenes in the indoor environment. When a scene presents similar pattern at different locations, incorrect feature matching will lead to ambiguity issues. According to the experiment results, the proposed method is robust to the aforementioned problems.

Regarding time and storage efficiency, during localization, predicting each query image takes averaged 0.04s on the aforementioned desktop using the proposed method. The map size of the proposed method is just the network itself, which is 35MB in total. In comparison, the state-of-art feature-based image localization method implemented in [23] needs an averaged 0.3s to finish localization in a map with only 900 registered images. Also, with 900 registered images and 400 feature points on each image (Each feature point is represented by 128 floating point numbers), the map size of the feature-based method reaches 175 MB and it will increase as the number of registered image increases. The fixed map size of the proposed method makes it more suitable for providing location services in a mobile computing context considering the limited memory resources of mobile devices.

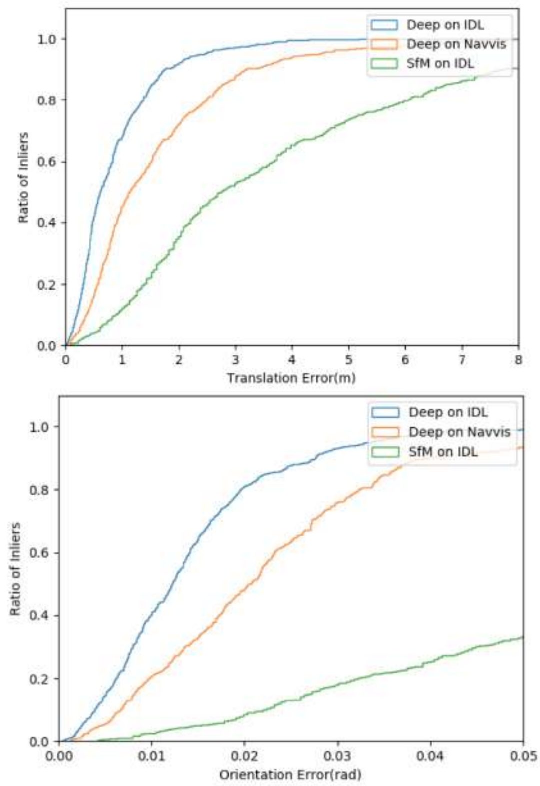

Figure 8. Translation and orientation error distribution on the testset of IDL dataset

5 Conclusion

In this paper, the authors explored an end-to-end image-based indoor localization method and proposed an approach of integrating it into a general facility management framework. Compared to signal-based localization methods, image-based methods do not require special infrastructure installed in the building and can output 6-DoF poses. Compared to conventional image retrieval and feature-based localization methods, end-to-end localization is robust to poor texture and repetitive scenes. Though feature-based methods can achieve high accuracy given accurate feature matching results, they are susceptible to inaccurate registration and reconstruction ambiguity as shown in the experiment. Moreover, end-to-end localization has a fixed map size and can provide real-time locations while the map size of feature-based methods will grow over time. Therefore, compared to feature-based methods, the proposed approach is more suitable for running on mobile devices such as cell phones or tablets.

In conclusion, end-to-end image-based localization is an alternative of indoor localization methods. It has the potential of being integrated with a facility component detection module to support facility management. However, there are also a few challenges when using end-to-end image-based localization. First, it requires ground truth poses (usually captured from a laser scanner) as input for training, which can be hard to capture in the industry due to the difficulty of cross-sensor calibration. Second, the performance of the proposed approach might be affected by image quality, over-lapping between images, texture richness, lighting conditions, and camera intrinsic difference. The authors will continue to evaluate the end-to-end image-based localization considering these variances and integrate it with the facility component detection module in future research.

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The Module of Rebar Modeling for Chinese Building Standard Detailing Drawings by BIM-based Methods

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Abstract –

Reinforcement engineering is one of the most important parts in projects of large reinforced concrete structures. Its quality directly affects the quality of the whole structure. As a matter of fact, many difficulties in rebar engineering remain to be solved, owing to its complexity and variability. Fortunately, the emerging BIM technology can overcome most of the difficulties. To efficiently build up a rebar model of a structure based on the Revit@ software, this study carried out a module for rebar modeling using the Revit@ API and the C# programming language. This module can establish the rebar part of structural elements, according to two-dimensional drawings of a structure. In addition, the module can provide an interface that is easy to be used for those who are not familiar with the standard detailing drawings. Simultaneously, this module generates a database regarding the rebar modeling, which can be further utilized in a future.

Keywords –

BIM; Rebar; Revit@ API; Secondary development

1 Introduction

Reinforcement engineering is one of the most important parts in projects of large reinforced concrete structures. Determining the costs of it is essential for the whole project. In addition, its quality directly affects the quality of the whole structure. Owing to its complexity and variability, many difficulties in rebar engineering remain to be solved. Fortunately, the emerging BIM technology can overcome most of the difficulties.

Building Information Modeling (BIM), as a new concept and technology, has been widely used by construction industries in the world since it was introduced. It can transform 2D drawings to a 3D model of a building structure. Because this 3D model allows for modifications to be made to the building's design during the stage of audit or construction, the amount of time and money needed to incorporate the changes is also reduced. In addition, the 3D model can provide 3D reviews, which can help constructors getting through the details of 2D drawings especially for the plan of reinforcement.

Many research studies have shown that the use of BIM technology for reinforcement engineering can provide satisfactory results. For example, Aram et al. (2011) mentioned that making use of BIM technology can improve productivity of the reinforcement in supply chains. Porwal and Hewage (2012) reported that if BIM technology can be used reasonably, it can reduce the loss of rebar. Pratoom and Tangwiboonpanich (2016) pointed out that the quantity of rebar resulting from the use of traditional methods is 17.76% more than that resulting from the use of BIM-based methods. Meanwhile, the application of BIM in China is just beginning, compared with the developed countries. How to take advantage of BIM technology has become the rising issues of the construction industry in China.

One of the issues nowadays is the deficiency in rebar modeling when using BIM software. For example, Cho et al. (2014) mentioned that a detailed structural model built by using Tekla@ cannot interface directly with some other software tools for structural design, such as ETAB@ and ADAPT@, while Revit@ Structure can. As a result, Revit@ Structure was used in their study to interface with ADAPT@. Still, the details of rebars for structural design needed to be improved, when building up the frame models by means of Revit@ Structure. Shao (2017) developed a plug-in using Revit Extensions 2014@ to carry out the modeling of rebar in beams, columns, slabs, walls and so on.

The Revit@ software is the most popular BIM software used by companies for design and construction in China. However, its functions for rebar modeling are limited. A series of tedious settings are required for the drawings of rebar when using Revit@. The lack of the proper functions in the software not only affects the working performance of the designers, but also hinders the application of BIM technology in the reinforcement engineering.

This study proposed a module using the Revit@ API and the C# programming language for rebar modeling. The module provides an interface that is easy to be used especially for those who are not familiar with the standard detailing drawings. This module includes the modeling of columns initially, but it can be extended to the modeling of beams, slabs, and walls in a future. This module can help to build rebar model efficiently and can promote BIM application in reinforcement engineering.

2 Method

Revit@ API provides certain functions that can access the graphical and parameter data of a building

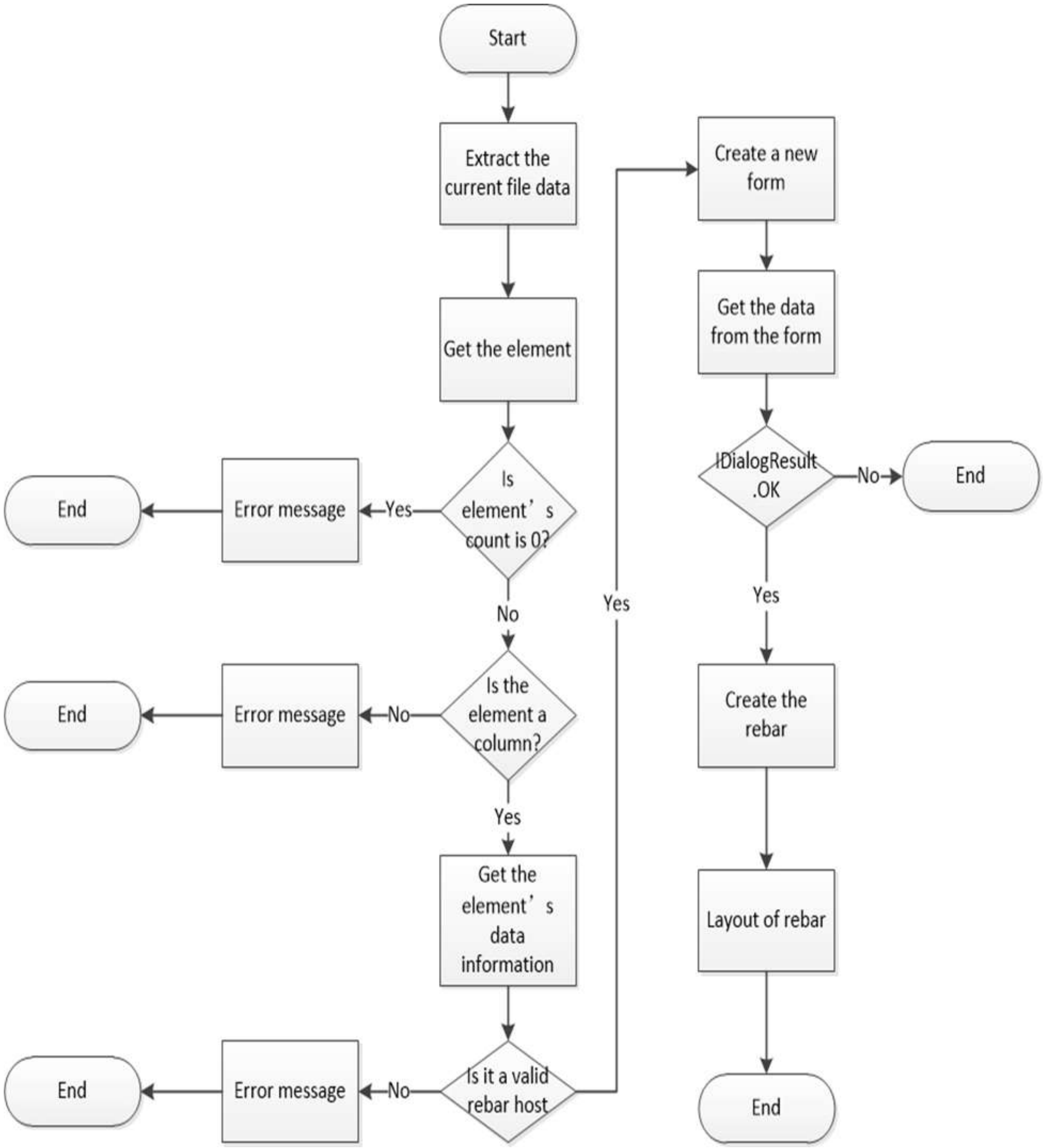

Figure 1. The flow chart of main program.

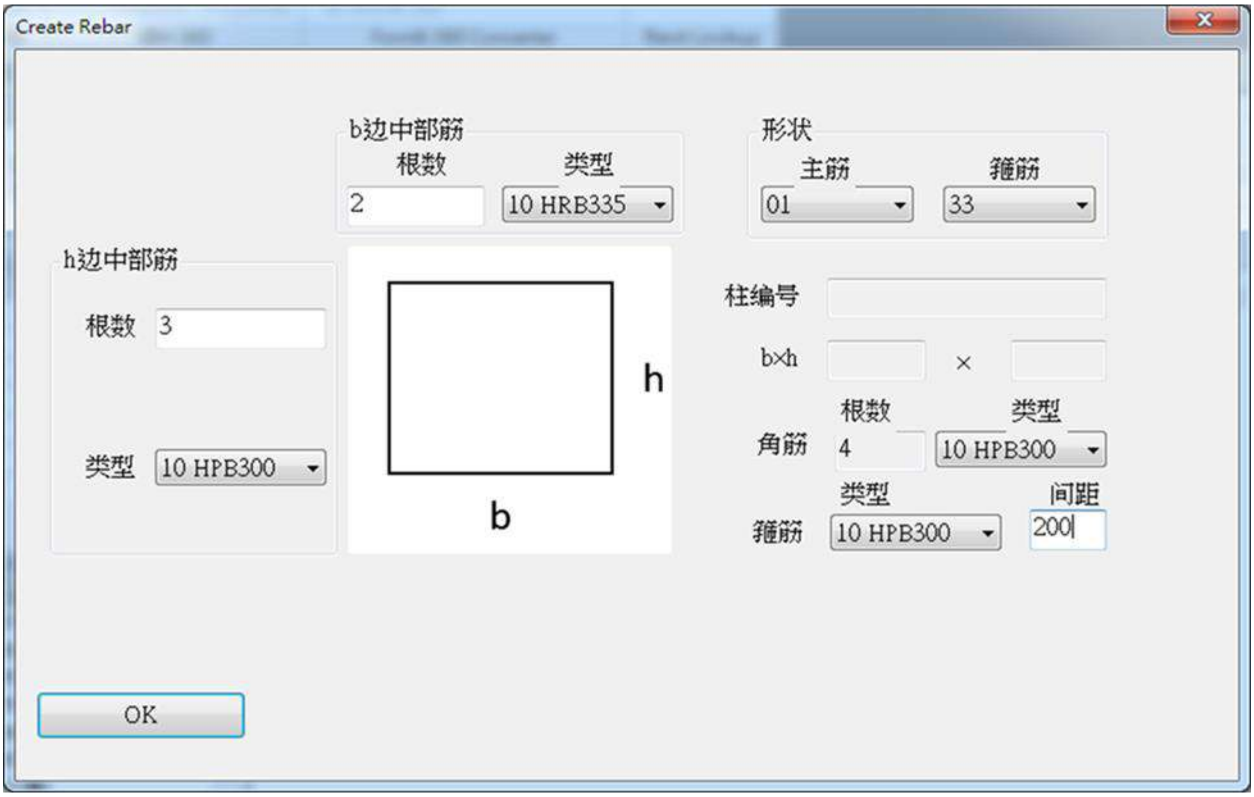

Figure 2. The user interface of column

information model. Besides, it can create, modify, and delete the structural elements in the model. Moreover, it can create plug-ins that can enhance the user's interface and automate the repetitive tasks. The C# programming language is the other tool used in this study, which is easy to learn for a beginner. Using the Revit@ API and the C# programming language, this study developed a module for rebar modeling. The steps of generating the rebar model in the component are roughly divided into: 1. Extract the current file data; 2. select the main body of the rebar; 3. ensure the type of the element; 4. define the rebar generation element; 5. restrict the rebar to the main body. Shown in Figure 1 is the flow chart of the main program in the module for creating rebar.

The brief introduction of the module follows. Firstly, the elements of a structure are established by means of Revit@. Once the desired element is selected for the arrangement of rebar, one can run the module. Shown in Figure 2 is the user interface in which the parameters related to the rebar can be assigned in the interface of the module. After clicking the "OK" button, the rebar are arranged in the element as planned.

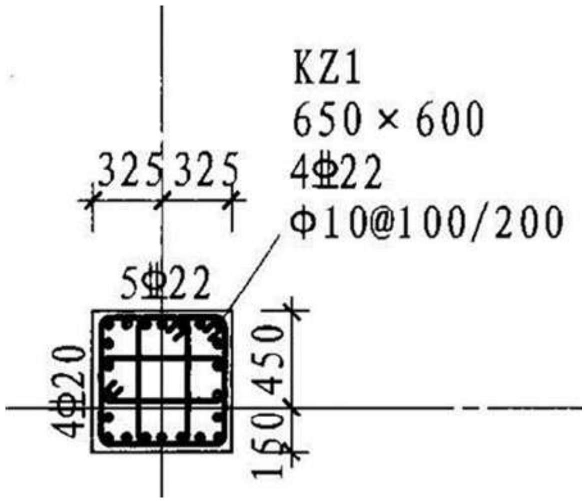

Figure 3. The tagging of column in the standard detailing drawings. （From B16G101-1[7]）

3 Results

Taking the element of column as an example, the parameters consist of the quantity, the number, the type, and the shape of the main bar, and the type, the spacing, and the shape of the stirrup as well.

At the left of the interface in the Figure 2, a user can input the quantity and choose the type of the main bar of

Figure 4. The rebar modelling for column

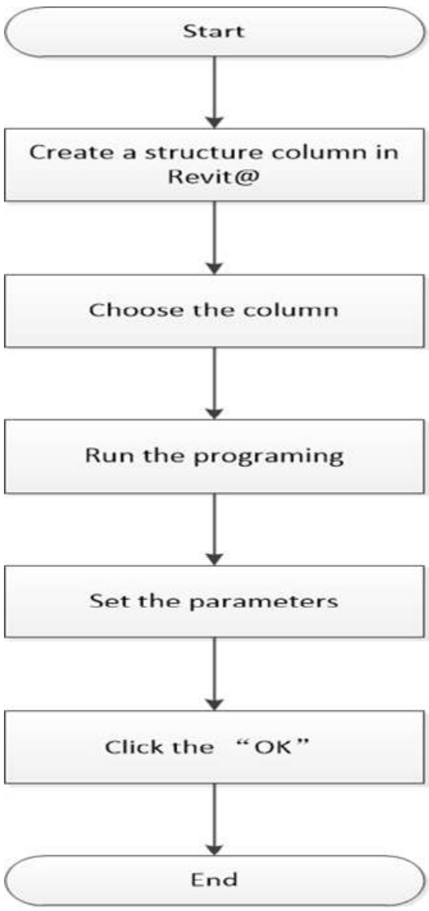

Figure 5. The flow chart of using the module

the "h" side. At the upper middle of the interface, a user can input the quantity and choose the type of the main bar of the "b" side. The lower middle of the interface shows the simple schematic diagram of column. At the upper right of the interface, a user can choose the shape of the main bar and stirrup. At the lower right of the interface, the serial number and the size of the column respectively show in the first and second lines. The third line gives the type of the main corner bars and the fourth line gives the type and the spacing of the stirrups. The user interface is like the standard alters as shown in the Figure 3. Shown in the Figure 4 is the rebar modeling resulting from the Figure 2. The flow chart of using the module is shown in Figure 5.

4 Conclusions

Currently, lots of BIM software for rebar modeling is deficient. Particularly, some of them cannot satisfy the needs of Chinese users, when using the Chinese building standard detailing drawings. This study developed a module for rebar modeling using the Revit@ API and the C# programming language. Revit@ is a convenient and popular BIM tool that can efficiently build up a rebar model of a structure. Compared to other BIM software，this module can result in a user interface that allows users to easily use the Chinese building standard design drawings. Even when one is not familiar with the standards, the module can be employed to create rebar modeling resulting from 2D construction drawings.

In the next study, the programing not only will finish the modeling of beams, slabs, and walls modeling, but also will create a database related with the model. People can use this module to build a detailed rebar modeling. The database will store all data about the rebar, such as quantity, type, shape, length, etc. Users can generate multi-purpose quality take-off reports extracted from the database, to promote BIM application in reinforcement engineering.

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Construction Process Simulation in Tunnel Construction – A Prerequisite for Automation

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Abstract

Construction process simulation allows producing a virtual copy of an existing or planned construction site. The detailed analysis of construction processes and construction logistics with the support of simulation models creates a better understanding of the performance defining aspects. In many construction sites, the actual performances lag behind the planned levels. This is due to the insufficiency of planning instruments. The authors have performed an in-depth analysis of the internal supply chain of an actual tunnel construction project. While the presented study has focused on the inner outfitting of the existing tunnel, similar work has been done for the excavation processes by the authors. The paper reviews the role, simulation plays for construction planning and investigates the benefits of simulation as a step towards increased automation levels.

Keywords –

Simulation; Tunneling; Process Modeling;

1 Introduction

Within the construction industry, tunneling is a highly specialized discipline due to its very strict spatial restrictions. Whether for the actual tunnel excavation itself or for the subsequent inner outfitting of the structures, delivery routes and workspace are limited. This poses challenges for the organization and execution of the supply chain processes that are necessary to keep work going. Often, different processes compete for space and must therefore be scheduled in such a way that they don't conflict with each other.

Since the involved capital cost and ongoing operating expenses of large civil engineering projects are very high, reducing execution duration is a key target of planners. Therefore, planning should allow for a maximum degree of parallelization of works. If this target can be reached, mainly depends on the possibility to deliver the required material to the worksites on schedule. The study presented by the authors uses process simulation to investigate the robustness of the supply chain concept for the inner outfitting of a railway tunnel in Germany. The study has been part of the bidding documents of a contractor for the execution of the works. The project owner's tender called for a verification of the bidder's logistic concept by simulation with particular consideration of the logistic restrictions, evacuation routes and all material transports. The tender requirements for the simulation study included:

- Core processes and work cycles with references for the underlying performance data.
- Possible interactions between system elements.
- Sensitivity analysis and study of alternative scenarios and their influence on the project completion.
- Mitigation strategies for bottlenecks shown by the evaluation.
- Description and explanation of the simulation study methods.

2 Process Simulation in Tunnel Construction

Although simulation studies have been used successfully in the planning of tunnel construction projects, the usage of simulation usually has been restricted to high level planning for strategic management purposes. The application of simulation as a tool for the improvement of work level processes has been rare. Nido et al. provided the planners of the Holes Creek Tunnel in Ohio, USA with a cycle time analysis based on the Cyclone simulation framework [1]. Liu et al. used a Cyclone model to evaluate the mucking system for a hard rock tunnel project in Xinjiang, China [2]. Ioannou et al. used Stroboscope to optimize resource allocation for the Hanging Lake tunnel project in Colorado, USA [3]. Fernando et al. used the Symphony simulation environment to evaluate different options regarding the use of one or several tunnel boring machines (TBMs) and their related logistic systems in the North Edmonton

Sanitary Trunk in Alberta, Canada [4]. For the Glencoe tunnel project in Calgary, Canada. Al-Bataineh et al. have used a Simphony model to investigate the influence of different geology scenarios and to determine the cost / time parameters for these different layouts [5]. The general-purpose simulation framework Anylogic has been used in several studies for a detailed analysis of work processes in tunneling [6] and [7]. One focus of these studies has been improved performance prediction for tunneling projects with regards to the influence of jobsite logistics on production rates [8] and [9].

3 Work and Transport Processes in Tunnel Outfitting

Once the excavation and structural construction of a tunnel is completed, the inner outfitting can be performed. The project which has been analyzed in this study consists of two parallel railway tunnels of 4km length in Germany. The bored tunnels are transitioning into a cut and cover structure of 1km length at each end. All sections are to be equipped with a slab track system as well as walkways and driveways at each side of the track. A drainage system and cable ducts are installed below these structures.

The construction process is separated into discrete process cycles. Within the schedule, these are defined by distinct construction stages which are executed along individual work sites. For each work site, the corresponding material requirements and delivery paths are defined by the contractor's logistics concept. The general construction schedule can be separated into the following stages which again make up the core processes:

1. Construction of drainage pipes and filler
2. Pouring of concrete invert
3. Installation of cable ducts
4. Concreting of side walkway and driveway
5. Construction profile concrete
6. Installation slab track and rail cover

Generally, the processes in the east and west tunnel are identical. To reach logistic independence, the work in the cut and cover sections is performed after completion of the works in the bored tunnel sections.

4 Simulation Modeling

The simulation model has been implemented in the commercial simulation framework Anylogic. Anylogic supports the integration of different simulation paradigms in a single model. This includes system dynamics, discrete event and agent-based modelling approaches [10]. Furthermore, embedded object libraries allow efficient modeling of vehicles, road networks and railway systems. In the presented study, the individual construction processes have been modeled by statecharts, using the discrete event approach. A road network which is dynamically adjusted to the respective situation, especially the changes in the logistics restrictions in each construction stage has been used to model the vehicles of the supply chain within the construction site. The embedded road library of the Anylogic software has been used to implement the road network. The system boundaries have been set to the physical boundaries of the cut and cover sections. Figure 1 shows the jobsite layout and the model boundaries.

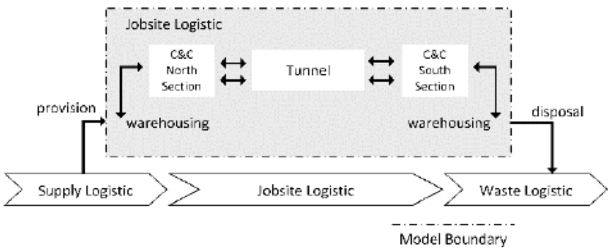

Figure 1 System- and Model Boundaries

It is assumed, that the external supply chain is always able to deliver the required performance. As an additional abstraction, the transport required for material disposal are ignored as they are minimal during the outfitting stage of construction. As construction only proceeds during dayshifts, transports during nightshifts are not modelled as well. Furthermore, personnel transport is assumed to take place between the material transports without disturbing them.

4.1 Modeling of Core Processes

The overall completion duration of the project is defined by its core processes and the resulting process chain. Each core process is defined by a set of properties which uniquely identify it and set its behavior within the overall model. The parameters are:

- Process Name
- Requirements for starting (logical or date)
- Separation into production intervals or sections
- Location of start and endpoints
- Required resources for execution
- Productivity per unit
- Material requirements (type and amount)
- Process related logistic restrictions
- Process related waiting durations

Due to slight differences in the execution logic, the processes for the outfitting of the bored tunnels and each cut and cover section are defined separately.

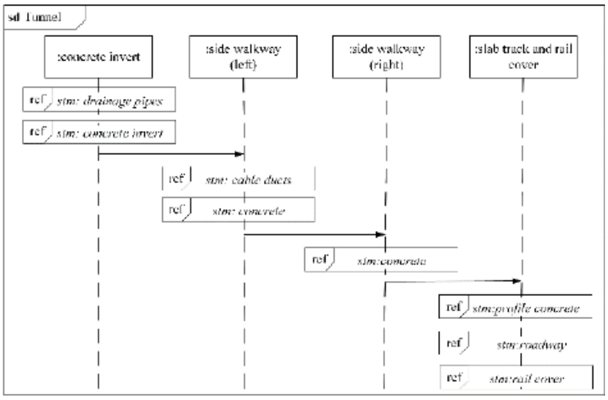

Figure 2 Logical order of process execution in the bored tunnels

Figure 2 shows the logical order of the process execution for different core processes as a SysML Sequence Diagram. Each of the core processes is implemented by a generic state chart. Functions, parameters and variables are used to customize the generic model to each respective process.

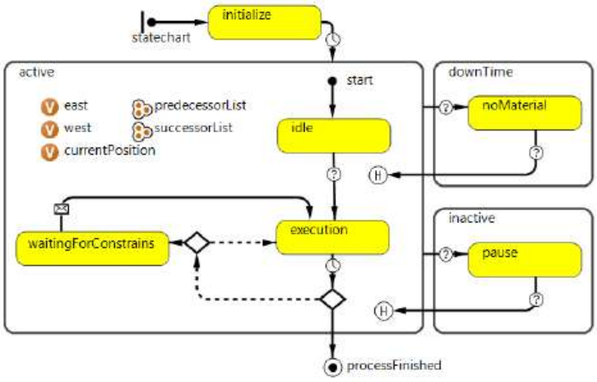

Figure 3 Generic statechart for work process modelling

The state chart shown in Figure 3 is used generically to model all work processes. For each work process, an individual instance of the state chart is generated. Within the chart, each rectangle reflects a particular state of the system. At any given moment, the system is on one particular state.

At the time of project start, all processes are in the state "initialize". The state "execution" is initiated, once the defined conditions are fulfilled (for example completion of the predecessor). Based on the process performance, the current position of the worksite is permanently updated. The variables "east" and "west" indicate in which tunnel the process takes place. The remaining available construction material are determined based on the processes consumption data. If the material is used up completely, the "working" state is interrupted and the system transitions into the "noMaterial" state. An underlying shift schedule defines when the system moves into the "pause" state. A history function "H" allows resuming work at the point where it stopped after an interruption. By using the "predecessorList" and "successorList" elements, the logical order of execution is defined. Communication functions organize the interaction with other model elements.

4.2 Modelling Transport Processes

The transport processes are modelled by the Anylogic embedded road traffic library. It uses movement processes and queues through which objects are moving according to a defined set of rules. The traffic model is separated into distinct sections that reflect the road sections that vehicles must pass through. For each section, different traffic conditions such as one-way traffic, two-way traffic and waiting points are defined. This allows modelling bottlenecks and passing locations for trucks.

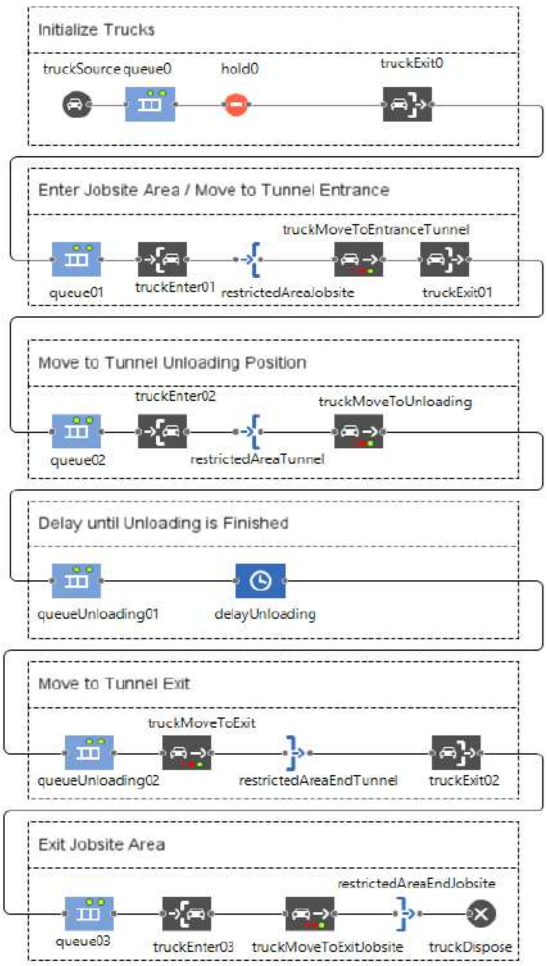

Figure 4 Dynamic traffic model for the site logistics

Figure 4 shows the logic structure of the road traffic model. The underlying logic of the model and its visualization are implemented separately. Figure 5 shows a screenshot of the traffic visualization within the simulation model. The driving paths are idealized as straight sections in the view. Inclination and curves are reflected by their effect on the driving speed of the vehicles.

Figure 5 Visualization of traffic processes

The key information for the transport processes are the following:

- Transport batch sizes
- Driving speed (full and empty) in different sections
- Driving routes / supply strategy
- Unloading durations

To deliver material to the different work sites, four different supply strategies can be distinguished:

1. Drive through from north to south. The full trucks enter the tunnel on the north side, unload the material at the work site and once empty, they drive out to the south.
2. Drive through from south to north. The full trucks enter the tunnel on the south side, unload the material at the work site and once empty, they drive out to the north.
3. Delivery from North. Trucks drive into the site backwards from the north side and after unloading dive out forwards to the north again.
4. Delivery from South. Trucks drive into the site backwards from the south side and after unloading dive out forwards to the south again.

For each work process, one particular supply strategy is defined in the simulation model. Once material is ordered by a work process, the associated transport strategy is assigned to the vehicle.

4.3 Interaction of System Elements

With regards to the logistic processes that supply the inner outfitting of the tunnels, especially the implementation of material orders and deliveries is of importance. The interaction of the individual construction processes is based on the embedded lists of predecessors and successors that define the possible execution order. Thus, the current state of all processes is permanently communicated between model elements to check if any process reached its requirements for work start or completion.

The transport processes are coupled with the construction processes by a material ordering system. For each work process, a set of variables and parameters defines the execution of material orders. Figure 6 shows this element within the simulation model. The element defines the required material type, its consumption rate, delivery batch size, performance rate and remaining material amount. The process “invert concreting” in the east tunnel requires for example the material invert concrete which is of the class “material” and is represented by the generic agent “agent material”. The required material is permanently compared to the available material. As soon as it becomes visible that the available material does not suffice for the completion of the current work section, a material order is triggered. This is executed within a defined time buffer to avoid downtime due to lack of material. The time buffer reflects the lead time for the order.

Each material order triggers a delivery process. With consideration of the information contained in the order, a suitable vehicle (truck / mobile mixer) is provided and starts driving to the work site which placed the order. The driving duration depends on the vehicle type, the transport route, transport strategy and interaction with other vehicles which could cause waiting durations at bottlenecks along the way. Upon arrival at the work site, a certain duration is needed for unloading after which the vehicles drive back out.

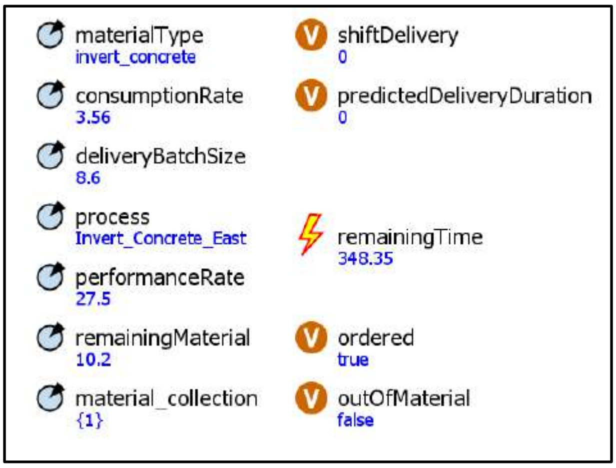

Figure 6 Control variables for the ordering process

4.4 Model Verification

Simulation models must be verified to ensure the correctness of the conclusions drawn from their results. A number of verification techniques are employed either during modeling or after completion of the model. The following methods have been used throughout the presented study:

- Completeness has been ensured by comparing all work processes from the project execution schedule with the event logs of the simulation model execution.
- The consistency of the model has been reviewed by checking the logical order and relation of all work processes in the simulation model and comparing them to the technical requirements defined in the project planning documents.
- The suitable level of detail has been confirmed as no performance relevant processes take place below the level of detail that has been modeled.
- To evaluate the plausibility of the results, the process logs during model execution and the material consumption patterns have been checked and compared to the planned amounts.

5 Simulation Results

The simulation model has been created based on the project execution schedule and the logistic concept that have been prepared by the bidder. The main purpose is the validation of the chosen logistics strategy. To evaluate the simulation results, construction performance with consideration of the supply chain simulation has been compared to the progress rates which have been assumed in the construction schedule. This comparison has been performed for different scenarios to determine sensitivity to varying progress rates. The first scenario is "standard", with all performance values and transport capacities assumed as in the planning documents. The second scenario is "fast completion" with increased construction performance rates (+10%) and the third one "reduced transport capacity" with reduced transport speeds (-10%) for all trucks. Figure 7 shows that even in the second scenario under aggravated circumstances, all work processes can be executed with an acceptable performance rate. Consequently, the same results could be verified for the other two evaluated scenarios. The results show, that the capacity of the proposed logistical system provides adequate buffers in the process chain to ensure an undisturbed construction progress even under hindered boundary condition. Thus, the simulation study verifies the bidder's logistics concept as sound and robust.

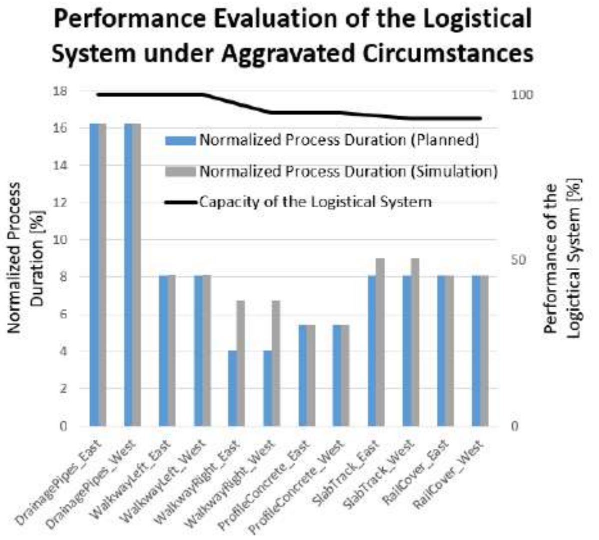

Figure 7 Simulation results for the second scenario with increased construction performance rates

Additionally, to the verification of the supply chain strategy, the simulation model can be used to derive valuable information on the expected traffic volume during different stages of project execution. Figure 8 shows the summary of required transports from and to the jobsite throughout the project. Such information is especially relevant to authorities if projects are located in congested urban areas.

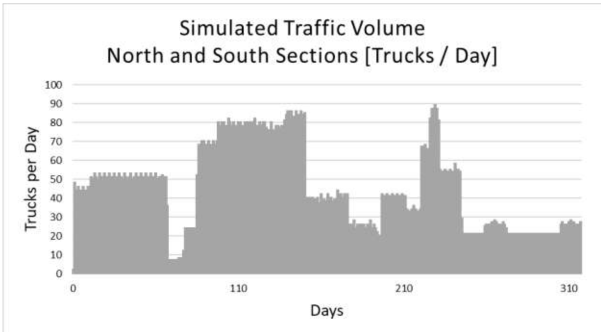

Figure 8 Traffic volume for standard scenario

6 Other Simulation Applications in Tunneling

While the study presented here is focusing on the inner outfitting of tunnels, much value can be added to tunneling projects by supporting their planning with simulation studies during planning the actual drilling. During this stage, large amounts of material are moved, and often special constraints highly restrict the available options for logistics. Cranes, trains, trucks and storage areas compete for scarce space. Figure 9 shows a 3D model of an urban tunneling jobsite on which two tunnel boring machines have to be supplied through a small shaft. In such conditions, the performance of the jobsite is often severely limited by logistic bottlenecks. Simulation studies help estimating these effects and assist the development of counter strategies.

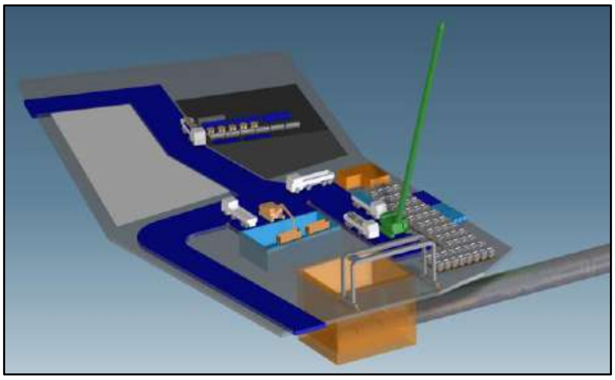

Figure 9 Screenshot of a simulation model for a tunneling site

7 Conclusion and Outlook

Simulation studies have helped dramatically increasing the productivity in the manufacturing sector. As currently the construction sector moves towards higher productivity rates and fields such as automation and robotics are entering the industry, simulation becomes an increasingly important factor in planning. The underlying knowledge about the interaction of processes is crucial for finding ways to automate them. The authors are confident that the construction industry bears great potential for productivity gains in the future.

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Trajectory-based worker task productivity monitoring

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Abstract

Over the past decades labour productivity in construction has been declining. The prevalent approach to estimating labour productivity is through an analysis of the trajectories of the construction entities. This analysis typically exploits four types of trajectory data: a) walking path trajectories, b) dense trajectories (posture), c) physiological rates such as heart rate (beats/minute) and respiratory rate (breaths/minute), and d) sound signals. The output of this analysis is the number of work cycles performed by construction workers. The total duration of these cycles is equal to the labour input of a task. However, all such methods do not meet the requirements for proactive monitoring of labour productivity in an accurate, non-obtrusive, time and cost efficient way for multiple workers. This paper proposes a method to address this shortcoming. It features a promising accuracy in terms of calculating the labour input.

Keywords – Productivity, monitoring, construction.

1 Introduction

In general, productivity is defined as the ratio of output to input [1]. Productivity rates are used by project managers during planning and scheduling in order to reduce the labour cost and improve the performance of workers. The construction sector has gradually created a significant labour productivity gap compared to other industries over the past five decades. It is estimated that only 50% of the total construction time is productive [2,3]. This is due to factors that affect on-site construction tasks negatively. Almost all of them are related to the way that productivity is monitored. Construction project managers currently evaluate worker performance based on questionnaires, manual observations, and work sampling practices [4–7]. Construction requires proactive monitoring of labour productivity in order to detect issues sufficiently early. However, this is not feasible as current practices are labour intensive and time consuming due to the large number of employees and the long lasting tasks. This paper presents a method to address this issue.

The remainder of this paper is structured as follows. Sections 2 analyses the current state of research in monitoring of labour productivity in construction. Section 3 presents an overview of the overall proposed method presented in this paper. Section 4 summarizes the outcomes of this paper.

2 Background

This paper reviews the latest studies that focus on monitoring of labour productivity. Current studies are divided in two main categories based on the methods they employ to infer productivity. The first contains the region-based studies that link the location of workers to regions of management interest (work zones) such as steel fixing zone, concrete pouring zone. The second consists of the activity-based studies that detect and link activities such as bending, hammering, and drilling to specific tasks.

Region-based studies monitor labour productivity through the time construction entities spend at zones of management interest (e.g. excavation zone, concrete pouring zone). In order to achieve this, the location of monitored entities is tracked across the jobsite. The studies of this category are sub-divided into tagged and tag-less. The tagged (RF tagged) studies employ tags which are physically attached on workers and earthmoving equipment. The most frequently used tags are the Global Positioning System (GPS), the Radio Frequency Identification system (RFID), and the Ultra-Wide band system (UWB). The above systems provide the input data of tagged studies. On this basis, the speed and the location of a haul truck were both combined for monitoring its productivity while performing an earthmoving operation [8]. If the haul truck's location was within the range of fixed known distances from specific work zones (e.g. load and dump zones), then the time during which its speed was equal to zero was converted into labour input. On the other hand, the labour productivity of workers, was monitored by linking their presence at predefined work zones [9–13]. For instance, if a concrete worker is located at zones “A” and “B” which are scheduled for concrete pouring, then the total time the worker spent in these zones is considered productive and equal to his/her labour input. The studies of this category also sub-divide the areas between the actual work zones into waiting and travelling zones, for a more detailed insight of worker productivity. The most important disadvantage of the tagged studies is that they can neither identify the unproductive time (idle time) nor the low productivity pace. For example, even if a worker is located in the correct work zone, but without performing any task due to shortage of materials or congestion he/she will be still considered productive. This is due to the fact that labour productivity is monitored only based on the presence of workers at work zones. The tagged studies do not provide any extra information about what really happens within these work zones. In addition, the purchase and maintenance of multiple tags impose a regular cost in the long term [14]. Last but not least, the physical attachment of tags creates a feeling of discomfort to workers [15]. The tag-less studies rely on computer vision-based 2D tracking methods in order to calculate the location of workers. This location is 2D instead of 3D. Therefore, entities are tracked only within the range of a camera's view. This type of tracking is non-obtrusive as it processes video data collected through surveillance cameras used for security purposes. The studies in this category convert the location data into labour productivity through two approaches. The first, links the presence of tracked entities (workers, earthmoving equipment) to specific work zones similar to tagged studies [16]. For this reason, the ambiguity about what really happens within these zones arises again. The second, fits the monitored entities to operation process models [17–19]. Such models [20,21]: a) break down the construction tasks into sub-tasks (semantic context), b) describe how the sub-tasks relate to specific work zones across the jobsite (spatial context), and c) define the sequential order (i.e. workflow) between the sub-tasks (temporal context). However, such approach relies on human intervention in order to adjust the appropriate process model to each entity. It takes 5-10minutes for an operator to achieve this. Such adjustments should be repeated for every entity on a daily basis. The large numbers of workers and earthmoving equipment entails that such type of studies will be labour intensive if applied in practice.

The activity-based studies firstly detect and secondly link activities to specific construction tasks in order to monitor labour productivity. These activities are the physical description of tasks. For example, a brick layer bends to pick up bricks and stretches his arms to place them. Bending and stretching are both activities that describe the brick laying task. This type of studies exploit posture, physiological (e.g. heart, breathing rate) and audio data. The posture-based studies have been used for monitoring both the labour productivity of earthmoving equipment [22,23] and construction workers [22–26]. Posture data are detected via feature descriptors such as the Histogram of Oriented Gradients [27] and skeletisation algorithms [28]. Machine learning-based algorithms such as Support Vector Machine Classifiers (SVMs) [29] and Artificial Neural Networks (ANNs) [30] are then trained to link (label) the detected activities to construction tasks. The highest achieved accuracy so far is equal to 59% [24]. In particular, this study was tested on workers while performing 11 types of tasks i.e. brick laying, transporting, plate cutting, drilling, re-bars fixing, nailing, plastering, shovelling, bolting, welding, and sawing. The authors admitted that this low accuracy was due to the fact that most of these tasks were not distinguishably described by posture data. On the other hand, posture-based studies perform very well (accuracy >80%) for the case of earthmoving equipment, as such entities have a small but well defined range of postures. For example, an excavation task performed by a dump truck is described only by two postures. The first depicts the unloading of materials and the second the transportation of materials. In addition, earthmoving equipment is used for only one type of tasks whereas workers perform a much larger variety. Physiological data such as heart rate (beats/minute), breathe rate (breaths/minute), body's force and angular rate [31–33] are acquired through physiological status monitoring (PSMs) and inertial measurement unit (IMU) wearable sensors. The physiological data are used for training machine learning-based classification methods similarly to the studies that exploit posture data. However, it has been proven that heart and breathe rates cannot establish any relationship with individual's labour productivity [31]. On the other hand, body's force and angular rate, extracted with accelerometers and gyroscopes of IMUs sensors, achieved a promising performance (≈80% accuracy) in terms of detecting and labelling activities such as hammering, sawing, turning a wrench, loading/unloading/pushing a wheelbarrow [32]. Physiological-based studies have been also successfully used for identifying abnormalities in the performance of workers (awkward postures) for health and safety purposes [33]. Their main limitation is that they rely on data collected with wearable sensors that give rise to privacy issues. Lastly, audio data which are recorded by microphones placed at construction jobsites have also been exploited for monitoring the productivity of construction entities [34,35]. These audio-based studies are applicable only to tasks that produce discrete sounds such as nailing, hammering, excavating, and drilling. Although they have managed to successfully remove background noise, they are still not designed to monitor the labour productivity of multiple entities that perform similar tasks simultaneously.

3 Methodology

Figure 1 illustrates a method for monitoring labour productivity of multiple workers at the same time. The skewed parallelogram shapes refer to methods and the circular to inputs/outputs. The method consists of two main sub-methods illustrated with black coloured skewed parallelogram shapes. The output of the first is the input for the second. The inputs of the method are video data streamed from multiple cameras, whilst the output of the method is the total productive and unproductive time spent by each worker. This paper hypothesizes that task productivity of construction workers can be monitored through their trajectory data.

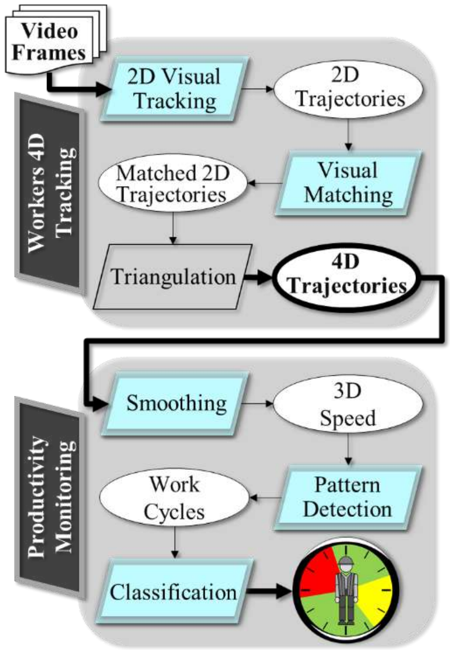

Figure 1. Method for automated construction worker task productivity monitoring.

The labour productivity is calculated by dividing a worker's total output over the total input [5]. The determination of output is quite straightforward through visual inspections (e.g. number of pipes installed, number of m^3 being excavated). Hence, this paper focuses only on the input. The main assumption of this paper is that all construction-related tasks fit to the same pattern. This pattern dictates that if a worker's "move" is followed sequentially by one "stop" and a second "move", then these three semantic events define a work cycle. This assumption is based on the fact that workers "stop" in order to perform a construction-related task and they "move" to start another. In construction, a work cycle is defined as the total time a worker spends on a task [4]. Hence, the duration of a work cycle is equal to the duration of the semantic "stop" event. Sequentially, the duration of all work cycles is equal to the labour input of a worker. Therefore, the labour input can be extracted by detecting these work cycles.

The first method of the proposed method is a computer vision-based method for 4D tracking of construction workers. This type of tracking is unobtrusive as it is tag-less. The input data are videos collected through the cameras of jobsites' surveillance systems. It returns one 4D trajectory for every worker as output. These 4D trajectories depict the 3D (X, Y, and Z) location of workers across the entire range of a jobsite over time. This 4D localization overcomes the limitation of previous tag-less studies that monitored workers only within a camera's view. An intra and an inter camera tracking are performed sequentially in order to achieve this 4D tracking [36]. The former matches workers under the same unique ID across subsequent frames of a camera, whilst the latter matches workers across multiple cameras. Then, a triangulation method [37], is applied in order to convert the 2D trajectories into 4D.

The second method of the proposed method is productivity monitoring. It uses the output of the 4D tracking method as input. Initially, a smoothing method removes the noise from the 4D trajectories. Then, the 4D trajectory of each worker is partitioned into smaller 4D sub-trajectories. The 3D speed values of these partitions are exploited to cluster them into work cycles based on the main assumption of this paper. The accurate detection of these work cycles addresses the second aim of this paper as their total duration is equal to the labour input of construction workers. The 3D speed values depict the motion of workers along the floor (XZ) and the vertical plane (Y). The detected work cycles are classified as: a) unproductive, b) normal productive, and c) abnormal productive. Initially, they are classified as either productive or unproductive through region-based classification that splits the jobsite into two types of areas, "active" and "inactive". The former contains the areas of the jobsite where tasks such as excavation, brick laying are performed. The latter consists of areas where no construction-related tasks take place. These are the: a) rest areas, b) materials' storage areas, and c) office areas. The work cycles that take place at "active" areas are classified as productive while those that take place at "inactive" areas are classified as unproductive. Then, the productive work cycles are further classified in order to detect potential abnormalities in the pace of the labour input. The durations of the productive work cycles are compared for this purpose. Those with the highest duration are classified as potentially abnormal and the rest as normal. This second classification is used as an indicator. It shows project managers whether something appears to be "wrong" with workers' productivity pace. Managers can then look into the video data at the time of the day the abnormalities occurred and check whether something was actually incorrect with these work cycles. This way problems are identified and treated fast. The productivity monitoring method does not need any prior knowledge about the type or the number of tasks workers perform. Therefore, labour productivity of multiple workers can be monitored at the same time. This entails proactivity.

4 Results

This section evaluates the performance of the method presented in this paper in terms of translating the trajectory data into labour input. This is achieved with a C# implementation in Microsoft Visual Studio.Net framework running in a Windows 8.1 operating system. The integrated development environment is Visual Studio 2013, using Windows Forms (WinForms). A desktop PC with the following specs is used: Intel core i7 CPU, 4.0GHz, and 32 GB RAM. The cameras used in the experiments are two GoPro cameras, black edition 4 with a 1920x1080 frame size, and selected 90^0 narrow field of view to reduce the distortion of camera fish eye effect. Both cameras are mounted in such a way that monitored workers are captured within their overlapping field of views.

Precision, recall, and accuracy metrics are used for the evaluation of this chapter's proposed method. Precision is the fraction of the total number of correctly detected work cycles (TP, True Positive) over the total number of incorrectly and correctly detected work cycles (TP + FP, True Positive + False Positive). Recall depicts the detection completion level and is equal to the total number of correctly detected work cycles (TP) divided by the total number of correctly detected and incorrectly not detected work cycles (TP + FN, True Positive + False Negative). Lastly, accuracy is defined by the number of correctly detected work cycles (TP) and the number of work cycles which were correctly not detected (TN, True Negative), over the total sum of work cycles.

The proposed method is tested on an electrical task (see Figure 2). This data set consists of two recordings (part A, B) with a duration of approximately 17minutes each. Both recordings were collected the same day. In total, steel worker performed 29 work cycles that depict the following sub-tasks: a) fixing steel re-bars, b) picking re-bars or equipment, and c) reading drawings. Only one is unproductive, whilst none of the productive work cycles corresponds to idle time.

Figure 2. Tested data set.

This section colours red the unproductive, yellow the abnormal productive and green the normal productive work cycles. Figure 3 illustrates the 4D trajectories of part B.

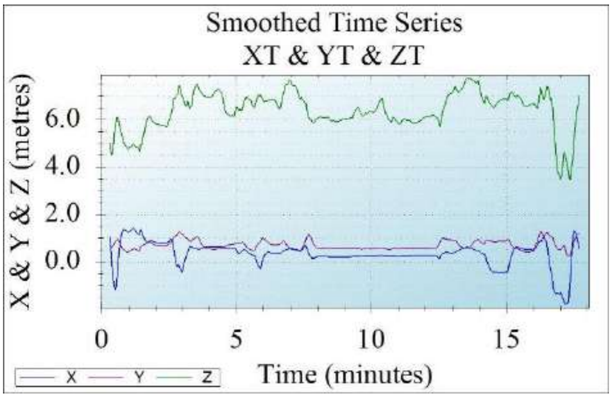

Figure 3. X, Y, Z trajectories over time (part B).

The proposed method detects 9 TP, 1 TN, 0 FP and 0 FN work cycles in part A, and 10 TP, 2 TN, 7 FN and 1FP work cycles in part B. Table 1 shows the ground truth of the manually collected work cycles vs the automated detected ones. The 3 TN results (#1, #11, and #12) result from the way trajectories are smoothed. The smoothing step k is equal to 19sec if divided by camera frame rate i.e. $\frac{k}{fps} = \frac{570}{30}$. Hence, all smoothed time series are 19sec shorter in length at the beginning compared to the unsmoothed. Hence, work cycles that fall within the initial 19sec cannot be detected. All TN results occur at the beginning of each recording. The missed #17 and the 1FP work cycles of part B are due to instabilities of the implemented computer vision-based 2D tracking method. All the rest FN work cycles are of short duration (< 4sec). This shows that that the proposed method does not perform well in terms of detecting work cycles of such short duration.

Table 1: Manually collected ground truth of semantic "stops".

#	Start - End
	Part A (GT)
#	Start - End
1.	00:00:033-0:05:105(TN)
2.	00:12:645-03:37:884(TP)
3.	03:39:153-07:48:035(TP)
4.	07:50:036-11:41:067(TP)
5.	11:42:268-11:44:070(TP)
6.	11:52:545-15:31:798(TP)
7.	15:35:101-15:40:273(TP)
8.	15:45:645-16:49:609(TP)
9.	15:57:317-17:02:989(TP)
10.	17:11:131-17:42:962(TP)
	Part B (GT)
#	Start - End
11.	00:00:033-00:13:680(TN)
12.	00:19:919-00:21:287(TN)
13.	00:25:258-00:30:697(TP)
14.	00:33:867-00:34:768(FN)
15.	00:37:771-01:24:150(TP)
16.	01:28:855-02:36:322(TP)
17.	02:40:293-02:47:667(FN)
18.	02:49:202-02:51:071(FN)
19.	02:52:205-05:53:687(FN)
20.	05:55:021-14:14:087(TP)
21.	14:15:388-15:02:268(FN)
22.	15:03:670-16:15:175(TP)
23.	16:18:645-16:28:988(TP)
24.	16:32:359-16:42:102(TP)
25.	16:47:173-17:02:422(TP)
26.	17:05:658-17:08:628(FN)
27.	17:09:896-17:18:171(TP)
28.	17:23:943-17:29:416(FN)
29.	17:30:517-17:41:227(TP)

In Part A, the work cycle #3 shows that steel worker was unproductive i.e. definitely not performing the steel fixing task, for 4.15minutes. Work cycles #5, and #7 to #10 are all classified as normal productive whilst the work cycles with the largest duration #2, #4, and #6, are all classified as abnormal productive (see (a) Figure 4). In part B, nine out of ten work cycles of this recording, are returned as normal (#13, #15, #16, #22 to #25, #27 and #29) and only one is classified as abnormal (#20) (see (b) in Figure 4). The interesting observation about the recording of part A, is that the abnormal cycle has a duration of 11.56minutes which is by far the largest compared to the rest cycles of both parts A and B. This raises an ambiguity about the performance of steel worker during this time. It can be easily observed, if we check the video footages at the exact time the abnormal cycle #20 occurred, that steel worker could not fit a reinforcing steel bar in the formwork due to complexity of drawings. This is a common issue that affects labour productivity. If we sum all the TP normal and abnormal work cycles, then the labour input of the steel worker is equal to 28.29minutes for both parts (A, B). The manually calculated labour input is equal to 30.62minutes. Therefore, the proposed method measured the total labour input of the steel worker with an accuracy of 92%.

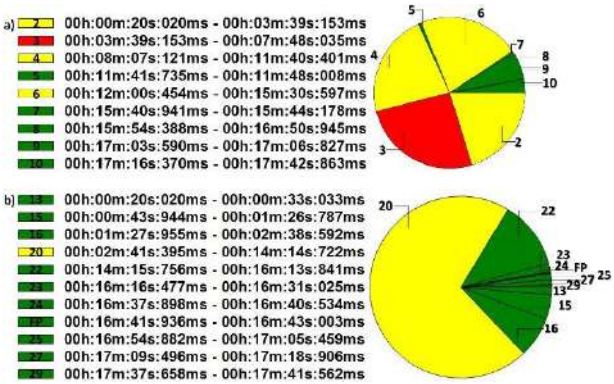

Figure 4: Detected work cycles of steel worker (red: unproductive, yellow: abnormal productive and green: normal productive).

5 Conclusions

The current state of research has not yet proposed a method that performs a non-obtrusive, accurate, cost efficient and generalized monitoring of labour productivity for construction workers. This paper presents a method that addresses these issues in order to detect repetitive patterns in the trajectories of construction workers that depict work cycles. The total duration of these work cycles is equal to the labour input of workers. The novelty of the proposed method lies in clustering. Firstly, the 4D trajectories of workers are smoothed in order to remove noise. Then, they are segmented into 4D sub-trajectories and classified as either "move" or "stop" semantic events. The former event depicts the motion of workers along the floor plane, whilst the latter depicts the motion of workers along the vertical plane. The classified 4D sub-trajectories are finally grouped into clusters based on the main assumption of this paper that: every work cycle is described by two semantic "move" events and one semantic "stop" event.

The main limitations of the method presented in this paper are the following. Firstly, work cycles that depict workers who while at "stop" do not perform any task (idle time) are mistakenly detected as productive. However, as previous studies [38–43] stated "idle" time is not of the main causes behind low labour productivity. Secondly, the productivity of workers who perform tasks mainly characterized by motion such as transferring materials, supervising work progress etc. cannot be monitored. This is because the “move” events depict the actual labour input instead of the “stop” events in such cases. This second limitation indicates that the automated monitoring of workers presented in this paper cannot be applied to the entire range of construction related tasks. Only if the proposed method was updated with the type of tasks of workers it would be possible to turn also the detected “move” events into labour input.

Acknowledgments

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Applying Object-oriented Analysis and Design to Digital Construction Logistics Planning from a Material Flow Perspective

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Abstract –

Current construction logistics planning in practice is executed as an experience-driven planning and proved as inefficient. Previous outcomes of Building Information Modelling (BIM) provide the fundamental of a digital construction logistics planning. However, an underlying logistics concept and a guidance from the production theory for applying BIM in logistics are missing.

This paper aims to elaborate existing problems in the construction logistics planning and initiate an exploration towards a digital logistics planning with a underlying concept of the on- and off-site material flow. A design methodology of OOA/D (Object-oriented Analysis and Design) is applied to the conceptual design of a digital on- and off-site logistics planning. An object-oriented definition of logistics element with a start from predefined BIM element and a use case about logistics Quantity Take-off (QTO) are explained. The research helps to reflect the material change in the construction logistics more accurately, and to further evoke the rethinking of the production theory in the construction field.

Keywords –
Logistics; Material Flow; BIM; OOA/D

1 Introduction

Logistics is the management of the flow of resource between the point of origin and the point of consumption in order to meet requirements of customers (owner or end-user) or corporations [1]. It is a tough task to achieve an efficient logistics planning in the construction field, because the resource flow of a construction project is broken between off-site and on-site domains. The critical reason is not the geographical separation but the non-conformant resource planning.

With the development of Information and Communication Technology (ICT), the manufacturing industry achieves better logistics planning and control by Product Data Management (PDM) system [2]. The fundamental of PDM is a series of well-structured digital Bill of Materials (BOMs), basically including Engineering BOM (EBOM), Plan BOM (PBOM), Manufacturing BOM (MBOM). The material flow in the manufacturing industry is clearer than it in the construction industry, however, the essence of it is the same. Actually, a construction BOM used at the material purchase stage is a typical EBOM, while a construction Bill of Quantity (BOQ) with schedule is equal to a MBOM. What is missing in construction is the PBOM, which essentially is a data form of the construction logistics planning.

Building Information Modelling (BIM) can be applied to build a digital logistics planning and supports its execution. It is a set of concepts, technics and digital methods to encode information of facilities about 3D design drawings, schedule, material characteristics, costs, and safety specifications etc. BIM model is an object-oriented representation and specified by but not limited to Industry Foundation classes IFC (ISO 16739) [3]. Further, the four-dimensional (4D) BIM (i.e. three dimensions plus time) is capable to improve construction scheduling and site monitoring [4], which can also improve the logistics management in a digital way.

However, an underlying logistics concept and a guidance from the production theory for applying BIM in logistics are missing. Meanwhile, current pattern of logistics planning and control in the construction practice is proved as inefficient, thus it cannot be adopted as the fundamental of the design of a digital logistics planning.

Therefore, this paper will provide an analysis of non-conformant resource planning and adopt the understanding of on- and off-site resource flow to a conceptual design of an efficient digital construction logistics planning. The focus of the digital construction logistics planning which will be introduced in this paper is on the materials, while related equipment or transportation tools are treated as constraint or supplementary conditions of materials.

2 Literature Review

Current construction logistics planning in practice is executed as an experience-driven planning with an as-designed site-layout and a series of periodic (e.g. daily, weekly, monthly) look-ahead schedules, and mainly relies on project QTO (Quantity Take Off), BOM and construction master schedule[5]. Generally, BOM is generated from QTO and is applied for the material purchase with a list of subtotals of each material type, which is a guidance document to calculate the periodic quantity of material supply[6]. Another document BOQ, which is also generated from QTO, is applied to calculate the periodic quantity of material consumption associated with a construction master schedule[7]. The problem is that the quantity of material supply does not match the quantity of material consumption, because of different levels of periodic measurement.

From the consumption perspective, a construction BOQ generally follows a division-component method (e.g. earth work, foundation work, frame shear-wall work) and it is the foundation of most 4D construction logistics planning. For example, Tulke and Hanff (2007) presented a solution for creating schedule based on data from BOQ and the building model[8]. From the supply perspective, a construction BOM applies an enterprise level of periodic measurement (e.g. project duration, sub-project duration) to dovetail with the enterprise accounting. It is possible to introduce in the construction schedule to make a detailed construction plan with material constraints[5]. However, a BOQ from the consumption side applies a periodic measurement based on the division-component project level, which is inconsistent with the supply side.

The difference in periodic measurement between enterprise level and division-component project level directly causes the mismatch of the periodic quantity of material supply and material consumption. It makes construction project management adopt a Just-in-Case strategy towards the material resource. According to the Just-in-Case strategy, the succeed of one or a series of construction tasks is the highest goal and any shortage of on-site inventory should be avoided, which may causes any of following problems, but not limited to the followings:

- Excessive amounts of orders
- Overstock on-site
- Waste of site capacity
- Difficulty in materials and related equipment maintenance
- Difficulty in site monitoring

It is worth noting that, even a good Just-in-Case plan cannot guarantee to avoid failure of a construction task in some situation e.g. major construction change, long term or continuous supply delay.

Therefore, an effective construction logistics planning is not only about the development of an excellent avoidance strategy. To understand and accurately grasp the information of the material flow, to overcome the incompatibility in the periodic measurement, and further to solve the mismatch of the quantity of material supply and consumption are main goals of this paper, which is an initial exploratory of a proactive on- and off-site construction logistics planning.

3 Methodology

There are various approaches to develop a construction logistics plan with as-designed building information and related on-site information. However, to grasp the off-site information properly and try to achieve a proactive digital logistics planning is a challenge, and therefore this paper only focuses on the conceptual design of it. A complete software design or a management mode is beyond the scope of this paper.

This paper adopts a design methodology of OOA/D (Object-oriented Analysis and Design) [9] and it contains two phases, as shown in Figure 1:

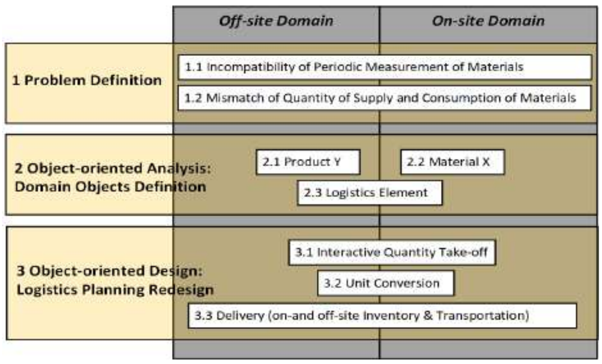

Figure 1. Paper Structure and OOA/D Methodology

1. **Practical Problem Definition**: as discussed previously, is to provide a basic understanding of the weakness of current construction logistics planning and guide the following analysis and design.
2. **Object-oriented Analysis**: with an emphasis on finding and describing the logistics objects or concepts in the problem domain. It is conducted to conduct an analysis of the basic features of the construction material flow from the off-site domain to on-site domain;
3. **Object-oriented Design**: with an emphasis on

defining specific logistics objects and how they collaborate to fulfil the requirements (e.g. attributes and methods). This paper also provides a use case to describe this design by applying Unified Modelling Language (UML).

It is worth noting that, a design and development of a proactive digital logistics planning with both on- and off-site information should be a Iterative process, and this paper provides only the initial efforts.

4 Object-oriented Analysis: On- and Off-site Material Flow

To initiate a construction logistics planning, the first task is to analyse the basic features of the construction material flow. As shown in Figure 2, a certain type of material (e.g. Material **X**) contains three basic status of the physical presences:

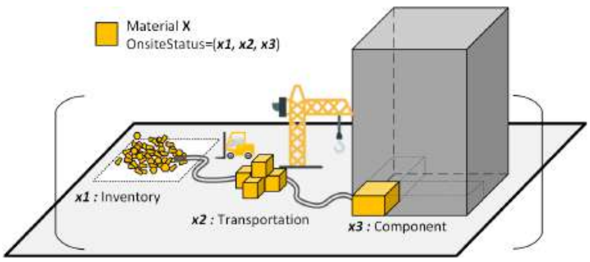

Figure 2. On-site status of the physical presences of Material **X**

- ***x1*** Inventory: on-site stocks of Material X;
- ***x2*** Transportation: Material X in on-site transit;
- ***x3*** Component: Material X placed in one or several construction components.

For an effective construction logistics planning, only considering on-site material flow is incomplete, because the start of a material flow is the off-site production rather than the on-site inventory. Figure 3 illustrates the on- and off-site material flow with a begin of final goods. This paper does not include a complete off-site process because of its scope, however, it can be considered when a construction logistics plan is established.

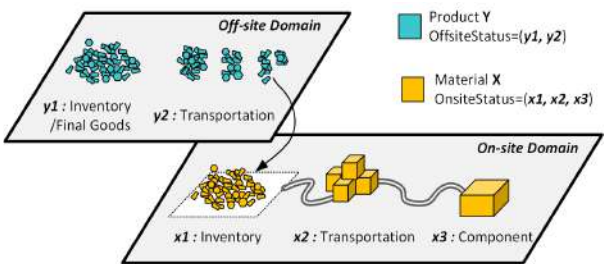

Figure 3. Status of the physical presences of Material **X** and Product Y along an on-and off-site material flow

As it is shown Figure 3, the off-site form of Material **X** named Product **Y**, in order to distinguish different domains i.e. off-site domain and on-site domain. The off-site data of Material **X** is handled by a supplier. It is more for the supplier to provide required data of Material **X** when it is treated as a kind of product. The physical presences of Product **Y** are:

- ***y1*** Inventory/Final Goods: Product Y ordered by construction project (Final Goods) and produced by a supplier (Inventory);
- ***y2*** Transportation: Product Y in off-site transit.

The difference between Final Goods and Inventory depends on whether the supplier needs to produce this kind of product (Final Goods) or can directly delivery it from the off-site inventory (Inventory). For example, when the production process of a kind of product is error-prone and the supplier usually hold no inventory, it is better for a construction project to treat y1 as Final Goods and pay attention to the status of the off-site production. In this case, an off-site production process look-ahead checking and guarding has been discussed [10].

5 Object-oriented Design: Logistics Element Definition with BIM

According to the nature of the on- and off-site material flow discussed before, it is not appropriate to simply treat a kind of material as a simple attribute of the construction component, which is the traditional way taken by a 4D BIM plan. It is to some degree an oversimplification of the real world and causes the difficulty in applying digital planning in construction logistics.

Actually, the material change of any construction task follows the Law of Conservation of Mass and the essential features of a kind of material does not change along the flow. It provides possibility to apply an OOA/D method to define the Logistics element. It is appropriate to define it from the start of a predefined BIM component (shared building element) which is a long-established practice, as shown in Figure 4:

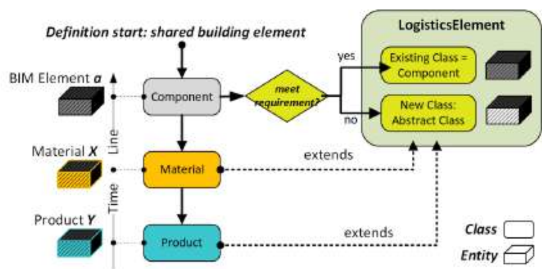

Figure 4. Logistics element definition with BIM

BIM model itself is an object-oriented representation and provides a series of well-designed properties or property sets, which can be applied for LogisticsElement definition. However, it is conditional because of the logistics requirement (see Figure). For example, if the predefined BIM Element ***a*** contains complete property for a logistics plan of Material ***X*** (on-site) and Product ***Y*** (off-site), the definition of them can directly refer to the existing class, otherwise it is required to define a new abstract class to share property.

However, to judge if the predefined BIM element meet the logistics requirement needs to consider both time and quantity parameter and pay attention to different types of materials input:

1. **Simultaneous Materials Input**: includes Single-Material Input (material 1) and Multi-Materials Input (material 1,2..n), as shown in Figure 5. The BIM element of a component contains basic property which can share with materials.

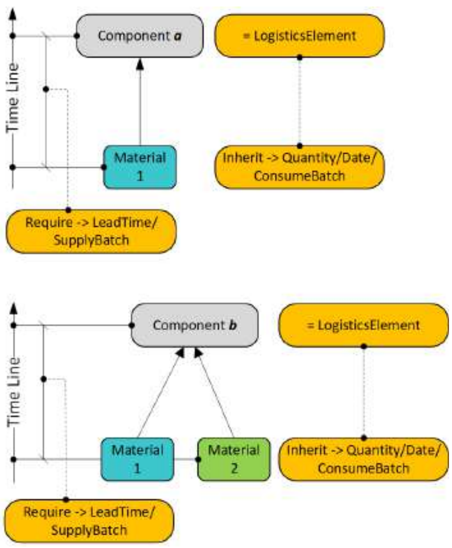

Figure 5. Pattern of the simultaneous materials input

2. **Successive Materials Input**: applies for the situation when the BIM element of a component cannot directly reflect the time and quantity features of every required material. A conversion method is required, for example, to allot quantity of material 1 and material 2 and define time constrains among material 1,2 and component ***c*** (see Figure 6).

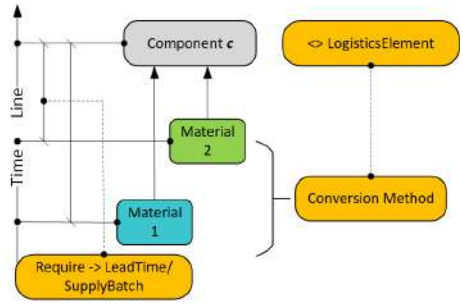

Figure 6. Pattern of the successive materials input

6 Use Case of Logistics Quantity Take-off

- To further understand how to consider the material change as a flow and apply the definition of logistics element to solve logistics planning problems, e.g. mismatch of the quantity of material supply and consumption, a use case of Logistics Quantity Take-off is written (see

Table 1) and explained as following:

Use Case: Logistics Quantity Take-off
Primary Actor: Material Manager, Supplier, Construction Worker, Project Manager
Stakeholders and Interests:

- Material Manager: Wants accurate quantity of construction components and related required materials. Wants sufficient information of supplier's products to support contract and trade.
- Supplier: Wants sufficient information of project required materials to support contract and trade.
- Construction Worker: Wants to finish regular work with no material problem.
- Project Manager: Wants accurate quantity of construction components, related required materials. Wants automatic and fast updates of site transpiration and inventory status.

Table 1. Description of the use case of Logistics Quantity Take-off

Actor Action	**System Responsibility**
1 **Material manager** starts a new **logistics quantity take-off**.	
2 **Material manager** selects **construction components** (known quantity).	3 Records each selected **construction component**, identifies its **material items**

	and calculates material subtotals of quantity with a **material catalog**.
4 **Material Manager** repeats steps 2-3 until indicates done.	5 Logs the completed calculation, presents **material item specification** and generates a classified list of **Quantity of Materials**.
6 **Material Manager** sends **Supplier** related partial list of **Quantity of Materials**, sends an **enquiry** and asks for a **product item specification**.	
7 **Supplier** sends the **product item specification** to **Material Manager**.	8 Handles **product item specification** and converts the **unit** and calculates product subtotals of quantity with a **product catalog**.
	9 Logs the completed conversion and presents a classified list of **Quantity of Products**.
10 **Material Manager** sends **Supplier** related partial list of **Quantity of Products** and an **offer**.	
11 **Supplier** gives an acceptance to the offer and both sides reach a **supply contract**.	12 Handles and records the **supply contract**.
13 **Material Manager** and **Supplier** decide the quantity of **product supply batch** (inventory input) according to the **product catalog**, **price policy**, **material consume batch** (inventory output) and **inventory policy**.	14 Records the **product catalog**, **price policy**, **material consume batch** (inventory output) and **inventory policy**, and calculates **product supply batch**.
	15 Logs the completed calculation and presents **a list of product supply batches**.
16 **Supplier** deliveries **product supply batch** according to the list.	17 Records each delivered **product supply batch** quantity and sends information to the **off-site inventory** systems (update off-site inventory) and the **off-site transportation** systems (update transportation status).
18 **Product supply batch** arrives the construction site and is put into the **on-site inventory**.	19 Records each arrived **product supply batch** quantity and sends information to the **on-site inventory** systems (update inventory)
20 **Construction worker** takes materials from inventory.	21 Records **material consume batch** quantity, and sends information to the **on-site inventory** systems (update inventory) and the **on-site transportation** systems (update transportation status).

** Conceptual classes are in bold*

In this use case, there are three essential tasks which influent logistics status:

3. **QuantityTake-off**: is to work out a model-based Quantity of Materials which supports the division-component project level of periodic measurement;
4. **UnitConversion**: is to get sufficient information from supplier and work out a model-based Quantity of Products, to avoid an excessive Just-in-Case strategy;
5. **Delivery**: is to balance the batch amount of product supply (off-site) and material consumption (on-site) and keep both off-site and on-site inventory safe and economical.

The QuantityTake-off process to generate a Quantity of Material is a model-based process i.e. ConstructionComponent and MaterialItem contain their own quantity information, rather than adding material attributes to a list of QTO (i.e. list-based BOM). As discussed before, the list-based BOM applies an enterprise level of periodic measurement and it is insufficient to a logistics planning. The model-based Quantity of Materials is explained as following:

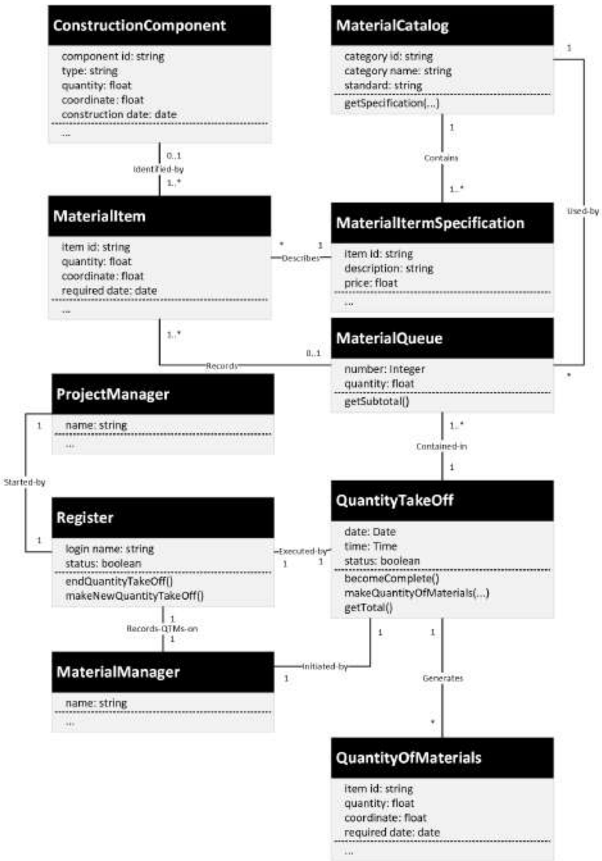

Figure 4. Domain model of QuantityTake-off

Besides Quantity of Materials, there is another important document: Quantity of Products, which is treated as an essential conjunction of the on- and off-site logistics at the planning stage. This Quantity of Products is a concentrated reflection of the off-site information from both sides. To work out a Quantity of Products, the Quantity of Materials and production specification are needed as the fundamental and a UnitConversion method is applied as following:

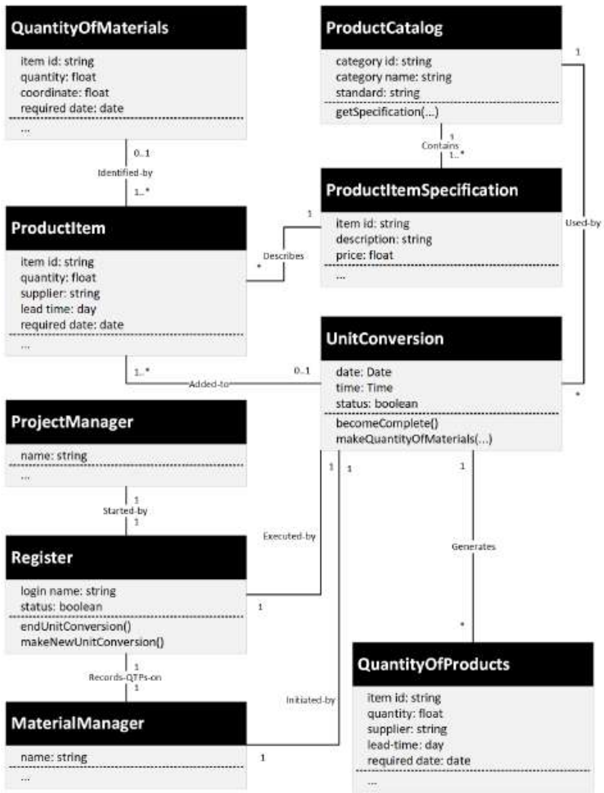

Figure 5. Domain model of UnitConversion

After Quantity of Materials and Quantity of Products both worked out, specific MaterialConsumeBatch and ProductSupplyBatch are taken into account. To design an optimized ProductSupplyBatch is not a simple task, because the on and off-site production, transportation and inventory data should be collected and a series of policies should be considered e.g. PricingPolicy and InventoryPolicy, as shown in Figure 6:

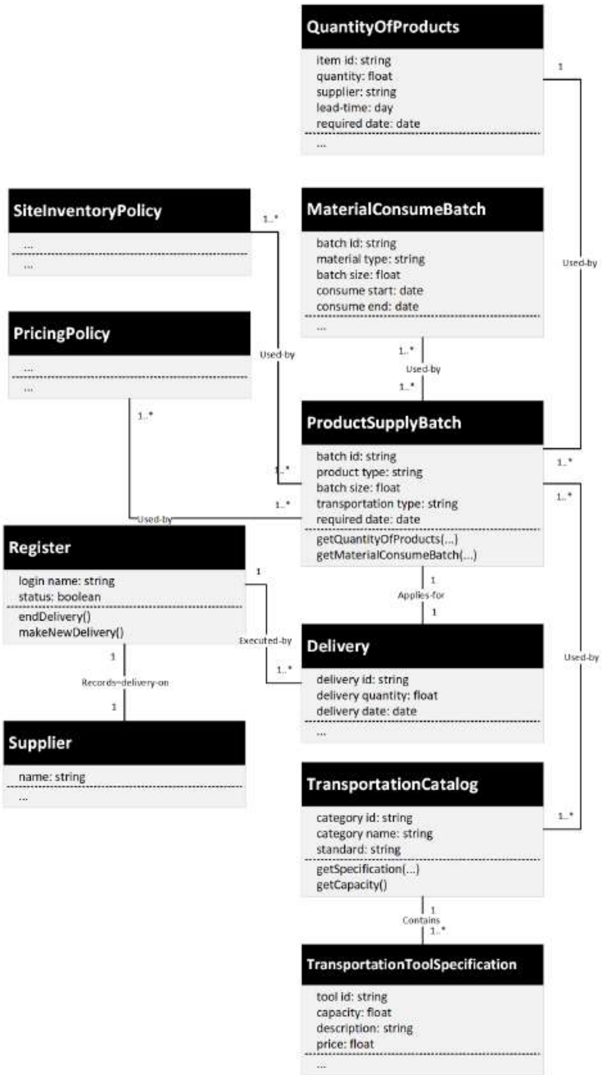

Figure 6. Domain model of Delivery

These three essential tasks of QuantityTake-off, UnitConversion and Delivery in this use case are essential to overcome the incompatibility in the periodic measurement, solve the mismatch of the quantity of material supply and consumption and further to develop more detailed on- and off-site logistics planning.

7 Conclusion

The aim of this paper is to explain existing problems in the construction logistics planning and initiate an exploration towards a digital logistics planning with a underlying concept of the on- and off-site material flow. This paper first introduced the material flow and analyzed the basic status of the physical presences of a certain type of material from the on-site to off-site domains. Then an object-oriented definition of logistics element with a start from predefined BIM element was discussed. Finally, a use case of Logistics Quantity Take-off with three essential tasks of QuantityTake-off, UnitConversion and Deliver was explained.

However, the logistics element definition and use case at this stage are not complete, there are several aspects need to improve, for example, logistics requirements in element definition should be specified and the method of UnitConversion should be designed in detail. Further, a new pattern of the logistics planning and management is not only to reflect and control the material change to make a project succeed, but also to rethink the construction industry itself and its own production theory.

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Construction Worker Detection and Tracking in Bird's-Eye View Camera Images

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Abstract -

Construction sites are continuously changing environments where construction workers have to adapt to dynamic situations while executing their work tasks safely and efficiently. Simultaneously, they are surrounded by heavy construction machinery and massive crane loads which they have to be aware of at any time. Frequent interruptions may often lead to a loss in productivity and also causes hazardous conditions or even incidents, injuries or fatalities. Tracking workers' paths on site can be used to approach these issues. Recorded tracks can be used to identify close calls of inexperienced or distracted workers. To date, pedestrian workers may participate in customized trainings in order to overcome individual deficits. Machine operators can be assisted to mitigate hazardous situations by warning them from construction workers approaching their machines.

Since surveillance cameras are already existent on most construction sites, a video-based detection and tracking system can be implemented at low costs. Relying on video streams, the detection of workers becomes similar to pedestrian detection. Some effort has already been made to elaborate those methods to the needs of construction worker detection. However, in contrast to the frontal view supposed in most pedestrian detection approaches, cameras on construction sites commonly provide oblique or bird's-eye view perspectives. This complicates the detection task as most body parts of a worker are occluded. Hence, we evaluate the applicability of pedestrian detection approaches in terms of the camera settings at hand. Ensuing, we propose a concept for the detection and tracking of construction workers which allows to improve the productivity and safety on construction sites.

Keywords -

Cascaded Classifier, Detection, Monitoring, Productivity, Safety, Tracking.

1 Introduction

Construction sites constitute highly complex, dynamic environments. Often, workers execute their working routines in collaboration with heavy machinery operating in their own workspace. For example, excavators and other construction vehicles cross the paths of construction workers and cranes lift massive loads over their heads. A variety of hazardous situations may arise from that such as incidents involving material and equipment or injuries and fatalities happening to workers or persons standing nearby. Hence, construction workers have to be trained to be sensitized for potential hazards. Hazardous situations such as close calls can directly be identified from the workers' actual paths across the construction site. Recording these could facilitate the identification of the necessity of further trainings as well as the customization of trainings with respect to the workers' deficits.

Concurrently, machine operators should be assisted in recognizing potential hazards involving workers in advance so that accidents can be avoided. Augmenting their field of view with the positions and walking path trajectories of workers as sketched in Figure 1 could further improve the safety on site as it enables operators to perceive distracted workers even if they are laboring in blind spots. Warning machine operators of such hazards could mitigate such situations which otherwise could end fatal.

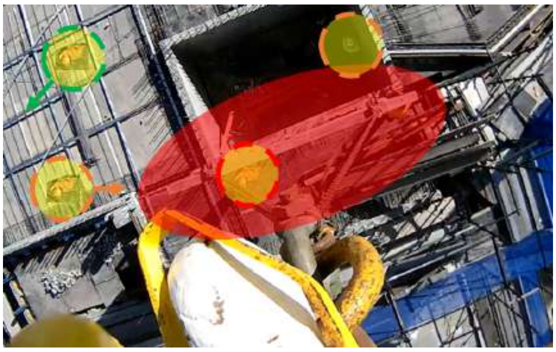

Figure 1. Augmented field of view of a crane operator. Yellow circles represent detected construction workers color-coded according to their level of hazard. Green highlighted workers are in sufficient distance to the hazard zone of the crane's load (red ellipsoid) and are predicted to walk away from it. Workers are marked orange if they approach the hazard zone or already stand near to it. Workers exposed to the hazard are marked red.

The obtainment of the construction workers' trajectories in construction-related areas of a site and in the surrounding of machinery, thus, allows to significantly decrease safety issues. Further application areas may also benefit from this, such as checking workers for wearing appropriate safety equipment, site access control systems, or even the improvement of productivity. A reasonable tracking of workers during their working routines tackles multiple issues on site and is already in the scope of research. Depending on the surrounding, common approaches rely on different radio signal emitters like radio-frequency identification (RFID), ultra-wideband (UWB), and global navigation satellite system (GNSS) tags. These are attached to the gear of each construction worker which involves high costs [1] and causes discomfort [2]. In contrast, a camera based tracking of workers on construction sites provides a cost-saving and less obtrusive approach.

Relying on video streams, the task becomes similar to pedestrian detection which is a well researched topic today. There are already approaches adapting methods of this field for construction worker detection. Nevertheless, crucial differences between the application areas have to be taken into account. Due to the actual scope of application in advanced driver assistance systems, pedestrian detection approaches commonly assume a frontal view. In contrast, surveillance cameras on construction sites as well as cameras for crane operator assistance are usually mounted in heights to existing structures resulting in bird's-eye view perspectives recording the workers sometimes even over far distances. This complicates detection since most parts of the bodies are occluded by the workers' heads and shoulders or physical obstructions. Therefore, we evaluate previous pedestrian detection approaches with respect to their applicability in bird's-eye view images. Based on this research objective, we propose a conceptual system which improves over previously made approaches tracking construction workers for safety and productivity issues. For this purpose, we apply a background subtraction method which identifies regions of interest in the camera image. A cascaded classifier investigates these regions and detects construction workers. In order to track the detected workers through multiple camera frames, we apply Kalman filtering.

The remainder of this paper is structured as follows: in Section 2, we motivate our work by surveys and studies concerning safety and productivity issues. We investigate previously made approaches of pedestrian detection in Section 3 and discuss these with regard to the limitations in the video data in the field of construction monitoring. Based on the findings, a conceptual system for tracking construction workers on sites is proposed (see Sec. 4). Finally, we discuss the results and conclude on our concept in Section 5.

2 Motivation

High rates of injuries and fatalities in construction are often explained by its complex, dynamic, and continuously changing work environment. Whereas cranes play a central role in construction operations, federal labor statistics in many countries relate about 15-25% of all fatal construction workplace accidents to too close proximity of pedestrian workers to construction equipment or hazardous materials [3]. Struck by moving parts of crane equipment or hit by falling objects are some of the most frequent causes of crane-related construction accidents [4]. Their outcome is often fatal [5], which distinguishes crane-related accidents from the majority of other construction accidents where the outcomes are minor (e. g., cut in finger).

Cranes come typically in numerous configurations to fit unique sites [6]. Cranes carrying loads over, into, and/or around workers' environment add yet another dimension of risk to an already complex workspace. Though safe crane design, several on-board safety devices and operational procedures exist, large problems remain to operate them safely. Research studies state:

- About 16% of all construction fatalities relate to cranes [7]
- 33% of all construction casualties and permanent disabilities relate to cranes [8]
- 87% of crane-related deaths occur among workers and do not involve operators [9]
- Few in the transient construction workforce have operating or rigging experience [5]
- Little information about the causal factors or environments leading to the accidents or close call events is known [10]

Few safety statistics from around the world exist that explain the problem in detail. The Center for Construction Research and Training analyzed data collected by the U.S. Bureau of Labor Statistics in the years 1992-2006 [11]. In this time period, 632 crane-related deaths were identified which occurred in 610 crane incidents. These numbers equal to an average of 42 crane-related deaths per year. Whereas mobile or truck cranes (at least 71%) were the main types of cranes that have been associated with crane-related fatalities, tower cranes (5%), floating or barge cranes and overhead cranes, and other/unspecified cranes are the other crane types (24%). Of the total 632 crane-related deaths, 157 (25%) were caused by overhead power line electrocutions, 132 (21%) deaths were associated with struck by crane loads, 89 (14%) involved crane collapses, 78 (12%) involved a construction worker being struck by a (i.e. falling) crane boom/jibs, 56 (9%) included falls from cranes/crane baskets/crane loads, 47 (7%) were struck by crane or crane parts, 30 (5%) caught-in between, and 43 (7%) deaths were from other causes. The activities immediately preceding the workers' deaths related to deaths from struck by crane loads (132 between 1992-206) were: 32% of the workers were not involved with the crane, 32% loaded/unloaded, 15% performed other crane-related work, 14% were flagging/directing/guiding, and 7% operated the crane. The majority of the workers belonged to laborers (191 deaths), while the others trades were heavy equipment operators (101), supervisors/managers/administrative (86), ironworkers (42), mechanics (41) and other trades (171).

In their recommendation to prevent crane accidents from happening in the future, CPWR recommends the following actions to take: crane operators should be certified; crane riggers and signalpersons should be adequately trained; crane inspectors should be qualified; cranes should be inspected; only qualified and competent persons should assemble, modify or disassemble a crane; cranes should not be allowed to pass over street traffic; and more thorough investigations and immediate follow-ups should be performed. Despite the poor safety performance of cranes in construction and several recommendations that are already part of many construction safety leaders' best practices, no proactive approach has been taken towards detecting and resolving the identified crane-related hazards [12]. For example, when a crane load swings over an active worker environment, pedestrian workers and crane operator should be warned of the risk of falling objects or being struck-by.

In Germany, construction occupational safety and health is embodied in and shaped by numerous laws, regulations and ordinances with a view to ensuring the safety and health of construction workers in the workplace. Technical Occupational Safety and Health includes all areas that affect the safety of workers at work. The Safety and Health at Work Act (ArbSchG) regulates the underlying occupational safety and health duties of the employer, the duties and rights of workers, and the monitoring of occupational safety and health in accordance with this Act. In the control hierarchy (a) technical, (b) organizational, and (c) personal measures are typically embedded in an organization's safety culture. These respectively and whenever possible, (a) avoid hazards in the first place by replacing hazardous work practices with safer ones and separate workers from hazardous workspaces, (b) limit the exposure time to hazards, and (c) provide personal protective equipment (PPE) and instruct personnel [13]. Again, existing regulations, rules or best practices on safety in construction do not envision proactive solutions other than education, training, and enforcement. For example, by means of using technology, pedestrian workers and operators could be automatically warned in real-time from nearby or approaching crane loads. However, such technology does not exist today [14].

3 Detection Methods

The safety of construction workers on site can be improved by focusing on their working behavior. By tracking their paths across the site, hazardous situations like close calls can be identified. Additionally, operators can be warned from potentially distracted workers approaching their machines too closely. For tracking workers on construction sites different technologies have already been applied. Most prominent are radio signal emitters like RFID, UWB, and GPS tags which are attached to the gear of the construction workers. Besides the imposed costs for equipping each worker on the site [1], theses tags are perceived to be obtrusive, resulting in discomfort accompanied by a decrease in motivation [2]. Video-based techniques overcome these deficiencies and allow for a uniform method of detecting and tracking workers all over the site. As nowadays cameras are ubiquitous and not primarily meant to control workers, they can be considered to be less obtrusive. Moreover, by making use of already existent surveillance cameras only few cameras have to be additionally installed, keeping new investments and maintenance costs low.

Identifying workers in video streams is similar to pedestrian detection. By now, this is a well understood field of research in the computer vision area which already provides a variety of satisfying methods. Especially the automotive industry continuously advances the current methodology. Due to the usual application area in advanced driver assistance systems, approaches in this field assume frontal images of pedestrians. Some approaches already adapt those methods to construction worker detection [15, 16]. Referring to this, Park and Brilakis [16] propose a two-parted detection approach. They learn shape features using a support vector machine (SVM) to identify people in frontal view images. Using color features these detections are further processed by a k-nearest neighbor (k-NN) classifier to detect construction workers by their safety vests. On construction sites, however, frontal view images are merely an exceptional case. Surveillance cameras are usually mounted to high posts, scaffolds, or on nearby building facades or roofs. In particular, for assisting crane operators at lifts, cameras have to be mounted to the jib or at least high on the crane tower. Detection and tracking of workers on construction sites, thus, have to be done in bird's-eye view images. This complicates the detection task as the workers' bodies are barely visible as can be seen in Figure 2. For this reason, identifying construction workers on site requires a robust detector which yields reasonable results despite sparse indications for the presence of a worker caused by the challenging perspective.

Figure 2. Construction workers recorded by a surveillance camera mounted 15 m above ground.

In comprehensive surveys Dollár et al. [17] and Benenson et al. [18] summarize the state-of-the-art pedestrian detection algorithms and evaluate their performance. Benenson et al. propose to categorize the approaches into deformable part-based models (DPM), deep learning, and decision forests.

DPM Approaches based on DPM subdivide an object into a star-structured part-based model consisting of a root object and multiple parts attached to it [19]. According to this, a latent SVM can be trained using a pyramid of histograms of oriented gradients (HOG) features in order to classify pedestrians by detecting their body parts [20, 21]. Advancing the part-based model towards a multi-resolution structure improves detection results [22]. Nevertheless, in our case the view is generally narrowed to the heads and shoulders of pedestrian construction workers wearing personal protective equipment (PPE). Approaches relying on the detection of silhouettes and body parts, consequently, are ineligible in this context.

Deep Learning Deep learning comprises approaches using large artificial neural networks. These can be used for object detection by extracting features from the image data. Sermanet et al. [23] apply a convolutional neural network which learns relevant features from the training data. Albeit the network yields fair results on similar data sets, it fails on generalization. Up to now, it has not been shown that deep learning approaches can be used to learn sufficient image features [18]. For other deep learning approaches [24, 25] features have to be predefined manually. It is doubtful if such heavy techniques are necessary to evaluate manually selected features. Furthermore, the latter approaches again pursue the part-based idea which is not applicable for bird's-eye view images. Since the results obtained by deep learning on pedestrian detection tasks are yet at the same level with DPM and decision forests, advantages of deep learning are still questionable [18]. Hence, simpler methods should be preferred instead.

Decision Forests Decision forests are ensembles of decision trees in which the nodes represent weak classifiers. Samples are classified by passing through the trees. Viola and Jones [26] proposed an approach using AdaBoost to train a pruned decision tree with Haar features as weak classifiers. Originally developed for face detection, they showed that it is also applicable to pedestrian detection [27]. Bourdev and Brandt [28] improved the method by promoting the confidence of each evaluated weak classifiers through the tree. Coupled with a generalized feature approach, Dollár et al. [29] showed that this method outperforms previous pedestrian detectors. This indicates that the detection results of decision forests improve with the development of features. By now, other pedestrian detectors achieve a similar detection quality compared to decision forests. Nevertheless, boosted decision trees usually outperform monolithic classifiers like SVM on most detection tasks [30]. Furthermore, boosting automatically selects the most suitable set of features from a given pool. This overcomes the need for evaluating features manually as it is commonly unclear which features qualify best for a certain task.

Whereas Benenson et al. mainly categorize the approaches by their machine learning algorithms, Dollár et al. focus on the sets of features. They found that gradient-based features like HOG [31] are most prominent. Besides this, shape features [32, 33] and motion features [27] are frequently used. While HOG feature approaches perform best in comparison to other single feature settings, even better detection results can be achieved when combined with multiple features providing complementary information. Accordingly, combining Haar-like features, shapelets, shape context, and HOG features outperforms any single feature approach [34]. In their study, Dollár et al. [29] focus on the choice of features and propose a framework to efficiently compute multiple features based on integral channels.

4 Concept

We evaluated previously made pedestrian detection approaches regarding the requirements and general conditions of construction workers detection in bird's-eye view images. In the following, we develop a concept for tracking construction workers on site considering the insights gained in Section 3. Figure 3 depicts the conceptual system in total.

According to the findings in Section 3, methods relying on DPM are not applicable for our purpose as the perspective does not allow for the detection of body parts. Also deep learning is not preferable in this context since it could not be shown that deep neural networks are advantageous over other approaches. In contrast, decision forests prove to be well suited for construction worker detection in bird's-eye view images.

For our conceptual worker tracking system, we propose a single classifier approach using a decision tree as this highly improves the speed over the two-parted detection system by Park and Brilakis [16]. We decide for the soft cascaded approach proposed by Bourdev and Brandt since its detection results exceed those of the Viola-Jones detector. Additionally, its likewise pruned cascading layout further improves the speed of classification by rejecting negative samples early in the cascade. Hereby, the entire cascade has to be processed for positive samples only; for negative samples only few image feature are evaluated before rejection. This eases real-time processing on video data. Moreover, since it is unknown which image features qualify for this task, boosting automatically selects the optimal set of features for our purpose. Accordingly, a manual selection as in the approach of Park and Brilakis [16] is not required.

We exchange the originally proposed thresholded Haar features by integral channel features. This further improves the detector as various image feature types can be efficiently computed using integral channels, and the combination of multiple feature types advances the detection quality over single feature approaches. Similar to Park and Brilakis [16], our concept relies on the identification of shape and color in order to detect construction workers. Since features responding to contours yield reasonable results on pedestrian detection, we draw on adjacent second-order integral channel features on grayscale images. These are equivalent to Haar features which act as edge detectors and, thus, indicate shape information. Apart from contours, construction workers are commonly characterized by their PPE including their helmets and safety vests. Thus, color features may improve detection by incorporating the prominent colors of these items. Color histograms can be efficiently computed by applying first-order integral channel features to quantified versions of each color channel separately. For both feature types, illumination has to be taken into account as it affects the features' responses. Grayscale images can be variance normalized to minimize the influence of different lighting conditions. In case of color histograms, the color space has to be chosen properly. In Figure 4 we compare RGB and HSV color spaces with respect to safety vests in different illumination. As can be seen, color histograms over red, green, and blue channels significantly change when altering the lighting conditions. As brightness is implicitly encoded in each channel of this color space, varying the illumination conditions directly affects the color information of these three color channels. Contrarily, in the HSV color space hue and saturation channels are invariant to illumination since brightness is explicitly encoded in the value channel so that only hue and saturation represent color information. Color spaces like HSL or YUV should also be considered as these offer equivalent channel characteristics.

Instead of scanning the entire image for construction workers we favor background subtraction beforehand. By identifying areas of motion within each video frame, classification can be limited to regions of interest. Albeit the speed of the soft cascaded classifier allows to scan images in real-time, restricting the scope of the classifier may significantly reduce false positive detection. Areas of motion can be identified by frame differencing. Assuming the previous video frame as background, subtracting it from the current frame reveals changes which imply movement (see Fig. 5). By thresholding the results, its sensitivity can be controlled:

$$|I_{t-1}(x, y) - I_t(x, y)| > \tau$$

where $I_{t-1}(x, y)$ and $I_t(x, y)$ denote the previous and current video frames and τ is the threshold.

The quality of the results highly depend on the choice of the threshold τ. Furthermore, image noise and fast illumination changes may be interpreted as motion. For a higher robustness we advance to learn a more complex background model. By averaging the background over multiple frames [35] a background model emerges which is insensitive to momentary changes between few frames.

In order to predict the paths of construction workers, the detected workers have to be tracked throughout the video frames. For this, we suggest the application of Kalman filtering to the detections. Given position and velocity data of a detected construction worker, the Kalman filter predicts its future state ongoing. Subsequent measurements of position and velocity are fed into the Kalman filter to reduce the uncertainty of the predictions. This approach also supports the detector as it provides further regions of interest in which construction workers may be detected even if they are standing still.

5 Conclusion

On construction sites, workers are exposed to a variety of hazards. Construction machines cross their paths and loads are lifted over their heads. This often results in close calls or even accidents. Thus, construction workers have

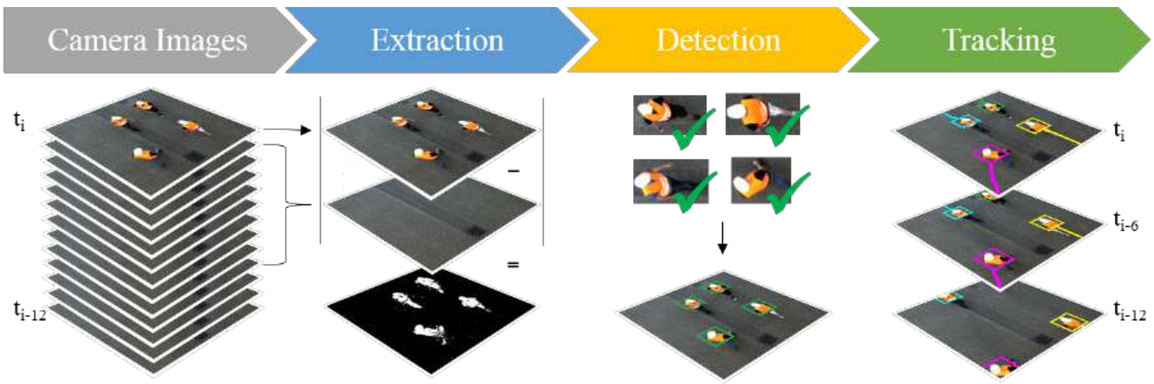

Figure 3. Conceptual system for tracking construction workers on site in bird's-eye view images. Initially a foreground extraction of the incoming camera images is made via background subtraction averaging the background based on a certain number of previous frames. Construction workers are, then, detected in the foreground by means of edge and color feature. Using a Kalman filter, these detections are tracked in the camera frames over time.

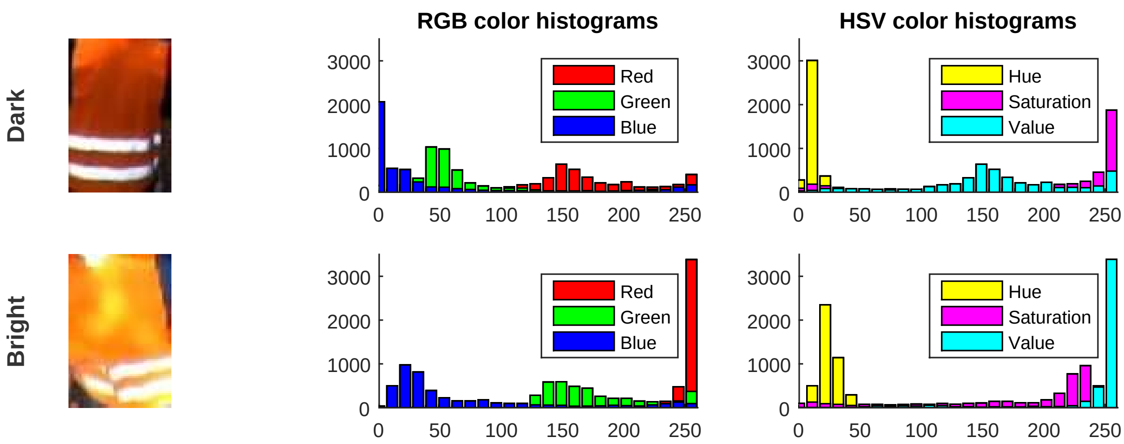

Figure 4. Comparison of histograms in different color spaces with respect to a safety vest (first column) in dark (first row) and bright (second row) illumination. In the RGB color space (second column) high variation occurs in the peak positions of each channels. On the contrary, hue and saturation channels of the HSV color space (third column) are significantly more robust to illumination changes.

Figure 5. Frame differencing applied to two consecutive frames showing a construction worker with a threshold τ of 40. White areas in the resulting binary image indicate areas with motion.

to be trained individually in order to sensitize them for potential hazards. Tracking workers during their working routines in construction-relevant areas on sites may improve the customization of the trainings since these can be adjusted to individual deficits. Furthermore, the tracking of workers can be used to avoid accidents involving heavy machinery by assisting machine operators and providing position and walking path information. The optimal for communicating such valuable and potentially life-saving information has yet to be found for applications in construction.

A video-based tracking system offers a cost-efficient and uniform alternative compared to conventional tag-based methods. Although detecting construction workers is similar to pedestrian detection, the perspective of high mounted cameras complicates the task. Thus, we investigated common pedestrian detection approaches with respect to the applicability for construction worker detection in bird's-eye view images. We discussed detectors of different categories and found that decision forests qualify best. Using a multi-feature approach enhances common edge feature approaches with complementing information which further improves detection. For this reason, we prefer to apply a soft cascaded classifier in our conceptual tracking system. As weak classifiers, we propose edge features and color histograms of the integral channel feature approach. Background subtraction is used to focus the classifier on regions of interest and to reduce false positive detections. In order to track detected workers and to predict their future walking paths, Kalman filtering can be applied.

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RobotEye Technology for Thermal Target Tracking Using Predictive Control

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Abstract –
Thermal cameras are widely used in the fatigue analysis of mechanical structures using the thermoelastic effect. Nevertheless, such analysis is hampered due to blurry images resulting from the motion of structure-under-test. To address the issue this paper presents a system that utilizes robotic vision and predictive control. The system comprises of a thermal camera, a vision camera, a RobotEye, and a fiducial detection system. A marker is attached to a thermal target in order to estimate its position and orientation using the proposed detection system. To predict the future position of the thermal moving object, a Kalman filter is used. Finally, the Model Predictive Control (MPC) approach is applied to generate commands for the robot to follow the target. Results of the tracking by MPC are included in this paper along with the performance evaluation of the whole system. The evaluation clearly shows the improvement in the tracking performance of the development for thermal structural analysis.

Keywords –
Automation and control, Computer Vision

1 Introduction

Kelvin's Law has laid the scientific foundation on which the mechanical stress measurements can be derived from the temperature measurements [1]; and the formation of the Thermoelastic Stress Analysis (TSA) system has further taken shape alongside with the emergence of the suitable modern thermal camera where it can be used to remotely measure the stress distribution of a structure under load [2].

The effective use of TSA for full-field stress measurement, structural fatigue detection and crack propagation have since extended its prognostic capabilities to the construction industry, where TSA has been used to inspect and measure the usage stress load of aging infrastructures such as steel bridges, railway tracks, power poles, pipelines, heavy industrial equipment and vehicles [3], [4]. Even though full-field TSA measurement can be remotely conducted for large civil engineering structures, it would often demand for expensive optical setup and the resources required.

Since the structure is continuously under loading motion, with the thermal camera fixed looking at a region of interest, the resultant motion blur would stop TSA from being useful. To account for the resultant shift of pixels in the thermal images, the thermal camera can directly be mounted onto the structure under test; unfortunately, this approach has not always been practically or physically feasible. Thus specific attempts have often been made to compensate for this motion blur under each individual experimental setup; Wong & Ryall first presented a single axial loading, video-processing motion compensation technique [5], yet the search for an elegant and effective motion compensation method is still ongoing.

Attempts to visually track a moving structure with camera mounted on motion platforms such as a servo controlled pan-tilt mechanism, active gimbal devices and 6-DoF robotic systems etc. are some of the tactics that have been widely explored and developed [6]. Nevertheless, due to the demand on complex multidimensional loading dynamics, and due to nonlinear dynamics such as backlash and friction, tracking performance of such system degrades when it comes to random motion.

In order to tackle this problem, researchers from Defence Science and Technology Group have put forward a unique solution by having a stationary camera with a pointing mechanism to track moving structure. A major advantage of this technique is in having the stationary thermal camera staring at a low-mass pointing mirror, which undergoes a small angular motion to track an external structure's motion. This is where the complementary Ocular Robotics' RobotEye innovative optical pointing technology has made this solution practically possible [7].

This paper presents the solution proposed by Defence Science and Technology Group, where the high speed visual feedback is used to enable the optical pointing sensor to track the structural motion via a defined target, whilst at the same time it allows thermal camera to take long exposure, stable, un-blurred images of the region in the vicinity of this defined target.

This solution comprises of a RobotEye, the state-of-the-art pointing technology which has been developed and commercialized by Ocular Robotics Limited [7], a high-speed vision camera, a marker detection system [8], and a thermal camera embedded within the optical pointing system to capture the view where the eye is pointing. The pointing technology uses mirror-based technology [9], which significantly reduces the inertia of the sensor in comparison to the pan-tilt system. A fiducial marker is attached to the target, where its position is calculated using the marker detection system, as explained in [8]. Included also is the design of a predictive tracking controller based on the Model Predictive Control (MPC) for the optical pointing sensor's head motion. Since the robot is connected to a computer network, its tracking performance is affected by delays. Nevertheless, owing to the MPC, the control system for the actuator can generate control signals even in the presence of the unexpected delays.

Furthermore, this study canvasses a transformational idea that aptly fits to the advancement of modern day robotics and inspection technology, where our proposed solution here can be retrofitted onto a suitable autonomous vehicle platform to deliver a low, cost-effective in-situ structural health prognostic monitoring and management system. We envisage the potential benefits of having large infrastructures such as bridges, high speed rail tracks, pipelines and wind turbines inspected using such TSA autonomous systems, where the collected structural health information can be used to facilitate sound engineering analyses and decisions, and thus avoiding any surprise failures.

This paper is arranged in following sections. Details about the RobotEye technology and the proposed system are presented in Section 2, followed by the MPC for the robot's head motion in Section 3. Results are presented in Section 4. Finally, this paper concludes with a conclusion and recommendation for future works.

2 RobotEye Technology

The sensing technology used in this paper has a specific advantage in cutting-edge precision and responsiveness: it can be applied to enhance the dynamic control of LiDAR sensors for 3D mapping, navigation and automation, through to simultaneously tracking multiple dynamically moving objects even when mounted on a moving platform itself. In addition, the technology can be integrated with various types of sensors including vision, thermal and hyper-spectral, adding an extra dimension to sensing with these technologies [8].

2.1 Variables representing gazing direction

Orientation of the RobotEye pointing device or its the gazing direction can be described by two variables namely azimuth (ψ) and elevation (θ) as shown in Figure 1. The azimuth angle represents the rotation of the head about the vertical axis as depicted in the figure. Similarly, the elevation angle represents the angle made by the viewing direction with respect to the horizontal plane.

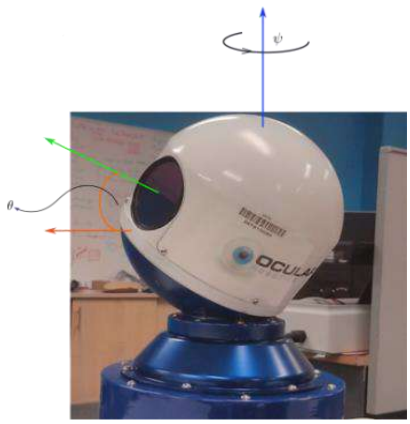

Figure 1: Variables representing robot eye head motion

2.2 Thermal target tracking

The advantage of light weight design makes the RobotEye technology a prefered choice in tracking applications. The laboratory set-up for this application consists of a high-speed vision camera, a RobotEye, a circular patches marker, and a thermal camera.

In the thermal target tracking system, the target is placed at the center of a fiducial marker which is within the field-of-view of the vision camera. The marker consists of circular patches. Details on the marker design and the detection algorithm are provided in [9]. The thermal camera is embedded inside the pointing sensor, thus, it captures the view where the RobotEye is pointing. This system has a huge implication in the fatigue analysis of mechanical structures which are under constant motion. As mentioned previously, fatigue analyses of such moving structures are adversly affected due to the blurry images captured by static cameras.

2.3 System Configuration

Coordinate systems assigned to the RobotEye optical sensor pointing device and the vision camera for tracking are shown in Figure 2. The reference frames for the vision camera and the RobotEye are represented by O_V and O_R, respectively. Similarly, the R_V^R is the rotational matrix that represents the orientation of the pointing device with respect to the vision camera reference frame. Consider an observation of the target position with respect to the vision camera be represented as p_V^t . Then, the observation can be represented with respect to the RobotEye reference frame as

$$p_R^t = R_V^R p_R^t + p_R^V, \tag{1}$$

where p_R^t is the position of target and p_V^t is the location of vision camera with respect to the pointing device.

As presented in Section 2.1, gazing direction for the RobotEye optical pointing sensor is represented by azimuth ψ and elevation θ angles which are in the spherical coordinate system. Therefore, for the representation of the thermal target as the gazing direction from the RobotEye, conversion from Cartesian to spherical coordinates should be applied as

$$\begin{aligned} \psi &= \tan^{-1}\frac{y}{x} \\ \theta &= \tan^{-1}\left(\frac{\sqrt{y^2+x^2}}{z}\right), \end{aligned} \tag{2}$$

where $p_R^t = [x\ y\ z]$.

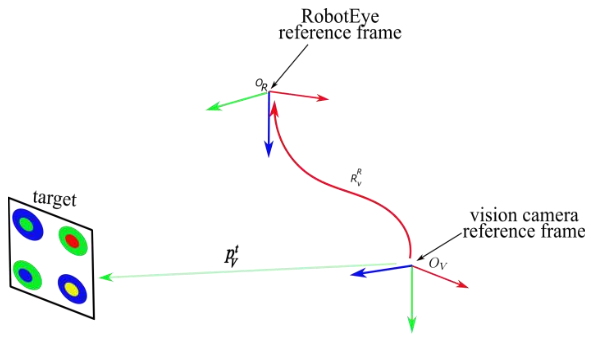

Figure 2. Arrangement of RobotEye and vision camera

2.4 Control architecture for thermal tracking

The system architecture for the proposed system comprising of a RobotEye, vision camera, and thermal camera is shown in Figure 3. In the system, the position and orientation of the target is estimated from the frames captured by vision camera which utilizes the circular marker detection algorithm [9].

After estimating the position of the thermal target with respect to the vision camera, it is calculated with respect to the pointing device in the azimuth and elevation space using equations (1) and (2). The conversion requires the extrinsic parameters such as R_V^T and p_R^V . After that, a prediction algorithm based on Kalman filter is utilised to predict its future trajectory. The filter uses a constant velocity model to represent the target motion. The model is represented as:

$$\begin{aligned} \hat{\boldsymbol{x}}[n+1] &= A_0\hat{\boldsymbol{x}}[n] \\ \hat{\boldsymbol{y}}[n] &= C_0\hat{\boldsymbol{x}}[n], \end{aligned} \tag{3}$$

where $\hat{\boldsymbol{x}} = [\psi\ \theta\ \dot{\psi}\ \dot{\theta}\ ]^{\mathrm{T}} \in \mathbb{R}^4, \hat{\boldsymbol{y}} = [\psi\ \theta\ ]^{\mathrm{T}} \in \mathbb{R}^2$,

$$A_0 = \begin{bmatrix} 1 & 0 & T & 0 \\ 0 & 1 & 0 & T \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix},$$

$$C_0 = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix},$$

and T is the sample period.

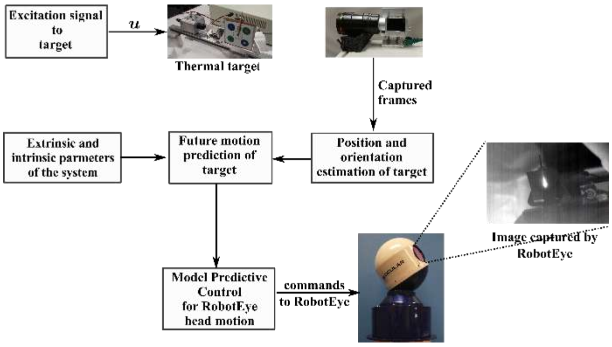

Figure 3. System architecture.

The predicted trajectory is then fed to a model predictive controller (MPC) which generates commands for the RobotEye drive controller. Here, the objective of MPC is to compensate for the lags in the system, which are introduced through various sources such as sensing and network delays, in order to improve the overall performance of the system. Modelling and Control System Design

2.5 Modelling

For the representation of the motion dynamics of the RobotEye sensor head, we have considered the state-space model in discrete-time as

$$\begin{aligned} \boldsymbol{x}[n+1] &= A\boldsymbol{x}[n] + B\boldsymbol{u}[n] \\ \boldsymbol{y}[n] &= C\boldsymbol{x}[n], \end{aligned} \tag{4}$$

where $\boldsymbol{x} \in \mathbb{R}^n$, $\boldsymbol{u} \in \mathbb{R}^m$, $\boldsymbol{y} \in \mathbb{R}^p$ are, respectively, the states, inputs and outputs of the system. In the case of the pointing actuator $\boldsymbol{y} = [\psi\ \theta]^{\mathrm{T}} \in \mathbb{R}^2$ and $\boldsymbol{u} = [\psi_{cmd}\ \theta_{cmd}]^{\mathrm{T}}$, where ψ_{cmd} and θ_{cmd} represent the command inputs to the system.

2.6 System Identification

For the identification of the system's parameter of equation (4), we measured the angles and inputs through the application programming interface (API) provided by the RobotEye. Then, we applied a standard identification algorithm such as N4SID in the framework provided by Matlab. Figure 4 shows the validation results of the identified method, which clearly indicate that the responses from the identified model is similar to that of the actual system. For instance, the similarity of responses in elevation and azimuth angles are, respectively, 95.4% and 94.39%. System matrices of the identified model are obtained as

$$A = \begin{bmatrix} -0.4141 & 288.6 & -848.2 & 54.97 \\ -75.28 & -40.89 & -495.1 & -127 \\ 757.5 & 43.73 & -546.4 & -80.56 \\ 75.16 & 48.69 & -210.6 & -13.13 \end{bmatrix},$$

$$B = \begin{bmatrix} -96.69 & -82.96 \\ -42.41 & -45.76 \\ -108.7 & -92.47 \\ -28.4 & -24.58 \end{bmatrix},$$

and

$$C = \begin{bmatrix} -9.633 & -9.392 & -8.936 & 72.69 \\ 19.64 & -11.09 & 7.066 & -98.29 \end{bmatrix}.$$

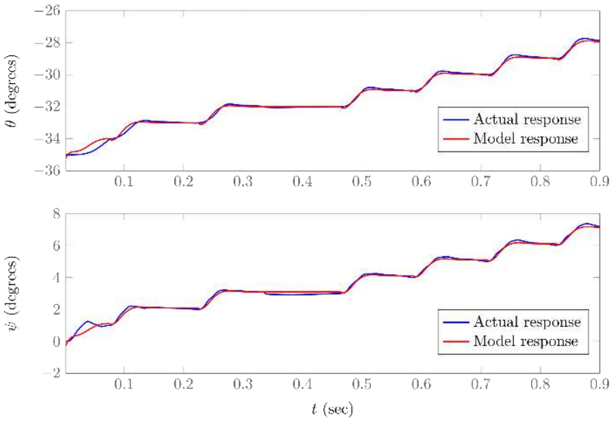

Figure 4. Validation of the identified model.

3 Model Predictive Control (MPC)

In order to apply the predictive control, we utilized the MPC in tracking the output reference signal. The problem is formulated as

$$\min \left\{ \begin{array}{c} \frac{1}{2}\sum_{i=1}^{N}\{(\boldsymbol{y}_i - \boldsymbol{r}_i)^{\mathrm{T}}\boldsymbol{Q}_y(\boldsymbol{y}_i - \boldsymbol{r}_i) + \boldsymbol{u}_i{}^{\mathrm{T}}\boldsymbol{Q}_u\boldsymbol{u}_i\} \\ +(\boldsymbol{y}_N - \boldsymbol{r}_N)^{\mathrm{T}}\boldsymbol{Q}_N(\boldsymbol{y}_N - \boldsymbol{r}_N) \end{array} \right\} \quad (5)$$

$$\text{subject to: } \begin{cases} \boldsymbol{u}_{min} \le \boldsymbol{u} \le \boldsymbol{u}_{max} \\ \boldsymbol{x}_{i+1} = A\boldsymbol{x}_i + B\boldsymbol{u}_i \\ \boldsymbol{y}_i = C\boldsymbol{x}_i, \end{cases}$$

where $\boldsymbol{y}_i = \boldsymbol{y}[n+i]$ is the i^{th} future output of the system, $\boldsymbol{u}_i = \boldsymbol{u}[n+i]$ is the i^{th} future input to the system, $\boldsymbol{r}_i$ is the i^{th} future reference, N is the prediction horizon, A is the system matrix, and B is the input matrix.

The cost function $V(\boldsymbol{U})$ can also be represented as

$$\begin{aligned} V(\boldsymbol{U}) \;=\; & (\boldsymbol{y}_0 - \boldsymbol{r}_0)^{\mathrm{T}}\boldsymbol{Q}_0(\boldsymbol{y}_0 - \boldsymbol{r}_0) \\ & +(\boldsymbol{Y} - \boldsymbol{R})^{\mathrm{T}}\bar{\boldsymbol{Q}}_y(\boldsymbol{Y} - \boldsymbol{R}) \\ & \boldsymbol{U}^{\mathrm{T}}\bar{\boldsymbol{Q}}_u\boldsymbol{U}, \end{aligned} \quad (6)$$

where

$$\boldsymbol{Y} = \begin{bmatrix} \boldsymbol{y}_1 \\ \boldsymbol{y}_2 \\ \vdots \\ \boldsymbol{y}_N \end{bmatrix}, \quad \boldsymbol{X} = \begin{bmatrix} \boldsymbol{u}_0 \\ \boldsymbol{u}_1 \\ \vdots \\ \boldsymbol{u}_{N-1} \end{bmatrix},$$

and

$$\boldsymbol{R} = \begin{bmatrix} \boldsymbol{r}_1 \\ \boldsymbol{r}_2 \\ \vdots \\ \boldsymbol{r}_N \end{bmatrix}.$$

With the system dynamics obtained and by using forward substitution, one can formulate the optimization problem as:

$$\begin{array}{l} \text{minimize } V(\boldsymbol{U}) = \boldsymbol{U}^{\mathrm{T}}\bar{H}\boldsymbol{U} + \bar{F}^{\mathrm{T}}\boldsymbol{U} \\ \text{subject to: } E\boldsymbol{U} \le \boldsymbol{\delta} \end{array}, \quad (7)$$

where

$$\bar{H} = \bar{S}^{\mathrm{T}}\bar{Q}\bar{S} + \boldsymbol{R},$$
$$\bar{F}^{\mathrm{T}} = 2\boldsymbol{x}_0\bar{T}\bar{Q}\bar{S} - \boldsymbol{R}^{\mathrm{T}}\bar{Q}\bar{S},$$

$$\bar{E} = \begin{bmatrix} I \\ -I \\ \bar{S} \\ -\bar{S} \end{bmatrix},$$

and,

$$\boldsymbol{\delta} = \begin{bmatrix} \triangle\, \boldsymbol{U}_{max} \\ -\triangle\, \boldsymbol{U}_{min} \\ \boldsymbol{Y}_{max} - \bar{T}\boldsymbol{x_0} \\ -\boldsymbol{Y}_{min} + \bar{T}\boldsymbol{x_0} \end{bmatrix}.$$

Now, this problem can be solved using the available QP solver [10].

4 Tracking results

4.1 Simulation

Figure 5 shows the results of the MPC controller for the sinusoidal reference signal. From the figure it is clear that the controller is able to track the reference signal. Similarly, from the plots of error signals, as presented in Figure 6, it is clear that the error in the Azimuth space is less than 0.03 degrees, compared to 0.01 degrees in case of the elevation angle.

The tracking performance can also be evaluated in terms of the performance index, e.g. Integral Square Error (ISE) which is defined as:

$$ISE = \sum_{i=1}^{M} e^2 [n]. \quad (7)$$

The ISE errors for Azimuth and Elevation angles are 0.34937 and 0.017448 degree^2, respectively.

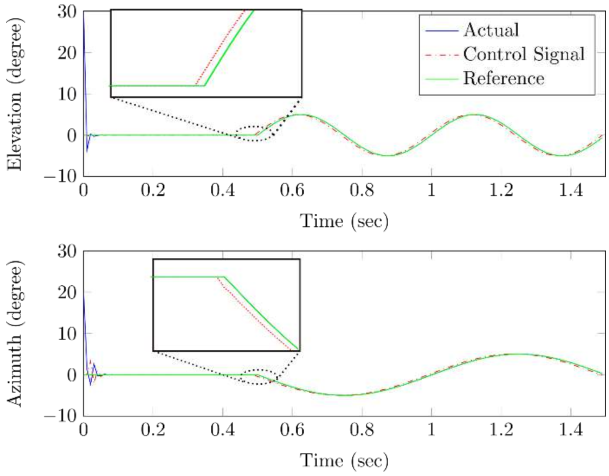

Figure 5. Plot of the angles along with command and actual values

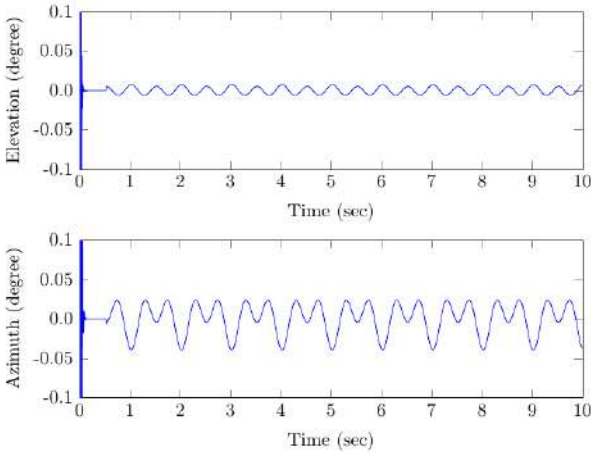

Figure 6. Plot of errors in Azimuth and Elevation angles

4.2 Real time tracking results

For the real-time testing, the MPC based predictive control algorithm was applied to a RobotEye with the specifications provided in Table 1. The block diagram for the experiment is provided in the Figure 7.

In the experiment, sinusoidal signals were provided as the reference signals. The frequencies of the reference signals were 1 Hz and 2 Hz for azimuth and elevation angles, respectively. To send the angular commands and receive the measurements we used the proprietary application programming interface.

The tracking errors during the experiment are shown in Figure 8. The error is less than 0.2 degrees for elevation and 0.1 degrees for the azimuth angle. Similarly, ISE errors for the azimuth and elevation angles are 3.947 and 33.73 degree^2, respectively.

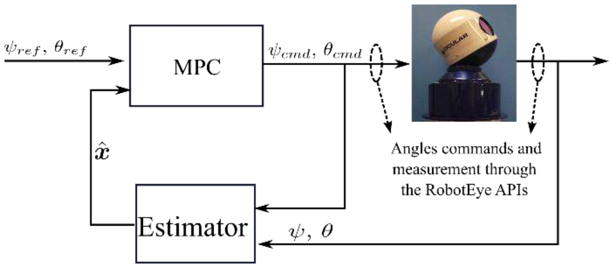

Figure 7: Real time experiment for MPC.

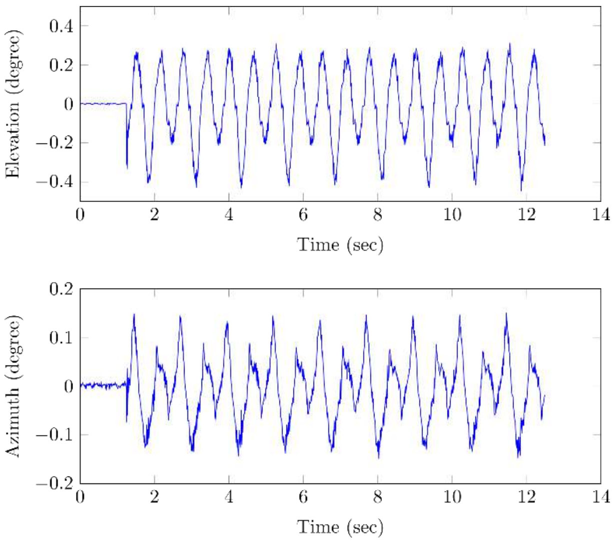

Figure 8. Tracking errors in azimuth and elevation angles in real experiment.

4.3 Performance evaluation for thermal target tracking

In this section, we evaluate performance of the proposed system described above and compare the performance with and without predictive control. The experimental setup for the evaluation of the system is presented in the Figure 9 with the specifications of all the components in Table 1.

The figure also shows the target consisting of the circular patched marker with a heat source at the centre of the marker. The heat source was used to detect the target in the thermal camera.

In this real time application, there is no direct way of evaluating the tracking performance of the system. However, as mentioned previously, the thermal camera is embedded inside the optical pointing device, to capture the view where it is directed to. Therefore, the thermal targets are detected via images taken by thermal and vision cameras, and then compared for evaluation.

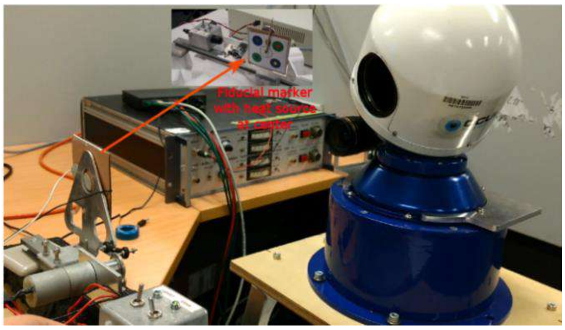

Figure 9: Experimental setup for tracking system.

The calculation of target pixels in the vision camera is obvious because the circular fiducial marker is attached with the target. However, the calculation of the target pixels in the thermal images is not straight forward. Therefore, a thresholding process is applied in every image, followed by a blob detection algorithm. The purpose of the blob detection algorithm is to detect hot spot on the image which is the location of the target.

Table 1: Parameters of the system.

	Parameter	Values
Vision camera	Focal length	16mm
	Resolution	658×492
	Frame Rate	100 fps
Thermal camera	Focal length	19mm
	Resolution	640×512
	Frame Rate	30fps
RobotEye	Model no	RELW 50
	Aperture diameter	50mm

After the calculation of target points in both vision and thermal camera, one can evaluate the target tracking performance of the RobotEye by comparing standard deviations of the target pixels in x and y-axis. Nevertheless, this approach does not give the clear indication of the performance. For example, if the variance of the target pixels in the vision camera is along y-axis but the variance of the pixels in the thermal camera is along x-axis then by comparing the above mentioned parameters does not represent the performance. In such situation, to better evaluate the tracking performance, the principal component analysis (PCA) of the target points can be applied. An example of the PCA of the target points is presented in Figure 10, wherein it is clear that the major axis and the minor axis of the PCA represents the direction of maximum and minimum variations of the target points. By using the principal component analysis, the following parameters:

- Maximum eigenvalues of the PCA of target pixels
- Minimum eigenvalues of the PCA of target pixels

are calculated for evaluation. It should be noted that in this system small variations of the target points in thermal cameras signifies better performance.

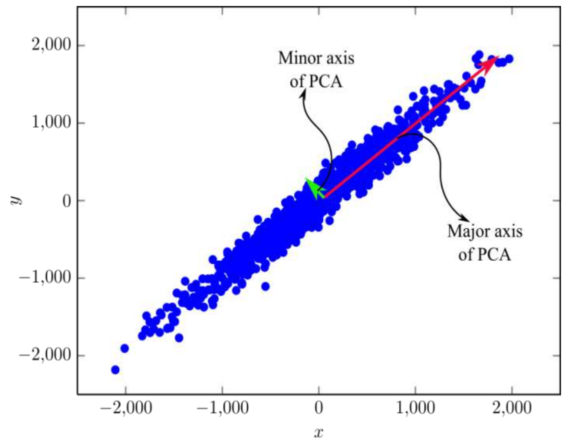

Figure 10. An example of the PCA of target points showing major and minor axis.

From the calculation of the above mentioned parameters, ratios of the parameters are obtained. Table 2 shows the summaries of the performance evaluations. From the table, it can be observed that there are improvements in all parameters. For instance, in terms of ratio of maximum eigenvalues there is the improvement by 74 percent. Similarly, in the case of the ratio of standard deviation in x-axis the improvement is about 42 percent.

Table 2: Summaries of the performance of the thermal tracking system with and without MPC.

	Without MPC	With MPC	% improvement
Ratio of maximum eigenvalues of PCA (thermal/vision)	0.0001	0.00002	74
Ratio of minimum eigenvalues of PCA (thermal/vision)	1.2213	0.8455	30
Ratio of standard deviation in X-axis (thermal/vision)	0.0101	0.005	42
Ratio of standard deviation (thermal/vision)	1.00659	0.8153	19

5 Conclusion

In this paper, we have presented a thermal target tracking system using RobotEye technology. The hardware comprises of the RobotEye optical pointing device, a thermal camera and a vision camera. Furthermore, the proposed system consists of an estimator for the target orientation and position with a Kalman filter using the application program interface for modeling and a Model Predictive Controller for command generation. In addition, a fiducial marker consisting of circular patches is attached to the target. The objective of the fiducial marker is to estimate the position of marker from the images taken from the vision camera. After the estimation of the target position, its future position is predicted using a Kalman filter, and a predictive control is then applied to generate command for the RobotEye. Experiments have been conducted and the tracking performance was evaluated for the system. The improvements of up to 74 percent is observed with the predictive control compared to the non MPC control case.

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Using wearable devices to explore the relationship among the work productivity, psychological state, and physical status of construction workers

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Abstract –

Due to the increasing growth of labor cost, academics and practitioners in this field have focused on finding ways to improve work productivity. Many previous studies have indicated that mental status has a deep influence on productivity. However, the relationship among work productivity, psychological state, and physical status has not been explored in the field of architecture, engineering, and construction (ACE).

As an initial exploration, this paper proposes a system to analyze how the psychological and physical status of construction workers influence their productivity. In this exploration, smart bands are adopted to measure the physical status of the bricklayers, STAI is used to collect the psychological data, and the time taken by construction workers to complete a unit of work (i.e., wall building) is recorded to reflect work productivity. Analysis on the correlations of the three dimensions (work productivity, psychological state, and physical status) was conducted. The initial experiment was conducted in Chongqing, China, from May 1st to May 3rd, 2018. The results show that bricklayers are in a relatively low level of anxiety, and that anxiety and heart rate levels are positively correlated with work productivity.

The wearable device-based system facilitates the real-time monitoring of construction workers' psychological and physical status. In turn, such information can help in planning their working schedules to enable them to work more efficiently.

Keywords –

Status monitor; Work productivity; Wearable devices

1 Introduction

Previous studies have suggested that mental health and psychological state are closely related to work productivity [1, 2]. Issah reported the association between mental health and emotional function with work productivity impairment, proving that the state of being nervous and depressed can result in lower work productivity [3]. Bubonya suggested that poor mental health can cause “emotional issues,” which may diminish the work productivity [4]. Bonnie studied the association between work productivity and depression, fatigue, and anxiety, and found that presenteeism is associated with increasing fatigue, depression, and anxiety [5]. Therefore, studying the relationship between mental state and work efficiency is necessary.

In the field of office work and manufacturing, researchers who tested the psychological state of workers recommended some solutions to achieve the goal of improving work productivity. Through an empirical study done in Australia, Bubonya proposed initiatives to reduce job stress and these offer the most potential to improve productivity [6]. Hillebrandt reported that psychological stress has a great impact on productivity. Setting some interventions can help increase job satisfaction, reduce adrenalin levels, and increase performance efficiency of workers in business [7]. Liff conducted a research in Northwest England and concluded that the productivity of women workers in the food factory industry can be affected by their mental status, which in turn, can reduce the overall work pressure and uplift work productivity [8]. All the studies above illustrate that, whether in the office or in the manufacturing industry, focusing on physical or mental states can avoid productivity inefficiency and lead to productivity improvement.

Due to the rapid growth of labor cost, increasing worker efficiency and reducing labor costs have become serious challenges in the architecture, engineering, and construction (AEC) field. Haas et al. presented for a prototype of a simple, low-cost, sensing solution for automatically monitoring undesirable movements and patterns of motion to help reduce Construction Work-related Musculoskeletal Disorders and help the workers work in a more efficient and safe way [9]. Gatti et al. propose that assessing physical strain in construction workforce is the first step for improving Safety and productivity management [10]. Lill use a simulation modelling to optimize the labour management strategies, and decrease the mismatch between required and available skilled labour and to discuss the consequences of ignoring the interests of craftsmen [11].

Unfortunately, few studies focus on how psychological and physical status influence work productivity. To fulfill this research gap, the current paper purpose a wearable device-based system to explore the relationship among work productivity, psychological state, and physical status.

The main problems and corresponding solutions in this paper are as stated below.

- For the measurement of psychological state, STAI questionnaire was used to reflect workers' mental status.
- For the measurement of physical status, the smart band was adopted to record workers' physical status.
- For the measurement of work productivity, the time spent by workers to complete a unit of work was measured.
- For the analyses of the three dimensions, regressive analysis was used to find the correlation

2 Research Method

This research proposes the use of a novel type of measurement (smart band) to monitor the physical data reflecting the mental status of the workers. Doing so can help us determine the relationship between mental status and work productivity. An initial experiment was done based on the logical framework of the experiment shown in Figure 1.

2.1 Psychological data collection

In this research, we collected psychological data, specifically data on state anxiety and trait anxiety. Trait anxiety is a relatively stable behavioral tendency of each individual, whereas state anxiety mainly indicates perceived risk or stimulation, producing brief emotional states, including individual tension, worry, anxiety, obsession, and euphoria of the autonomic nervous system.

Such data can be collected via a traditional but classic approach: by using the State-Trait Anxiety Inventory (STAI). First introduced in 1970 [12], this test has been proven to be effective in testing anxiety by many past studies, especially those in the medical field [13, 14]. This questionnaire is divided into two parts: one that tests trait anxiety and another that tests state anxiety. The test of trait anxiety mainly asks about how one person feels at the moment, whereas the test of state anxiety asks about how one feels in general. Each part has 20 items, and takes about 10 minutes to complete. These tests are answered on the basis of a scale with scores of 1 to 4 (1 - "not at all," 2 - "somewhat," 3 - "moderately so," and 4 - "very much so." It can reflex the emotion including tension, apprehension, and nervousness.

Table 1. Questionnaire of testing trait anxiety

Items	Options
I lack self-confidence	1 2 3 4
I am a steady person	1 2 3 4
……	

Table 2. Questionnaire of testing state anxiety

Items	Options
I lack self-confidence	1 2 3 4
I am a steady person	1 2 3 4
……	

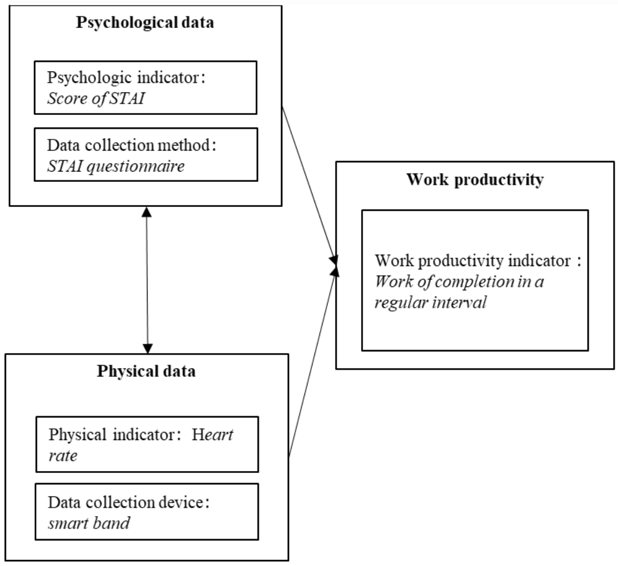

Figure 1. The logic framework of this study

2.2 Physical data collection

To collect the physical data, which can provide a real-time status of the jobsite workers, the physical indicators were selected. In the previous study, heart rate, ECG, electrodermal response, skin temperature, calorie, number of steps taken, and respiratory rhythm were used (Table 3). In this exploratory study, to make the study

Table 3. Questionnaire of testing state anxiety

Reference	[15]	[16]	[17]	[18]	[19]	[20]	[21]	[22]	[23]
Heart rate	✓		✓	✓		✓	✓	✓	✓
EEG	✓	✓							
Skin temperature	✓	✓			✓		✓		
Electrodermal reaction		✓		✓			✓		
Calorie				✓					
Movement steps				✓				✓	
Breathing rhythm			✓						

feasible and credible, we used heart rate, which is the most frequently used indicator.

The smart band was used to measure the two indicators. It has the following three main advantages compared with traditional physical status measurements.

First, the smart band is wireless and easy to wear. Wearable devices usually appear in the form of a bracelet, vest, glasses, and helmet. It can be worn like regular clothing or an accessory to allow movement without restrictions. In contrast, traditional monitoring instruments generally require the subjects to stay in a fixed location. Also, the smart band can provide real-time. monitoring. With such sensors as the heart-rate monitor, barometer, and angular velocity trans embedded, it offers the opportunities to detect human activities in real time.

Another thing which cannot be ignored, that the smart band is a practical and non-expensive option. In fact, some construction workers recognize the benefits of using a smart band [24], such as wearing it while working.

2.3 Work productivity measurement

Investigating work efficiency or productivity is the main study objective of this research. As ours is an exploratory study, we can easily calculate work efficiency or productivity by recording the time spent by each worked in completing a unit of work (i.e., wall building). In future works, however, this indicator should also consider accuracy and the quality of the final product.

3 Experiment and data collection

3.1 Selection of the experiment site and subjects

This experiment was conducted at the Dazhulin project located in Chongqing, China, as shown in Figure 2. This project, undertaken by Chongqing Wantai Construction Co., Ltd., is a frame-shear wall structure with a construction height of 123 m.

Figure 2. The experiment site

The subjects consisted of three bricklayers working on the 22nd floor. Their task was to build the walls, and this required them to pick up bricks, apply the mortar, climb numerous stairs, and so on. This type of work is very common in the field of construction. In past studies, researchers have proven that workers performing this kind of work are suitable subjects for the monitoring of real-time data on their physical and psychological state. For example, Chen designed an experiment, which included climbing a ladder, selecting a screw and installing the screw to test the physical and psychological state of the workers [25]. This kind of work is similar to what the bricklayers in the current study do in terms of complexity.

3.2 Experiment process

The experiment was carried out in the following procedures:

First, the subjects were numbered and asked to fill out the T-test in the STAI questionnaire.

Then, to collect their physical data, the subjects were required to wear the smart band daily. They should put it on in the morning when they start to work and take it off after work. The heart rate was measured every 1 minute.

During a regular interval (once every 2.5 hours), they were asked have a rest and fill in the S-test in the STAI questionnaire. The quantity of wall structure they completed was then identified.

Their behaviours, including talking with co-workers, and changes in the external environment, such as the project manager's inspection, were also recorded.

(a) (b)

Figure 3. The testees is filling out the STAI questionnaire (a) and working while wearing the smart band (b)

3.3 Experimental data collection

Since it is an exploratory study, the experiment had just been conducted for 3 days in March, 2018. The physical data was collected by using Millet bracelet. As a result, 1 time/minute*60*10 minute/day/people*3 people*3 days = 5400 data sample of their heart rate were collected (table 4).

As for the psychological status (including S-test and T-test) and work productivity data，4 times / day / people ∗ 3 days ∗ 3 people = 36 data samples were collected.

Table 4. A part of the original data (worker B; day 1; 6:30-9:00）

Heart rate data: Mean=77.9; SD=14.99									
104	77	95	60	67	80	80	98	87	72
69	101	108	61	106	52	103	95	75	63
75	85	82	106	94	80	43	95	60	76
103	87	78	68	87	62	82	80	96	100
69	78	103	84	53	84	72	87	83	74
70	93	82	83	105	87	70	85	79	103
102	71	96	69	103	70	98	60	86	69
77	87	56	80	83	90	76	58	124	105
73	97	99	70	86	92	65	100	108	77
81	83	84	69	89	64	72	67	74	104
69	75	70	94	91	68	106	68	64	77
108	62	73	90	74	92	77	94	108	89
99	91	77	51	89	60	84	78	95	98
80	83	98	102	68	88	82	74	69	67
90	73	68	80	83	76	71	74	86	80
S-test score =22; work productivity=2.08m^3									

4 Data analysis and results

The experiment collected 5400 physical data and 36 sets of psychological and work productivity data. From these, several findings can be concluded.

All the subjects scored below 30 in T-test, indicating relatively low levels of anxiety and stress. The three subjects scored 22, 25, and 28, respectively. Compared with other occupations, for example, undergraduate student, the level of anxiety is significantly lower. Through the observation during the experiment, this result may have been due to the following reasons:

The most likely reason is.that the level of security at the construction site improves and the perceived risk is reduced, so construction worker feel more safe and the anxiety(stress) level decrease correspondingly.

The rise in wages may be the second reason for this phenomenon. The high wage make construction workers more satisfied with their lives.

The third reason this that the repeatability of the job makes them extremely confident in their ability to finish the work, thus reducing anxiety and annoyance

We can also observe that the score in the S-test (state anxiety index) is positively related with work productivity (Figure 4).

The findings indicate that workers work more efficiently when they feel relatively high levels of stress and anxiety. This is because the initial anxiety level of the bricklayers is very low given that the perceived stress is not enough. When the workers were supervised or criticized by the foreman, they felt more stressed and uncomfortable, which then increased their S-test scores

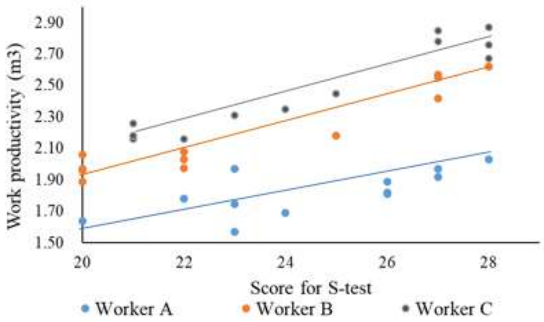

Figure 4. The correlation of work productivity and state anxiety index

and prompted them to work more efficiently. Another common situation is that workers talked to their workmates frequently, and such communication made them feel relaxed. As a result, their state anxiety index decreased, and their work productivity decreases correspondingly.

It can also be conclude that heart rate is positively correlated with state anxiety index and work efficiency

When bricklayers work efficiently, the peak values of their heart rates tend to be higher, and the standard deviation (SD) is also larger. A rapid heartbeat indicates the performance of efficient work (Figure 5).

The increase of heart rate during high work productivity can be explained from two perspectives. On the one hand, the amount of exercise increased, and on the other hand, relatively high degrees of mental stress and anxiety pushed them do better work.

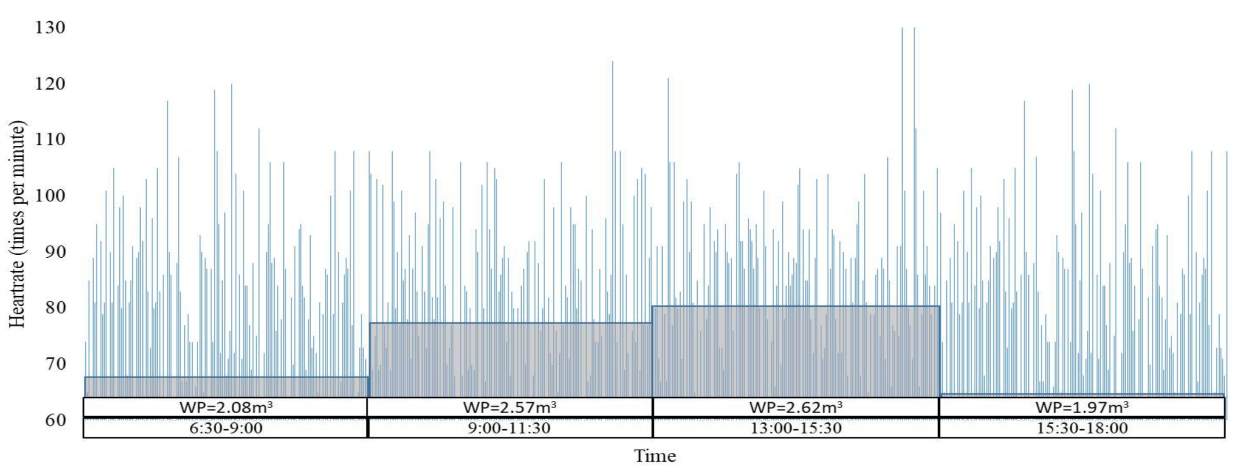

Figure 5. The relationship between work productivity and workers' real-time heart rate

5 Conclusion

This paper established a wearable-device based system that helped stakeholders understand the psychological and physical state of the construction workers in real time. Based on the experimental data, the following results can be concluded.

1. Bricklayers show a relatively low level of anxiety and stress.
2. State anxiety index is positively related with work productivity.
3. Heart rate was positively correlated with state anxiety index and work efficiency.

Though the real-time data, and the relationship among work productivity, psychological state, and physical status, the work productivity of construction workers can be predicted.

The significance of this research is that it provides an available approach to monitor construction workers' physical status and psychological state to predict their work productivity. A reasonable arrangement construction workers' working schedules can help improve their work efficiency.

Acknowledgement

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ANKLE DESIGN WITH ELECTROMIOGRAFIC ACQUISITION SYSTEM FOR TRANSTIBIAL PROSTHESIS

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***Abstract*— This work aims to show the importance of the different components that are immersed in lower limb prostheses, either at the Transtibial or Trasnfemoral level. this type of mechanisms substitutes a normal function of the human being as it is the function of the march. With the implementation of this research we intend to help design and build elements that allow us through good practices to generate different levels of well-being for patients with this condition. By having our own and local technologies we can manufacture components at low costs and with a high level of durability; the designs and prototypes are presented in the Center of Design and Metrology - SENA Capital District that has the Orthopedic technology school. Whose specific purpose is to train Technologists in Development and Adaptation of Prostheses and Orthoses.**

Keywords— Knee, prosthesis, transtibial, trasnfemoral, electromyography.

I. Introduction

Mobility in the human being is one of its most relevant factors within quality of life; absence or deficiency in mobility generates the marching functions to be compromised [1], in a mild or severe manner, depending on the injury for each patient. To our end, we will focus on analyzing and studying the different parameters affecting march in patients with amputated lower limbs, whether transtibial or trasnfemoral. These are the two cases of lower limb amputation with the greatest quantity of cases worldwide [2].

Through this research, we have achieved several proper and local advances from the Centro de Diseño y Metrología del SENA - (Colombia) Center for Design and Metrology SENA, in order to aid the improvement of some march conditions of a patient with this condition. Several devices have been designed, starting with the making of a dynamic foot in carbon fiber [3]. On the other hand, we have developed an electro-mechanic ankle component with a control system based on electromyographic signals from the residual limb of the patient [4]. Moving forward in the path of our research and increasing the degree of complexity as well as the level of amputation of the patient, we have proposed the design and manufacture of a mechanic polycentric knee, which, attached to the mechanical foot currently under testing, will enable us to work with patients whose amputation level is transfemoral at any level, whether proximal or medial. The knee design is given in design criteria compliant with the need of each patient and their personal mobility and physical configuration [5]. At the mechanical and functional aspects, we intend focusing our investigation on a polycentric knee which enables activity to a passive patient of 30-45 year old, 75 to 90 kg of weight, and 1,70 to 1,90m of height, with a moderately varied level of physical activity.

On the other hand, the prosthetic component under development intends to diminish the manufacturing cost of these elements, since it will incorporate low-weight, low-cost raw materials to make a component with great quality, low cost and light weight [6]. All of the previous us addressed to performing mandatory structural tests in accordance with ISO 10328, and thus obtaining a component with the highest quality standards.

II. General analysis of prosthetics

It is the multidisciplinary work of engineers, ortesists, prosthetist and some users along with a process of brainstorm, design thinking and possible empiric-analytical statements, that resulted in the design and construction of prototypes of some prosthetic components which were then assembled to solve the specific case of a user with transtibial lower limb amputation.

Digital modeling through the use of simulators enables a systemic methodology of correlation between the components and post-construction reality. This process leads to a functional model between structure and dynamics for effort analysis, movement axis, torque and other motor and mechanical factors required by the device.

Consequently, and based on available technologies at the creative lab of the formation center, participants carried out the first construction phase, through the use of 3D printing technology of polylactic acid polymers. This material allows design adjustment bearing in mind physical aspects to be corrected, such as the restriction of transmission rounds and displacement mechanical bumps. The product was then assessed by health professionals from the formation center, who provided technical certification to take the design to the next stage, which corresponds to functional prototyping in workshops dedicated to carbon fiber mechanizing and laminating.

On the other hand, some aspects were growing in importance along the development of the project, leading to subjects such as compact design, component miniaturization, efficiency, ergonomic and aesthetic factors which enable the improvement of visual perception. These challenges are deemed by users as highly important during the moment of adaptation of this type of components [7]. Because of this, it was necessary to include laminating and thermoforming technologies for high-hardness plastics, which enable cosmesis and improvement of all aspects considered in patient feedback to officially declare the product as completed.
Ethically speaking, it is required that, after validation, and for implementation there are good use practices, through a user manual containing a general vision of the component. For this reason, the user manual was constructed, as suggested by the International Classification of Functioning, Disability and Health (CIF).

Full articulation assembling

General assembly of prosthetics through the manufacture of each of the pieces occurred modularly, followed by the final assembly, which, according to the tolerance degree included in manufacture blueprints, occurred easily in all components.

Each of the pieces was manufactured bearing in mind three parameters; first, follow-up on specified planimetrics (fig. 1 a), where the level of tolerance, material and disposition of each piece provided a clear goal in the construction of the model.
Another of the parameters was modeling of each of the pieces using the software MasterCam V7, which used previous geometry from SolidWorks to provide the same model in coordinate points (fig. 1 b), so the four-axis lathe performs the mechanization process on the material selected.
Lastly, validation of each of the pieces was carried out individually and as a whole. This process occurred under the principle of modeling by Finite Element Method (FEM) with both, a specific static analysis of each piece individually, as well as a dynamic analysis of the whole set [8] (fig. 2 a and b). For this type of element, and given that it will be present on a human body, it is necessary to follow a thorough protocol in both piece analysis and structuration, as well as the consequent articulation controller [9].

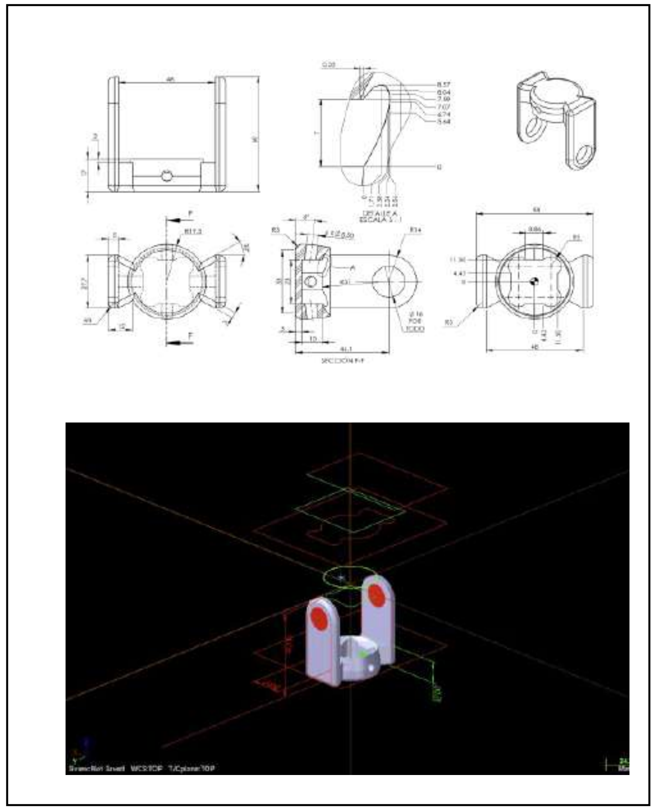

Fig. 1 a) Follow-up on proposed planimetrics. b) Design and parametrization in MasterCam V7.

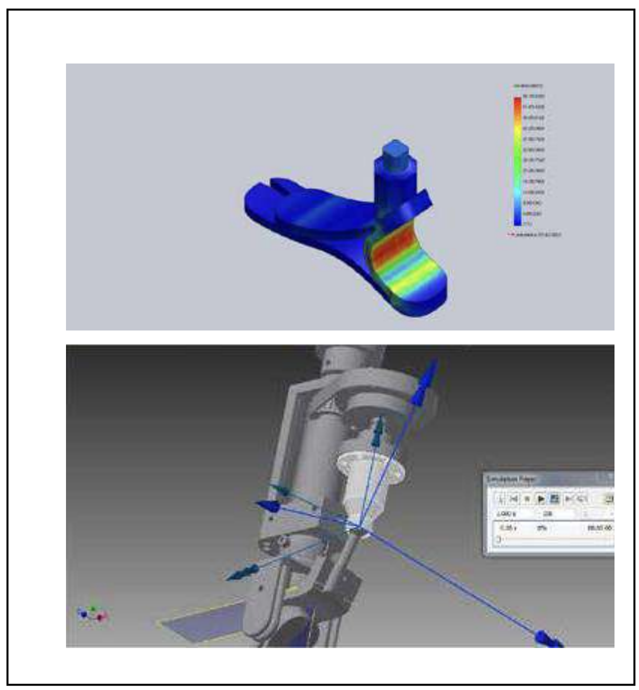

Fig. 2 a) Static analysis in SolidWorks. b) Dynamic analysis in SolidWorks.

For the specific case of foot manufacturing by carbon fiber modeling, the first step consisted on performing the molds for casting of fiber mixed with acrylic resin. In future papers we will clearly discuss how variation on the percentage of carbon fiber and resin changes the structural and resistance conditions of the final pieces. At the moment, a research group is building test specimens of the material used, in order to submit them to structural analysis by deformation and shavings, according to a lower-limb prosthetic.

Fig. 3 Design and manufacture of molds for carbon fiber casting.

The general assembly of the articulation was developed successfully with minor adjustments to distances in the perforations for screws. General and final assembly in dialuminium and carbon fiber was as follows:

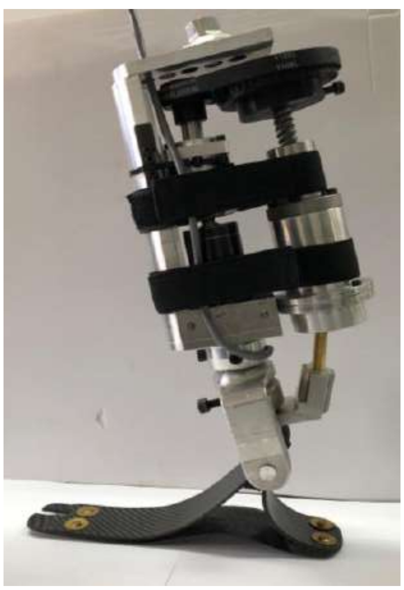

Fig. 4 Sagittal view of the prototype.

Fig. 5 Frontal view of the prototype.

This model clearly adjusts to the design parameters stated, and complies with the functional and mobility characteristics proposed for the patient object of study.

Future papers will focus on several fronts:

- Dynamic analysis of the articulation in the walk lab.
- Mechanic and structural analysis of materials used.
- Construction and adaptation of polycentric knee for each of the components designed.
- Transmission and gear mechanism.

III. Analysis and results by electromyography acquisition signal

Nature is filled with signals which are mostly classified and described through mathematical equations, which in turn pose a measurement variable. The human body is not without these qualities; there is a number of internal actions which enable movement. However, when follow-up on these parameters is required, other factors come into play to achieve the conversion to digital variables. The implementation of measurement and posterior control systems on an prothesis generates the need to transform body variables into analog; in other words, from variables in time to digital variables with only two logical states.

In the generation of the Project, it is born in mind that articulatory movements are not described on one individual axis, but rather, depending on the articulation under analysis, can have up to 6 degrees of liberty. This means that they require the implementation of a data acquisition system which separates variables in such a way that multiple systems can be developed for each degree of liberty; however, for this prototype we initially took as a reference 1 degree of liberty, more specifically, angular movement on axis Y, between +15 and -15 gradians.

Acquisition on the body is presented in two different ways, reading the movement of the muscle located in the higher section of the ankle, so that after training, the patient becomes able to move the limb only with muscular movements. The second manner consists on reading degrees of inclination of one part of the body directly linked to ankle movement during walk [10]. In this case, reading corresponds to the installation of a translator, which converts physical variables of the body (angular movement) into electric variables. Thus, it is possible for an electronic device to acquire movement data.

It is possible to measure the data from electric variables thanks to the wide spectrum of embedded devices, which enable us to manipulate data and make decisions regarding mechanical actuators [11]. Acquisition took place using Arduino Galileo, an embedded, printed, programmable card, with a high data processing velocity which uses a reading variable to generate a means for decision making on movement of the actuator.

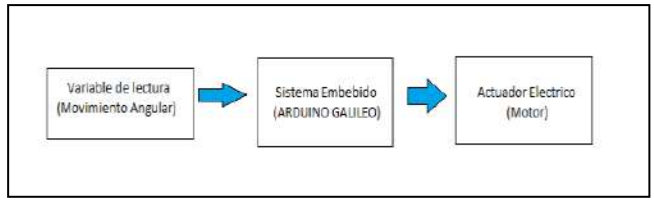

Figura 6. System of conversion of the signal taken by the body and sent to an electric actuator.

Digital posts and digital analogic converters enable the input of several external variables within a programmable logic. However, one of the great shortcomings in these devices is the watt power of the outlets, which is the reason that communication between the programmable device and the electric actuator occurs through an engine driver, which enables sending control signals to high-consumption engines through low-power signals generated by the imbedded system. Thus, it is possible to generate movement on an electric actuator from the acquisition of data from the body.

Regarding the implementation of the electric actuator, it was selected according to sole requirements. Although it is true that electrical induction engines do not have enough torque to generate the movement [8] of the ankle when lifting an average of 150 Kg, the adjustment was achieved using a 12-volt brushless engine and a reducing box with a ratio of 11 to 1, assuming that electric power consumption between the actuator and the driver are appropriate so the sole does not suffer. Thus, the functioning of the actuator is guaranteed without generating high consumption or damage to the acquisition card.

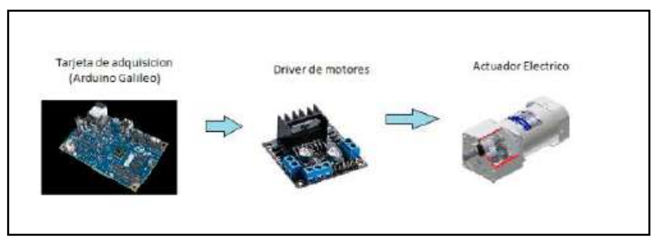

Figura 7. System of conversion of signal taken by the body and sent to an electric actuator.

The assembly of the various devices gives as a result the implementation of a system which allows control on the angular movement of the electric actuator [12], as shown in the figure.

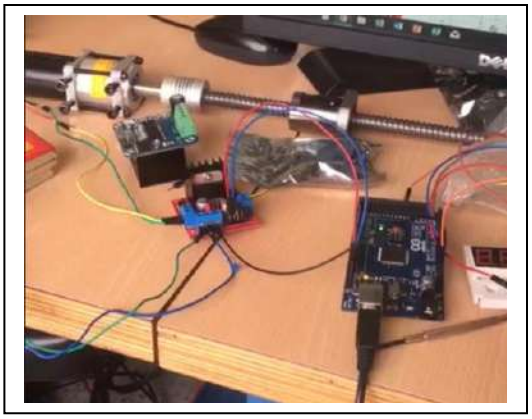

Figura 8. Real engine driver system and embedded system for actuator control.

In an electrically controlled system, when physical design parameters are modified, controller parameters are directly and proportionally affected as well. Therefore, it was necessary to establish the whole system with the electric actuator for final control analysis.

Figure 9. Functional model of the sole with the electric actuator attached.

Data acquisition, as well as the design of a functional sole which simulates assisted ankle movement, enables the generation of a system complying with the three fundamental stages: data acquisition, data processing and actuator movement, and lead to the following result:

Figura 10. Implemented Control System.

The current prototype has already been depurated and is now in feedback phase by the subjects of the study. This means that the initial goal was achieved in that we generated local components which somehow aid in the normal walk function.

IV. Conclusions

- The transmission mechanism must be rather well adjusted and synchronized, as it depends on two precision pulleys, which, if transmitted the improper force and required torque, could produce energy loss in transmission, which is translated into energetic costs and fatigue of the pieces composing the prototype.
- Piece mechanization requires a high degree of skills, since the various components present complex geometries, which make mechanization tiresome, leading to multiple setup of each piece.
- The control system of the mechanism or controller requires a high filtering stage, since stray signals present in the sensors prevent the mechanism to react as expected, transferring the uncertainty level to the patient.
- The controller, by being the brain of the component, cannot, under any circumstance, be present in slow cards or control strategies, since performance and success on the simulation of the various stage of walk depend on it.
- Due to patent registration at the Superintendencia de Industria y Comercio of the Republic of Colombia, it was necessary to avoid detail in this article; it was also necessary to place visual protecting bands around the prototype to avoid explicit divulgation which impedes proper registration of components.
- Due to mechanization and production time, it was necessary to implement the controller system in printed material initially, but not on the mechanized material. However, for tests with patients, the implementation is necessary on rigid 7075 dialuminium and carbon fiber, which resists the weight and activity level of the subjects of this study.

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Earthmoving Construction Automation with Military Applications: Past, Present and Future

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Abstract – Amongst increasing innovations in frontier engineering sciences, the advancements in Robotic and Autonomous Systems (RAS) has brought about a new horizon in construction applications. There is evidence of the increasing interest in RAS technologies in the civil construction sector being reflected in construction efforts of many military forces. In particular, Army or ground-based forces are frequently called upon to conduct construction tasks as part of military operations, tasks which could be partially or fully aided by the employment of RAS technologies. Along with recent advances in the Internet of Things (IoT) and cyber-physical system infrastructure, it is essential to examine the current maturity, technical feasibility, and affordability, as well as the challenges and future directions of the adoption and application of RAS to military construction. This paper presents a comprehensive survey and provides a contemporary and industry-independent overview on the state-of-the-art of earthmoving construction automation used in defence, spanning current world's best practice through to that which is predicted over the coming years.

Keywords – Construction automation; Earthmoving; Defence; Robotic and Autonomous Systems.

1 Introduction

Construction automation represents the field of research and development focused on improving construction processes by applying the principles of industrial automation [1-3]. Among general construction processes, there have been resurgent interests in the automation of earthmoving equipment such as wheel loaders and bulldozers. New thinking is occurring within a framework of modelling of control, planning and artificial intelligence with the use of sensing and information technologies [4,5] in combination with the frameworks for understanding robotic and autonomous systems (RAS) as applied to construction automation [6]. To this end, a great deal of research and development has been devoted to raising the level of autonomy of construction plant, in both civilian and military domains, to improve their efficiency, productivity, quality and reliability [7].

Robotic and autonomous systems tailored for the military call upon the ability to integrate sensors, vision imaging, actuators, end-effector manipulation, computer control and human interface for operations in unstructured, difficult and hazardous conditions. Army construction tasks for enhancing force protection include such earthmoving tasks as filling of protective barriers (HESCO baskets), building dirt bunding structures, as well as anti-tank ditches and trenching. For such tasks a variety of heavy construction machinery such as excavators, bulldozers, wheel loaders, graders and articulated dump trucks etc. have been customised to meet the special requirements of the military.

With the demand on combat engineering capability to provide greater force protection with more rapid rates of construction, there is an increasing requirement for the transformation of combat engineering construction plant into more autonomous systems. Studies in this field therefore have recently received much research interest. In [8,9], surveys of RAS used in military applications have been conducted with discussion on Unmanned Ground Vehicles (UGV) and air/sea-based robotic vehicles. However, the focus therein was mainly on combat and logistic operations rather than construction. Given the rapid developments in military construction automation with the use of high-mobility ground-based platforms, human-machine and machine-machine interfaces, teleoperation and control systems, data transmission systems, perception and manipulation capabilities [10], the survey presented in this paper aims to provide an overview and analysis on the state-of-the-art of earthmoving construction automation used for Army applications. This survey will cover construction tasks and corresponding platforms in alignment with defence applications. Platforms of interest include excavators, bulldozers and wheel loaders in tele-operated, shared-control, semi-autonomous, or autonomous modes of operation.

Most earthmoving tasks with their array of platforms and equipment are cooperatively coordinated within construction operations. On one hand, recent developments in networked robotics and the integration of IoT within intelligent digital infrastructure [11,12], could afford task coordination efficiency benefits to such construction operations. On the other hand, with digitally connected systems there also arises the inherent cyber risk compared to the traditional ones.

2 RAS in Ground-Based Construction – A Review

The application of RAS to typical platforms such as excavators, bulldozers and wheel loaders is evaluated through studies in teleoperation and autonomous operations [13] on the basis of the technology readiness level (TRL) framework [14] of 9 levels, from basic research (TRL 1) to operational deployment (TRL 9).

2.1 Excavator

2.1.1 Remote Control and Teleoperation

In remote control and teleoperation, a key challenge is to develop a reliable human-machine interaction model and real-time data feedback. One of the earliest studies in this direction was conducted in the early 1990’s by Burks *et al*. [15] in a study funded by the U.S. Army with the aim to find principles for the teleoperation of excavators to retrieve unexploded ordnance and radioactive waste (TRL1-2). At the subsystem development level (TRL 3-6), various studies have been conducted to develop models and prototypes for tele-operated excavators. In 1995, Ohmori and Mano introduced the concept of master-subordinate-slave tele-earthwork system, which replaced a human operator using a teleoperation system known as RoboQ [16]. Yokoi *et al*. (2003) developed a master-slave system which used a humanoid robot to operate and control a backhoe [17]. Teleoperation involving tele-grasping sensory perception, which is based on a master-slave teleoperation concept of a grapple-attached mini excavator, has been carried out by a group of researchers in Gifu University, Japan [18]. The proposed control system significantly improved the slow grasping of a soft object by improving the sense of grasping through the application of force feedback [19]. Such control requires the use of pressure and displacement sensors to be attached to the mini excavator. The research was verified by simulation and experiments confirmed the validity of the control system. Later, Yusof *et al*. (2012) conducted studies on operator sensitivity to various modalities, where the perception of the operator for each type of feedback was evaluated by using common 2D, 3D and virtual visual feedback [20]. Precision grasping was also tested by utilising auditory feedback, along with force feedback [21]. Kim *et al*. (2008) proposed an interesting study of controlling an excavator using the movement of the human arm [22] while Sasaki and Kawashima (2008) developed a remote controlled pneumatic robotic system, which can replace a human operator [23]. The benefit of the remote controlled operations conducted at local construction sites has been quantified by the increase in work efficiency of more than 50% compared to the direct operation of the excavator. The same concept was studied by using a teleoperated electro-hydraulic actuator, equipped with a 2.4 GHz remotely controlled system [24].

At the level of Integrated Pilot System Demonstrated (TRL 7-8), teleoperation of excavators has been tested in Japan for events involving post volcanic and earthquake disaster recovery [25], which was a milestone for application of RAS to a large-scale unmanned construction operation of post disaster recovery works.

2.1.2 Autonomous Excavation

Studies in autonomous excavation started in 1986 at CMU in which a prototype named Robotic Excavator (REX) was developed [26]. REX combined integrated sensing, modelling, planning, simulation, and action specifically to unearth buried utility piping at TRL 1-2. Human interfaces to REX included a joystick, keyboard and animated display, while a rugged hydraulic arm was appended to a four-link backhoe for actuation. Since then, a large number of studies have been conducted addressing various aspects of autonomous excavation. Excavator kinematics and dynamics can be analysed and derived by assigning coordinate systems to the manipulator configuration of boom, arm and bucket, and applying the Newton-Euler formula to the local coordinate frame for each link in succession as a free body [27]. In [28], full kinematic and dynamic models of the excavator arm represented as a planar manipulator with three degrees of freedom (boom, arm and bucket) are derived using the Lagrangian formulation. A virtual model for excavators was developed for an earthworks site, whose terrain geometry is continuously updated as excavation and earth-moving continue until completion, is used to study the interaction between the excavator and its surrounding environment [29]. In a recent work [30], the operation function is modelled through analysis of deterministic processes and trajectories of the relieving tool.

At the TRL 3-6 level, a number of studies focused on general control techniques for autonomous excavators. In [31], Bradley *et al*. (1989) discussed the developments necessary to operate a simple backhoe arm. Experimental studies were presented in [32] on mechanics of planetary excavation. In [33], the control of an intelligent excavator for autonomous digging in difficult ground was conducted on a mini excavator. Malaguti (1994) [34] proposed a decentralised variable structure control of joints, including the actuator dynamics, and considered the possibility to adapt the control dynamics on the system disturbs. In [35], the force and position control problem was addressed for electrohydraulic systems of a robotic excavator. The idea of controlling the force and position relationship was proposed by Ha *et al*. (2000) in terms of impedance control for a hydraulically actuated robotic excavator [36]. The control technique being implemented on a Komatsu 1.5-tonne excavator, demonstrated that the proposed control technique could provide robust performance when employed in autonomous excavation mode with soil contact considerations. The impedance control method was further developed by Tazafoli *et al*. [37]. Recently, partial automated blade control has been studied in [38] to control one of the excavator’s work cylinders while the machine operator controls the rest of non-automated work cylinders. A Time-Delay Control with Switching Action (TDCSA) using an integral sliding surface was proposed for the control of a 21-tonne robotic excavator [39], whereby analysis and experiments showed that using an integral sliding surface for the switching action of TDCSA was better than using a Proportional Derivative-type sliding surface. The proposed controller was applied to the linear motion of the entire excavator at the same speed level as that of a skilful human operator. In [40], the Time-Varying Sliding Mode Controller (TVSMC) combined with a fuzzy algorithm has been used for an unmanned excavator system. The computer control system [41] was implemented on a 1.5 tonne 3-link (boom, arm and bucket) excavator. Developments in high-level control have been studied for task level execution such as positioning, path planning and disturbance mitigation. In [42], Matsuike *et al*. (1996) developed an excavation control system, as a supporting system for large-depth excavation, in which the excavator was exactly positioned with the error being less than 30-50 mm. A control architecture was developed in [43] for autonomous execution of some typical excavation tasks in construction. Using the same platform, Maeda [44] dealt with disturbances arising from a material removal process by proposing the Iterative Learning Control (ILC) with a PD-type learning function as a predictive controller, to achieve a desired cut profile with non-monotonic transients which converged faster by learning disturbances directly from command discrepancies.

Interactions between construction tools and the soil represent highly-non-linear and dynamic processes [45]. There are two strategies to the problem of time varying soil-tool interaction forces: (i) to treat it as a disturbance and design a suitable controller for compensation, or (ii) to design an efficient soil-tool interaction model which can accurately model the dynamics of excavation in real time. One of the main challenges in designing an efficient, robust, adaptive controller for the excavator, emanate from the machine-environment interaction dynamics as the largest contributor of time-varying forces in the system. Complex rheological models capable of computing accurately soil behaviour require a large amount of computational time and hence are infeasible for a real-time dynamic controller [46]. To this end, some recent models have been proposed to predict soil-tool interaction sufficiently well. A 3D semi-infinite soil medium is often replaced by a non-coupled discrete rheological model, independent of its structural elements [47].

As the soil parameters required for accurate modelling are difficult to obtain experimentally, efficient methods must be used for soil parameter estimation [48]. A fuzzy system was proposed, using no information on soil conditions, and solutions offered were claimed to be sub-optimal [49]. Different tool-soil interaction models exist, e.g. the Finite Earthmoving Equation (FEE) model and its modifications [50], and the Linear Lumped Model [51], which is computationally more effective than the FEE. After all, soil behaviour by its nature is complex and the variation of some parameters can greatly alter the soil conditions. Sensors can therefore provide information to compensate for such variations and controllers should be able to handle such disturbances, a detailed survey of which can be found in [52].

Towards full-scale autonomous excavation at TRL level 7-8, a pioneer system was demonstrated by Stenz *et al.* (1999) [53]. The system is the first fully autonomous loading system for excavators being capable of loading trucks with soft material at the speed of an expert human operator. In another study, Yahya (2008) proposed the concept of parameter identification, as a key requirement in the field of automated control of unmanned excavators [54]. An automated excavating prototype was developed in [55] for excavating ditches for drainage. This system was composed of two sub-systems, an automatic surface finishing system and a laser guide system for excavating ditches up to 8 km in length. A vision-based control system for a tracked mobile robot such as an excavator was developed in [56], including several controllers that can be collaboratively operated to move the mobile platform from a starting position to a target location. A prototype of a autonomous hydraulic excavator was introduced to improve the basic technologies of construction machinery such as hydraulic shovels [57], which was also able to complete the autonomous loading of a crawler dump truck. More recently, a prototype system based on a Volvo EW 180B excavator has been reported as part of the autonomous excavator project THOR (Terraforming Heavy Outdoor Robot) with the goal of developing a construction machine which performs landscaping on a construction site without an operator [58].

2.2 Bulldozer

2.2.1 Principles and Subsystems

At TRL 1-2, pioneering work on autonomous bulldozers started several decades ago, as was the case for excavators. Muro (1988) introduced an automatically controlled system for maximising productivity of a dozer running on soft terrain [59], whereby a microcomputer was used to obtain information of terrain properties and vehicle states so that based on that information, optimum drawbar-pull and slip ratios could be computed during digging. Since then, various studies have been conducted, focussed on different research topics such as modelling and control, position and pose estimation, machine-soil interaction, navigation, teleoperation, simulation and real world applications.

At TRL 3-5, Olsen and Bone [60] investigated the modelling of a robotic bulldozing operation for the purpose of autonomous control. Later, in [61], the bulldozer's workflow was modelled using an adaptive neural network to simulate and predict the dependence of the resistive strain of gauge bogie displacement on the dig depth and trolley speed dynamically. The force acting on the blade was first modelled and a model-based adaptive control strategy was then proposed for controlling the blade. The control of the dozer blade could be addressed using fuzzy theory for the semi-automatic control of a real-world bulldozer [62]. Meanwhile, a control strategy for hybrid engines of tracked bulldozers was also addressed in [63], based on a multi-objective design optimisation of the engine control parameters to minimise fuel consumption.

In the soil cutting and pushing process, the dozer blade experiences soil resistance owing to friction, cohesion and adhesion between the blade and soil, and the soil and ground [64]. The forces acting on the blade vary in a complicated manner that may deteriorate the performance of the bulldozer. The resistance or draft force problem has been tackled either empirically [65] or using numerical methods [66], whereby a cohesive bond force model was introduced in which the microscopic behaviour of the cohesive force was evaluated against macroscopic shear failure characteristics. The dynamic behaviour has also been taken into account by considering velocity and acceleration in the model [67]. Numerical studies were conducted with the finite element method for soil mechanics and the failure zone using various models including constitutive equations of soil failure [68] and an elasto-plastic constitutive model [69]. In simulation and navigation, analyses of the driving system of a crawler bulldozer were carried out with two types of pavement, clay and hard, taking into account the driving force. The results provided a reference for improving the performance of the crawler bulldozer drive system [70]. Recently, a guidance system for the bulldozer has been developed using sensor fusion. The integration of an Inertial Measurement Unit (IMU) with two Real Time Kinematic (RTK) global positioning systems (GPS) allowed accurate estimation of the pose and position of the bulldozer blade, providing feedback to the navigation system [71]. Experiments on a full-scale bulldozer were implemented to validate the approach.

2.2.2 Integrated Pilot Systems

At TRL 7-8, a group of 20 prototype bulldozer robots were built to develop autonomous and cooperative capabilities [72], using tank-like treads driven by two independent actuators, and equipped with a scoop which can be lifted up and down and tilted back and forth. They also have a one degree-of-freedom head which constantly rotates with various sensors mounted onboard. Experiments were performed on an artificial lunar surface and the results were promising for various planetary tasks. Apart from space programs, autonomous bulldozers have been developed for surveillance, mining and construction. In [73], Moteki *et al*. have adapted the unmanned construction system technology to build semi-autonomous bulldozers for operations in a disaster situation. More recently, ASI Robotics Inc. has developed a system of robotic hardware components that allow users to control a vehicle in both modes, manual and autonomous modes. The system consists of NAV™ (the onboard computer and communications system), Vantage® (obstacle detection and avoidance features), and Mobius™ (command and control software) [74]. Together, these components form a universal automation solution for vehicles of different geometries, sizes, and applications.

2.3 Loader

Autonomous loaders are considered as an integrated system of hydraulic, mechanical and electronic subsystems. Being widely used at construction sites, these machines have received much research interest to continuously improve their performance and autonomy level. At TRL 1-2, since 1990's, the study on control and planning of frond-end loaders has become active [75]. By using a microcomputer, the computer controller is capable of positioning the linkage in either Cartesian or angular coordinate motion with the ability to store and recall trajectories. Since then, a number of studies have been conducted on model loaders, which are essential for improving their performance and autonomy level to TRL 3-4. Worley and Saponara (2008) presented a simplified dynamic model of a wheel-type loader to accelerate the structural design and analysis of the boom and bucket linkage subsystems [76]. The lateral dynamics of skid-steering high-speed tracked vehicles were presented, with a nonlinear track terrain model derived from classical terra-mechanics [77]. Recently, both kinematic and dynamic models of a skid-steered robot were identified via a learning process based on the Extended Kalman Filter and an efficient neural network formulation [78]. In terms of machine control, an automated digging control system (ADCS) for a wheel loader was developed using a behaviour-based control structure combined with fuzzy logic, and implemented on a Caterpillar 980G wheel loader [79]. A closed-loop digital velocity control was successfully implemented for those objectives with the results validated by experiments on a large Caterpillar 990 wheel loader, as reported in [80]. In another approach, an H-infinity based robust control design combined with feedback linearization was presented for an automatic bucket levelling mechanism wherein robustness of the controller design was validated in simulation by using a complete nonlinear model of the wheel loader [81].

At SRL levels 7-8 for integrated systems, Volvo Construction Equipment, developed a prototype of a fully autonomous haulage truck and wheel loader, and demonstrated it in 2016 [82]. Most recently, a fully autonomous track loader has been developed and tested in the field by Built Robotics Inc. taking advantage of the significant advances in self-driving car technologies. The developed software and sensor suite can transform off-the-shelf loaders and excavators into robotic platforms that can undertake earthmoving tasks with precision, and for hours without a break [83].

3 Earthmoving Construction Automation in Military Applications

3.1 EOD and landmine detection

One of the earliest RAS used in military applications was reported in 1992 [15] for the Small Emplacement Excavator (SEE), a ruggedized military vehicle with backhoe and front loader used by the U.S. Army for explosive ordnance disposal (EOD), combat engineering, and general utility excavation activities. Its features include teleoperated driving, a telerobotic backhoe with four degrees-of-freedom, and a teleoperated front loader with two degrees-of-freedom on the bucket. In [84], a terrain scanning robot can autonomously manipulate a typical handheld detector for remote sensing of buried landmines using map building and path planning implemented in real-time software. A commercial Modular Robotic Control System (MRCS) was first integrated onto a Nemesis HD Robotic Platform for the tasks of ground clearance and landmine detection Wetzel *et al*. (2006) [85]. It was then installed on the 924G Bucket Loader, shown in Fig. 1, for various construction operations including excavating, digging, lifting/loading, stripping, levelling, and stockpiling.

Another commercial-off-the-self robotic kit, the Appliqué Robotics Kit (ARK), was also designed to allow the modification of existing plant to remote controllable with the minimal modification of the host vehicle or its electro-hydraulic system. In [86], the ARK was installed on a front end loader/backhoe used for excavation of small emplacements, material handling, and general construction tasks as shown in Fig. 2. Experimental results showed that this RAS technology was suitable for operational use and supported hasty route clearance operations for the military. These unmanned ground vehicles can also be used for other purposes such as surveillance; remote monitoring; engineering and military policing tasks; and chemical, biological, radiological, and nuclear (CBRN) defence.

Fig. 1: MRCS installed on the 924G Bucket Loader [85].

Fig. 2: An Army loader/backhoe installed with ARK [86].

3.2 Earthwork for military purposes

Earthwork operations have been used for centuries as part of military defensive operations. This could be in the form of moats, foxholes, or bunkers to protect equipment and personnel. It is not difficult to organize such work as it does not involve technology and can be performed with rudimentary equipment. A more permanent form of earthwork may have facing materials on the parapet that makes up the higher part of the earthen embankment. This could be constructed with stones, sandbags, wood, or any other material. Such protection requires additional time and is rarely a form adapted in actual battle conditions. Other forms of military earthwork include moats, which are often built around inhabited areas and filled with water to slow down the enemy. Modern day warfare uses the same method to create tank trenches, quite often for miles to slow down an armoured column assault.

A *Forward Operating Base* (FOB) is a secured forward military position, commonly a military base that is used to support tactical operations. A FOB may or may not contain an airfield, hospital, or other facilities. The base may be used for an extended period of time. FOBs are traditionally supported by Main Operating Bases that are required to provide backup support to them. A FOB also improves reaction time at the local level rather than having all troops in the Main Operating Base. In its most basic form, a FOB consists of a ring of barbed wire around a position with a fortified entry control point. More advanced FOBs include an assembly of earthen dams, concrete barriers, gates, watchtowers, bunkers and other force protection infrastructure. They are often built from special retaining or shoring walls called bastions for defence. Figure 3 shows construction of a HESCO bastion by US Marine Corps with the help of an excavator [87], for a FOB in Afghanistan's Delaram District.

Fig. 3: Building Delaram FOB [87]

A common example of military earthwork is to put in place a *barrier* between the force and the enemy for force protection. The basic form of any such earthwork operation is a mound of earth or embankment rising above the general ground level. This embankment is formed from earth that is excavated in the same locale, thus simultaneously creating a ditch. The ditch adds to the height and depth available for protection. A *foxhole* is the simplest form of military earthwork normally dug in position by a soldier who will use it for self-protection in battle. A section of soldiers may connect up their individual foxholes to form a continuous trench that can be used to facilitate the supply of ammunition and allow communication ferrying with commanders.

The *HESCO bastion* is a modern gabion primarily used for military fortification. It is made up of a collapsible wire mesh basket and a heavy-duty geo-fabric liner. They are used as a semi-permanent blast wall against explosions or small-arms fire and used for FOB wall constructions as in Figure 3. One of the best features of HESCO is its ease in setting up. Flat pack and concertinaed HESCO can be pulled off a truck and erected quickly. With a front-end loader or excavator used to fill the baskets with dirt, sand or gravel, a wall can be built within hours and is much quicker than sand bagging.

Antitank ditches are constructed to strengthen prepared defensive positions. As they are costly in time and effort to construct, much is gained if the excavation can be made by means of cratering charges. An antitank ditch must be wide enough to stop an enemy tank, and it may be improved by placing a log hurdle on the enemy side and the spoil on the friendly side. Forming such ditches can be improved by digging the friendly side nearly vertical. Antitank ditches are usually triangular, rectangular, or trapezoidal in cross section and have a low parapet on the defender's side. Their dimensions vary and they are often reveted or contain water. Figure 4 shows a British Army Terrier combat vehicle employed for trench digging. Manufactured by BAE, it has drive-by-wire and teleoperation capability, equipped with a remotely controllable hydraulic front bucket and excavating arm. It is used remotely by operators for clearing routes, creating cover, digging anti-tank ditches and trenches under harsh conditions [88].

Fig. 4: Teleoperated trench digging [88].

3.3 Military use of RAS on earthmoving platforms.

The application of RAS is becoming more widely used on legacy earth moving plant within the military. Autonomous land vehicles have been developed for navigation, reconnaissance, surveillance, and target acquisition. Recently, the US Army has tested the autonomous vehicle technology in its fleet of logistical vehicles. The leader follower technique in robotic formation was used to form a convoy of trucks equipped with a laser-based sensor (LIDAR) used for maintaining the distance clearance. Figure 5 shows a test scenario to demonstrate the concept of V2I (Vehicle To Infrastructure) that allows for a formation of one manned truck leading seven driverless connected vehicles [89].

Fig. 5: The US Army is testing a "leader-follower" system that will employ up to 8 convoy vehicles [89].

For military use, bulldozer blades can be optionally fitted to platforms including, such as artillery tractors of Type 73 or M8 Tractor. Dozer blades can also be mounted on main battle tanks, where it can be used to clear antitank obstacles, mines, and dig improvised shelters. Combat applications for dozer blades include clearing battlefield obstacles and preparing fire positions. Bulldozers employed for combat engineering roles are often fitted with armour to protect the driver from small arms fire and debris, enabling bulldozers to operate in combat zones. The Israeli Army Engineering Corps have also completed an extensive project to equip unmanned bulldozers with autonomous capabilities, as shown in Fig. 6, to carry out specialized tasks for earth moving, clearing terrain obstacles, opening routes and detonating explosive charges [90]. Front end loaders are also commonly used in military applications for constructing and removing road blocks and building bases and fortifications.

Fig. 6: Robotic bulldozer used by Israel Defence Forces [90].

4 Construction Automation – A Projection Regarding Military Applications

Since the last decade of the 20th century, there has emerged increasing research evidence for the viability of RAS in autonomous construction tasks including the more challenging problem of autonomous excavation [91, 92]. The enabling technologies arising from the research and development into RAS for automating construction tasks using platforms such as excavators, dozers and loaders have become much more mature and better integrated, providing a foundation for the next stage of growth in off-the-shelf products. In addition, embracing the recent advances in manufacturing with Industrie 4.0 [93], cloud computing, cyber-physical systems and IoT, tomorrow's technologies for construction automation can be foreseen in the improvement of construction site efficiency with a plethora of technologies, systems, data and services.

Looking ahead at the use of RAS in construction, Kendall Jones, the Editor-in-Chief of the ConstructConnect blog [94], emphasises efficiency and accuracy, envisaging an automated construction site in the future that will have a fleet of dozers, graders, and excavators undertaking site works without any operators behind the cabin controls, and some without cabins.

During the Second World War, when the U.S. and Germany started to develop Unmanned Air Vehicles (UAVs), military robotics has made tremendous progress. As increasing evidence of defence interest in autonomous systems, in 2001 the US Congress mandated that, "By 2010, one third of the operational deep-strike force aircraft fleet are unmanned, and by 2015, one-third of the operational ground combat vehicles are unmanned"[1]. Unmanned Ground Vehicles (UGVs) are becoming more engaged in a variety of missions including Explosive Ordnance Disposal (EOD), combat engineering, reconnaissance, and civil works. RAS, including ground, aerial, underwater, amphibious vehicles [95], anti-munition systems, armed robots, cyber-attack and defence systems are anticipated to become a central piece of military operations in the years ahead.

According to Randall Steeb, a senior scientist at Rand Corporation, commented that the US Army's Future Combat Systems (FCS) program emphasised the use of autonomous, armed cooperative robots [96]. While eventually cancelled, the FCS program was further evidence of a growing interest in military application of autonomous systems. Cooperation of unmanned platforms with humans and inhabited machines in construction has been gaining interest in the RAS community. In parallel with this is the widening use of the military concept of teaming of unmanned vehicles [13]. For example, the flexible leader-follower formation of skid-steered tracked vehicles towing polar sleds has been studied with a developed dynamic model and a proposed control architecture. The results have shown that the follower tractor maintains the flexible formation but keeps its payload stable while the leader experiences large oscillations of its drawbar arm indicating potential payload instability [97]. In this context, efficient and adaptive RAS, along with artificial intelligence techniques and ubiquitous communication networks can effectively support the cooperation to meet the expectations of ever changing operational environments and recover from disturbances.

In construction and infrastructure, the emerging field of IoT is directly applicable to the technologies for interconnected systems, consisting of several communication layers, such as in the driverless vehicle technologies, or in advanced manufacturing. IoT is a paradigm that considers the pervasive presence of a variety of objects possessing digital intelligence in an environment. These make themselves recognizable and can behave intelligently by making context related decisions thanks to information aggregation and sharing with other objects.

Teaming of different platforms in military construction will find its root in the development of methodologies and techniques for interconnected systems [98] and the application of intelligence science, data science and IoT or cyber-physical systems [99]. In the military domain, IoT finds direct applications in such operations that are often conducted in a complex,

[1] Section 220(a) (2) of the Floyd D. Spence National Defense Authorization Act for Fiscal Year 2001 (as enacted into law by Public Law 106–398; 114 Statute 1654A–38).

multidimensional, highly dynamic and disruptive environment, e.g. a FOB, where commanders have to accurately and promptly assess the situation, to gather all possible information sources to obtain the most complete and relevant picture in order to make decisions [100]. Scenarios for use of IoT in warfare conditions may include its applications to support tactical reconnaissance, smart FOBs that incorporate IoT technologies in force protection at bases as well as maritime and littoral environments, health and personnel monitoring, and equipment maintenance. The technical challenges will rest with reliability and dependability, especially when IoT becomes mission critical; actuation of IoT devices, especially with real-time requirements; power for their tactical deployment; architectural aspects of military IoT infrastructure including security, information, and communication architectures; and interoperability and integration of disparate technologies.

5 Conclusion

We have comprehensively surveyed the use of RAS in earthmoving construction machinery with applications to the land force. Typical automated platforms such as excavators, bulldozers and front-end loaders are reviewed with regard to modeling, low and high levels of control, their system architecture, sensing and navigation, tool-soil interactions, simulation and experiments from laboratory set-ups to full-scale field tests, in remotely controlled, teleoperated, semi-autonomous and autonomous modes of operation. The developments of RAS for these platforms have been perused from several decades till the present day and, this survey has provided an overview of these in terms of their technology maturity and systems readiness. These developments range from basic research through to operationally employed systems.

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4D BIM for Improving Plant Turnaround Maintenance Planning and Execution: A Case Study

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Abstract –

Four-dimensional (4D) Building Information Modelling (BIM) has been credited with improving construction planning procedures. The integration of 3D model with schedule information has enabled the effective detection of design and planning flaws in many construction projects. Due to the lack of research on using 4D BIM in Turnaround Maintenance (TAM) projects, this paper firstly introduces a novel framework of applying 4D BIM to improve TAM process planning and execution. Then, a real TAM project was selected to validate the effectiveness and efficiency of the proposed framework. Finally, benefits such as time and cost reduction, and safety improvement are calculated and explained.

Keywords –

BIM; Turnaround Maintenance; Planning

1 Introduction

Turnaround maintenance (TAM), as a periodic comprehensive programme which contributes significantly to the long-term stability and continuous production availability of the oil and gas plants, is one of the most important maintenance strategies to minimise the risk of production losses [1]. TAM project is known for its complexity due to the involvement of massive man powers and financial resources during its planning and operation [2-4]. It is reported that a major TAM can potentially cause an annual productivity loss of 2-3% [5]. The peculiarities of high labor intensity and capital concentration make TAM project a time-sensitive project that any delay or inefficiency can lead to catastrophic failure.

Traditional project management techniques, such as Critical Path Method (CPM)/ Program Evaluation Review Technique (PERT), are commonly applied to manage TAM projects. However, these methods are believed to be inadequate to accommodate the complexity of TAM projects.

Building Information Modelling (BIM) is emerging as a method of creating, sharing, exchanging and managing the information throughout project life cycle among all stakeholders [6, 7]. A Four-dimensional (4D) BIM model results from the linking of 3D model to the fourth dimension of time [8]. In the 4D model, the temporal and spatial aspects of the project are inextricably linked, as they are during the actual construction process [9]. In project shaping stage, 4D BIM is useful in communicating and validating construction plans and processes, while during construction phase, they are helpful in identifying errors in the logic of the schedule, potential time-space conflicts, and accessibility issues [10, 11].

In recent years, 4D BIM has been largely implemented on building and infrastructure projects, and proven its capabilities in planning simulation and optimisation [12-16]. However, there is a lack of 4D BIM studies in TAM projects. Therefore, it is worthwhile to investigate the capabilities of 4D BIM in improving TAM planning and execution. This paper firstly introduces a novel framework of applying 4D BIM to improve TAM process planning and execution. Then, a real TAM project was selected to validate the effectiveness and efficiency of the proposed framework. Finally, benefits such as time and cost reduction, and safety improvement are calculated and explained.

2 Framework of Applying 4D BIM to Improve TAM Planning and Execution

This section describes a 4D BIM framework for improving TAM planning and execution (as shown in Figure 1). In the left part, a typical TAM project structure is developed which consists of six levels of details based on the functional logic [5, 17]. The first level is defined based on a TAM project unit, which explains the project scope, cost, planning, governance, key performance indicators, health, safety, environment and quality, and emergency response. For a major shutdown, a TAM project will contain jobs conducted in two or more independent trains. Therefore, a major TAM campaign is always divided into several sub-campaigns. Given a train-related sub-campaign, the third level classifies the jobs into a number of sub-sub-campaigns according to the plant unit, such as Compressor or Turbine. The fourth level further divides the related jobs within a sub-sub-campaign into different work orders according to the system unit, such as Piping, Mechanical, and electrical systems. The last two levels detail the work order into batch and activity units respectively. For instance, for a given work order of a spool removal, there are a number of elbows need to be uninstalled, in addition, detailed process for uninstalling a specific elbow also needs to be explained.

According to the TAM project structure, four levels of the 4D BIM simulation are developed including Plant, System, Batch, and Activity level (as shown in the right side of Figure 1). For a given level, the 4D BIM simulation is developed based on the corresponding level-of-detail 3D model and schedule. Each of them is explained in detail in the following sub-sections.

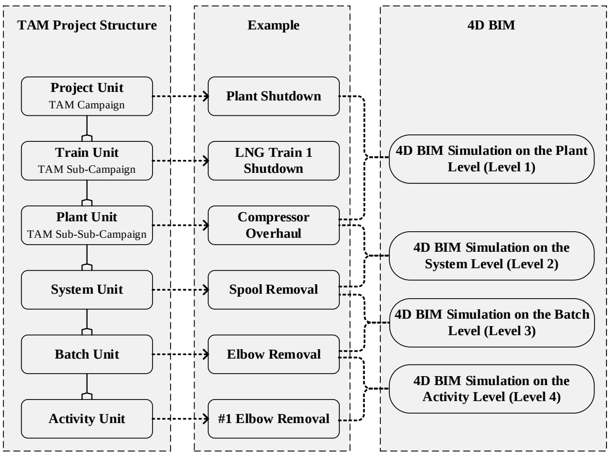

Figure 1: Framework of Applying 4D BIM to Improve TAM Planning and Execution

2.1 4D BIM Simulation on the Plant Level

The main objective of this level of 4D BIM simulation is to effectively engage core teams (i.e. Operations, maintenance & Integrity, and Turnaround Lead) to review the project scope. If the scope does not align with the initial plan, additional works, such as revising plans, need to be conducted before proceeding to the next stage. Therefore, the reviewing process is very critical to the turnaround success.

4D BIM modelling and simulation on this level is developed based on the 3D Plant Model and TAM milestone plan. In order to accelerate the agreement establishment among plant operation, maintenance, and turnaround teams, the 3D Plant Model should have all the main 3D objects (i.e. Compressor, Turbine, or Heat Exchanger) that defined within the project scope, and their functional location information. In addition, a general plant site model including site layout information should be also incorporated into the 3D Plant Model. The TAM milestone plan should lay out the key checkpoints and delivery dates for the planning cycle and form the basis for forecasting planning resources.

The plant-level 4D BIM simulation should be developed ten to twelve months before starting the field execution. For small turnaround projects with no major material lead times, the completion data of this simulation can be 6-8 months before actual starting.

2.2 4D BIM Simulation on the System Level

The main objective of this level of 4D BIM simulation is to engage teams of Planning, Work Pack Development, Engineering, and Procurement to: (1) communicate and review terms of reference, discuss initial risks, functional requirements, likely resources and establish delivery strategy; and (2) review initial scope against turnaround acceptance criterial, prioritise tasks and establish initial work list.

4D BIM modelling and simulation on this level is developed based on the 3D System Model and TAM work development plan. In order to efficiently review and confirm initial work list and initial preparations plan, the 3D System Model should include: (1) all the connected components (i.e. Spools and steel structures) of the instruments that plan to be replaced; and (2) major construction equipment, such as mobile cranes, that plan to be used to perform lifting tasks. The TAM work development plan should include: (1) an integrated plan (schedule, equipment and resources); (2) preliminary critical path schedule; (3) updated preliminary work list; and (4) critical lift plans.

The system-level 4D BIM simulation should be completed six to eight months prior to the shutdown of the plant or equipment.

2.3 4D BIM Simulation on the Batch Level

The main objective of this level of 4D BIM simulation is to engage external contractors and/or out-of-plant personnel to evaluate the critical path, and come up with alternative execution methods to shorten the project duration. Reviews of maintainability, reliability, and constructability are the main focus at this stage.

4D BIM modelling and simulation on this level is developed based on the 3D Batch Model and TAM detailed plan. In order to efficiently finalise the work list, the 3D Batch Model should include: (1) supported structures such as steel platforms and scaffolds; and (2) safety signs and tags such as frame signs, swing stand signs, and barricading. The TAM detail plan should include critical and sub-critical activities, lifting plans, mobile equipment requirements, detailed shop loading plans, and what-if scenarios.

The batch-level 4D BIM simulation should be completed three to five months prior to the turnaround.

2.4 4D BIM Simulation on the Activity Level

The main objective of this level of 4D BIM simulation is to ensure that all parties understand the work to be done and the sequence and details of the shutting-down process together with preparation for entry.

4D BIM modelling and simulation on this level is developed based on the 3D Activity Model and TAM execution plan. In order to efficiently (1) train operations, maintenance, and contractor personnel and (2) review environmental and safety requirements, the 3D Activity Model should include: (1) temporary facilities such as temporary offices, stores, tool houses; (2) functional equipment such as lighting tower, gas detector, and hydrostatic test unit; and (3) virtual avatar. The TAM execution plan should include: (1) shutdown and unit clean out sequences, (2) start-up plan; and (3) detailed execution sequences.

The activity-level 4D BIM simulation should be completed two weeks to two months prior to the turnaround.

3 Case study

The case study was conducted based on a major plant turnaround project that consists of LNG Train 5 and Fractionation Train 1. The key activities involved in this turnaround include: (1) Turbine major inspection; (2) Statutory vessel inspections; (3) Compressor blade carrier change-out; (4) Bearing and seal inspections; (5) Tray modifications; (6) Molecular sieve bed change-out; (7) Mercury guard bed change-out; and (8) Valve overhauls, upgrades and replacements.

3.1 3D Model Development

The selected gas plant was built more than 30 years ago. There is a lack of a 3D model that can be used to create a 4D simulation. Fortunately, the laser scanning technology is becoming mature enough, and is affordable for current industry. There are lots of automated methods that have been developed for transforming point cloud data into 3D model [18]. However, in this case study, the 3D model was created manually by engineers in order to assure the modelling accuracy. The underlying reasons are twofold: (1) Most of the existing algorithms developed for automatically transforming point cloud data into 3D model, are focused on building industry. When applying them in gas plant domain, the average accuracy of the transforming process is not acceptable. (2) The scope of this TAM project is small, only covering the Compressor-related area, thus both time and cost spent for creating the 3D model are affordable. Figure 2 shows the point cloud data, and Figure 3 shows the converted 3D model.

Figure 2: 3D Point Cloud Model

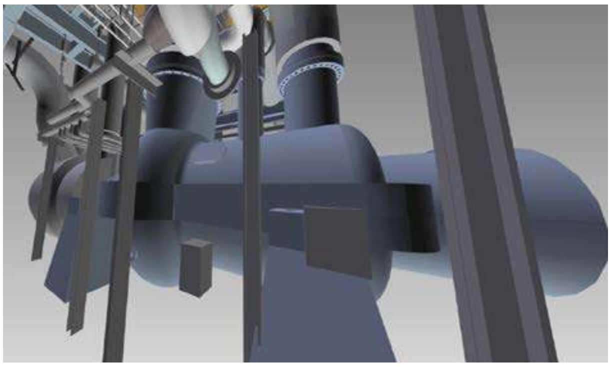

Figure 3: Converted 3D Model

3.2 4D BIM Simulation Implementation

In this case study, the four levels of 4D BIM simulation defined in Section 2 were developed as the project progresses. The aim of the 4D BIM simulation on the plant level is to help decision-makers to efficiently gain a better understanding of project scope and critical works. Figure 4 shows the 4D BIM simulation on the plant level which visualises the major activities defined within the project scope.

The simulation was created by the TAM core team and presented to the project steering committee for guidance. Through the simulation, the steering committee had gained a better understanding of

- The thirteen major maintenance happened in LNG train 5, such as: gas turbine overhaul of *5KT1410* and *5KT1430*, process compressor overhaul of

5K1410, *5K1420*, *5K1430* and *5K1450*, statutory inspections of 43 vessels, and *5C1410* tray modifications; and

- The nine major maintenance happened in LNG train 4 and Frac-3, such as: thirty control valve installations, three exchanger installation, product exchange of 4C2501, and compressor overhaul of *4K4401* and *4K4403*.

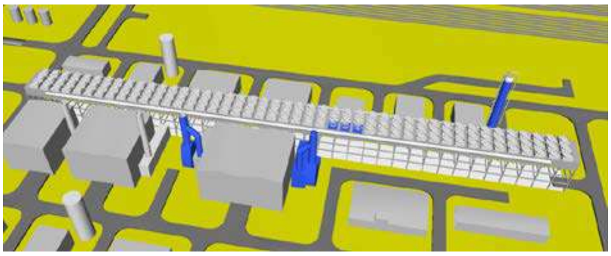

Figure 4: Screenshot of the 4D BIM Simulation on the Plant Level

In addition, one critical workscope and three sub-critical workscopes were also determined in terms of their durations and dependences. The *5K1410* compressor overhaul was the critical one and it would take 20 days to complete. The sub-critical workscopes includes: *5KT1430* turbine overhaul (24 days), *5KT1430* turbine overhaul (25.5 days), and *5C1410* internal tray modification (13 days).

Figure 5 shows the 4D BIM simulation on the system level which not only visualises the sequence of the main activities, but also evaluates the constructability and efficiency of the lifting and access plans created by the TAM execution team.

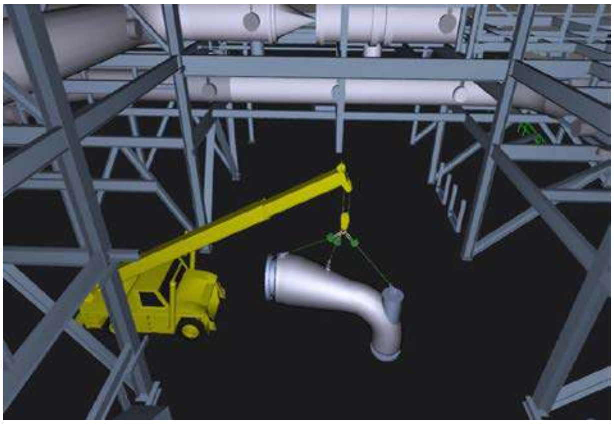

Figure 5: Screenshot of the 4D BIM Simulation on the System Level

Take LNG Train 5 as an example, the original lifting plan contains six mobile cranes. The working location and lifting capacity of each crane are shown in Figure 6a. According to the simulation result, seventeen major conflicts were identified between the planned construction sequence and the original lifting plan. For instance, Crane 2 was occupied by two main activities simultaneously during 9:30-10:18 on the 11th September 2015, and Crane 4 was occupied by two main activities simultaneously during 6:45-7:51 on the 18th September 2015. If these conflicts were not solved successfully before field execution, there would be fifty hours schedule delay and more than two hundred man-hours waste. These numbers were estimated by the TAM core team.

In order to solve the seventeen lifting conflicts, the TAM core team went through these conflicts one by one, and found that fourteen of them were related to the Crane 2 and 3. Therefore, they decided to add another crane located between Crane 2 and 3 to share the lifting load. The other three lifting conflicts were related to the Crane 4. Instead of adding a new crane, the TAM core team decided to enlarge the lifting capacity of Crane 5 from 20 tonnage to 50 tonnage so that it can share the lifting load of Crane 4. In addition, the working locations of Crane 4 and 5 were also adjusted to assure the lifting efficiency. Figure 6b illustrates the revised lifting plan for LNG Train 5.

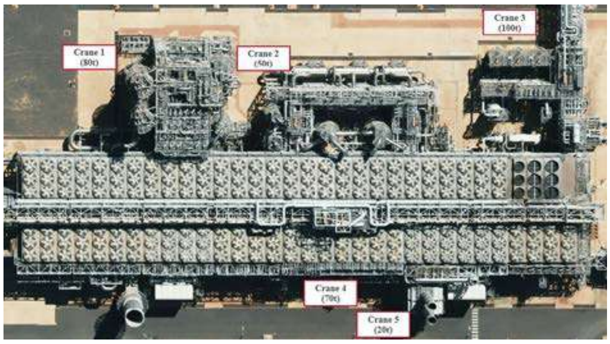

Figure 6a: The Original Lifting Plan for LNG Train 5

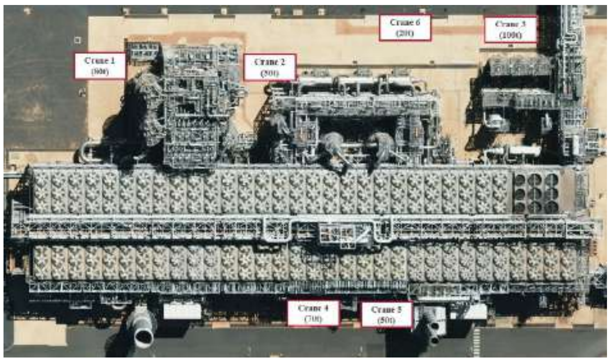

Figure 6b: The Revised Lifting Plan for LNG Train 5

The 4D BIM simulation on the batch level was developed by the TAM execution team, which visualises the sequence of all the activities involved including temporary jobs such as scaffold erection and dismantling (as shown in Figure 7). In order to improve site productivity and better focus on critical activities from stopping to restarting production, operations and maintenance teams were engaged at this stage to identify potential constructability issues and duration reduction opportunities. A cloud BIM platform (as shown in Figure 8) was also developed to allow people from other shutdown projects but has similar working experience to easily access this simulation and comment their ideas remotely.

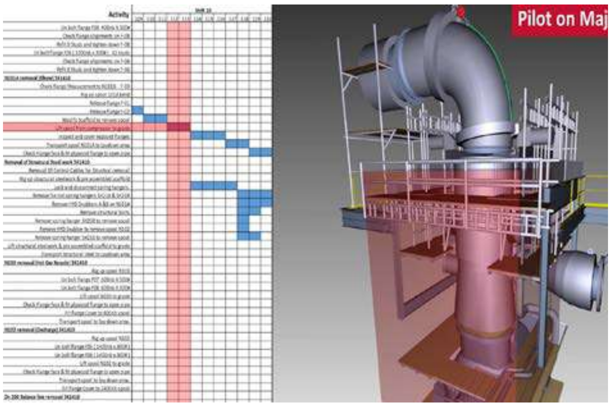

Figure 7: Screenshot of 4D BIM Simulation on the Batch Level

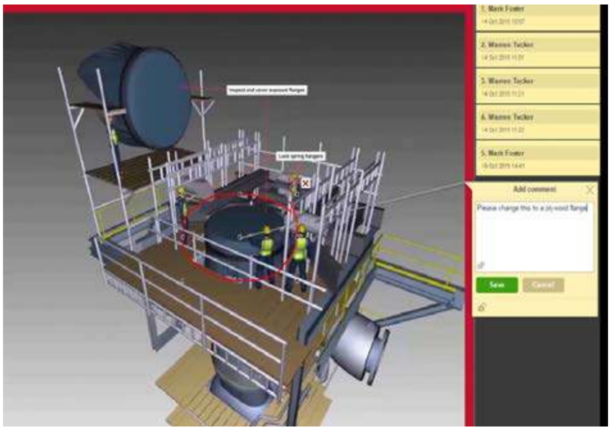

Figure 8: A Cloud BIM Collaboration Platform for Constructability Review

Figure 9 summarises the issues identified at this stage. A total of 104 issues were found by the TAM internal and external teams. These issues were further classified into eight categories, i.e. issues of Crane, Equipment & tools, Safety, Material, Work space, Permit, Activity Sequence, and Work front access. Incorrect activity sequence was the top one issue which accounted for 27% of the total issues. For instance, “This handrail is only installed once the steelwork has been removed”, “The scaffold should be modified first before removing the spool N101A”, “Remove spring hanger SH216 first before removing the spool”. Incorrect permit was the second most serious issues which accounted for 22%. TAM work requires extensive permits for every shift to ensure each work is performed safely. The plant engineering and operation teams contributed significantly on identifying these permit issues. For instance, they found that six activities were lack of appropriate permits, and another seventeen permits were incomplete and needed further development. Sixteen safety issues (i.e. 15%) and thirteen crane operation issues (i.e. 13%) were also detected through the Cloud BIM Collaboration Platform. The other three types of issues are work space (10%), work front access (9%), and equipment & tools (4%), respectively.

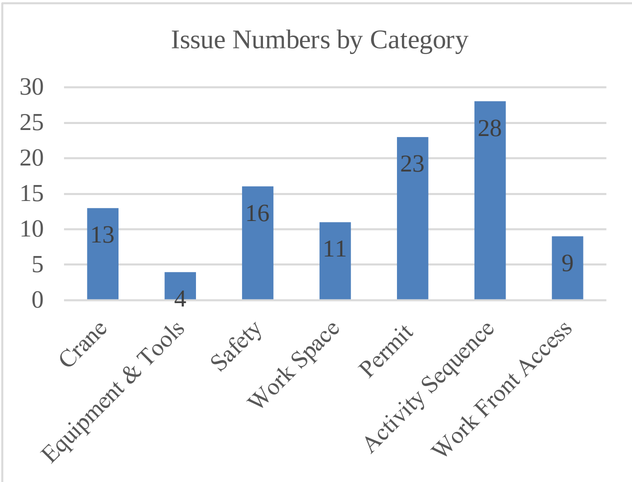

Figure 9: Issue Numbers by Category

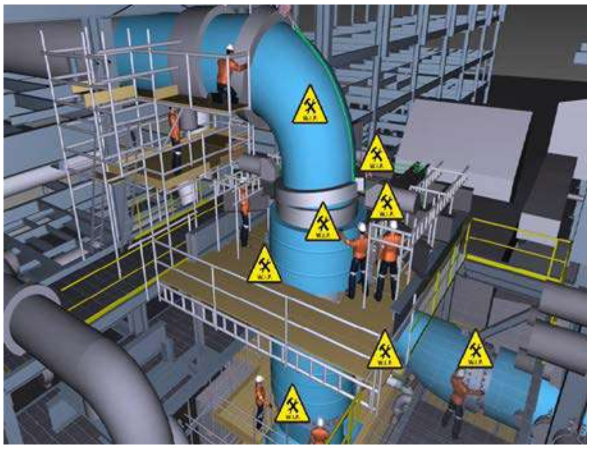

Figure 10: Screenshot of the 4D BIM Simulation on the Activity Level

Figure 10 illustrates the 4D BIM simulation on the activity level which takes account of maintenance work crews. At the peak, there are nearly 1000 people on site which creates a complex logistical task. In order to streamline the construction site work flow, locations and walking paths of each work crew were shown during the simulation, especially during those working periods that contain massive concurrent activities. Rigging plans were also visualised including shackles, turnbuckles, and slings being used.

4 Time and Cost Reduction Analysis

A quantitative analysis of the time and cost reduction is difficult because it should predict what would happen if the issues that detected by 4D BIM simulation are not resolved. Instead of directly calculating each issue effect, a previous equivalent TAM project that conducted two years ago was selected as a benchmark to measure the time and cost savings. The raw execution data of the selected case were extracted from the Document Retrieval Integrated Management System (DRIMS) (i.e. a type of corporate document management system) and SAP (i.e. an enterprise resource planning system).

Figure 11 illustrates the maintenance duration reduction. The left column with red colour indicates the actual duration of the valve replacement, i.e. 14 days. The planning of the current TAM project started from the previous one, and after the first two levels of 4D BIM simulation (i.e. Plant level and System level), the initial expected duration was adjusted to 13.5 days. Before the field execution, the TAM team set the project target duration to 12 days based on the results of the 4D BIM simulation on Batch and Activity levels. According to the final project report, this project was completed within 11.6 days.

Based on a rough comparison, the field execution work was finished 0.4 day (i.e. 9.6 hours) before the target schedule and 1.9 days ahead of the initial plan. When compared with the previous equivalent one, a total of 2.4 days were saved. Excellent results were also achieved on the health and safety front, such as: 50% reduction in minor first aid cases, no environmental incidents, no medical treatment incidents, and no high potential incidents.

For cost reduction analysis, considering the inflation and the changing prices for instruments procurement and equipment leasing, it is meaningless to compare the actual cost of the two TAM projects. Figure 12 illustrates the project cost estimated at three different stages: initial stage, pre-execution stage, and completion stage, respectively. The initial budget (i.e. AUD$ 24.1 million) was estimated based on the initial work list and estimated duration. The budget before field execution (i.e. AUD$20 million) was calculated based on the final confirmed construction schedule and resource plans. The actual cost for this TAM project was AUD$ 19 million according to the project completion report.

A total of AUD$ 4.1 million was saved when comparing the actual cost with the initial budget. Specifically, AUD$ 4.1 million cost reduction was achieved during the project planning phase while another AUD$ 1 million was achieved during the project execution phase.

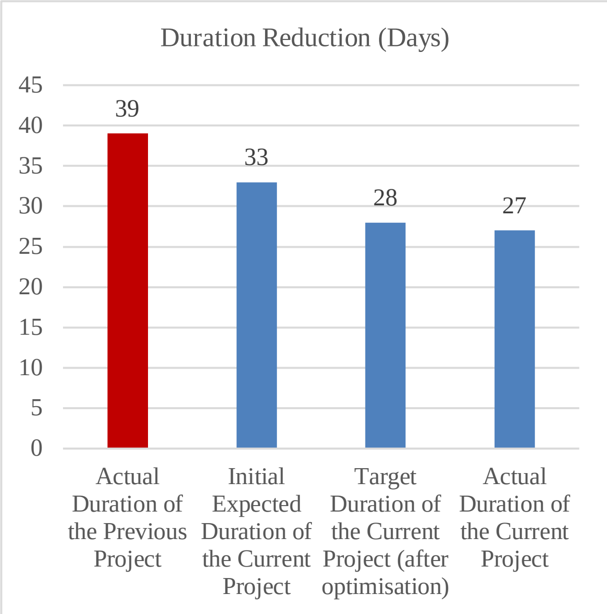

Figure 11: Duration reduction

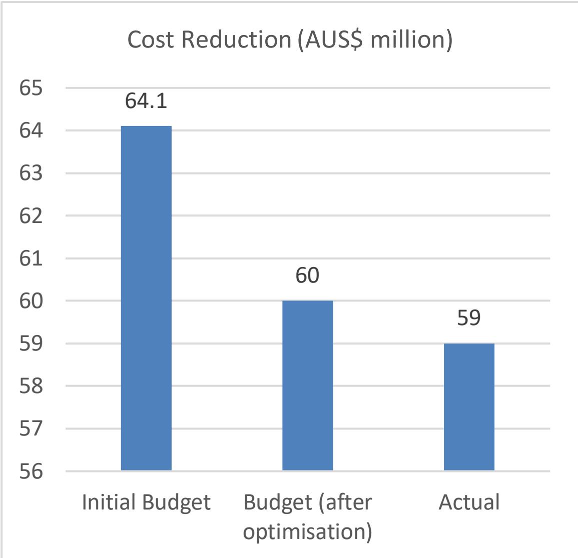

Figure 12: Cost reduction

5 Conclusions and Future Works

In this paper, a 4D BIM framework is developed for improving TAM process efficiency, which encompasses four different levels of BIM simulation, i.e. Plant, System, Batch, and Activity level. A real TAM project was selected to evaluate the effectiveness and efficiency of the proposed 4D BIM approach in waste elimination and time and cost reduction. The results show that: (1) the TAM project starts on time and finishes 0.4 day (i.e. 9.6 hours) before the target schedule and 2.4 days ahead of the original schedule; and (2) A total of AUD$ 4.1 million has been saved when comparing the actual cost with the initial budget. In the future, automated progress monitoring of planned activities will be investigated. Advanced technologies such as Ultra-Wideband [19], Photogrammetry [20], Laser Scanning [21], and Internet of Things [22] will be reviewed and tested in a plant turnaround environment for site maintenance activity tracking.

Acknowledgments

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Mathematical Optimisation of Rail Station Location and Route Design in Urban Regions through Minimising Noise Pollution

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Abstract

The number of cities that are implementing sustainable transportation programs has been recently on the rise. Reliance in large urban areas is on the use of public transportation systems such as busses and rapid transit lines (heavy rail) to act as the main mode of public transport in multi-modal transport systems. It should be noted however that operations of rapid transit lines are associated with heavy noise levels. When it comes to addressing the issue of noise pollution from rail lines, it is important to consider the design factors that affect the levels of noise disruption impacting the surrounding population. An important design factor that plays a significant role in determining the overall noise levels that propagate from the rail lines to the noise-sensitive residential zones is the choice of the rail route. As a result, careful consideration of the location of the stops of a rapid transit line is an important issue to address when attempting to curtail the noise pollution of rail operations. This paper proposes a novel mathematical formulation, based on a Binary Integer Programming model, to optimise the locations of stops for a typical rail line construction project. The focus in the proposed model is on minimising the total noise pollution levels associated with the operations of the transit line, given that noise is an important social and environmental factor that impacts the sustainability of the project. A case study is presented at the end to demonstrate the applicability of the proposed model.

Keywords –

Station Location Optimisation; Noise Pollution; Sustainable Rail Design, Binary Integer Programming; Location Theory

1 Introduction

Sustainable practice in the construction industry is based on balancing social, environmental and economic aspects when designing and planning projects. Designing sustainable infrastructure projects requires careful consideration of the resulting environmental impacts associated with the operation of the project [1]. One of the nuisances reported during and after infrastructure construction works is that related to noise pollution. The issue of noise pollution during the construction process can be handled through measures that target the noise source (i.e. noise dampeners installed at machines), noise receivers (noise insulation in wall buildings, or noise transmittance path (use of noise barriers around the construction site [2–4]. Once the rail line starts to operate then the issue of noise is harder to handle; as a result, enhanced decision making at the initial design stage requires a better understanding of factors that impact noise propagation when the rail line is operated.

Noise from rail tracks is a result of many elements, the most prominent of which is the impact between the wheels of the rolling stock and rough rail surface [5]. Other causes of noise from a rail system are the consequence of sharp turns of the vehicle due to large rail track [6], or the crossing of a vehicle over dipped weld within the track [2]. It is also important to note that there are certain factors which can exacerbate noise levels, and which need to be accounted for when assessing noise generated by a railway system; this includes the turbulent boundary created around the train and the Doppler Effect induced by high speed trains passing a particular point [7].

Noise pollution resulting from rail line operations is reported to be associated with a number of health ailments. Exposure to rail noise during the night leads to sleep disturbances [8]. This in turn creates stress, triggering the sympathetic and endocrine system, and causing a change to blood pressure and heart rate in individuals [9]. There are studies that indicate a link between sleep quality depreciation and railway noise [10]. Others report that lower cognitive performance results following nocturnal railway noise exposure [11]. The cardiovascular system in sleeping subjects was also observed to be impacted by nocturnal railway noise [12]. In some instances, when compared to well documented noise from highways, annoyance of railway noise was found to be similar if not worse [13]. What the majority of studies agree on is the fact that noise disturbance from rail lines is present and requires practical regulatory policies for it to be tackled [3]. Factors that play into the perception of noise are wide and varied; some are even due to socio-cultural traits of a particular region [14]. An imperative factor discussed by [15] that is a strong determinant of noise annoyance reception is the distance between the receiving end to the railways. In addition, train timetable and schedule are thought to have a direct association on the level of noise generated from the rail lines [16]. Even though there are various studies that examine the location of rail stations in the literature [17] and its impact on land value [18,19], their focus has not been on minimising noise pollution from rails when it comes to the location of the stations.

It is thus essential to target more effective measures when addressing the issue of noise pollution of rail lines during the initial design phase. This paper attempts to achieve this through introducing a novel mathematical optimisation model for locating stations of a rapid transit line such that noise pollution is minimised.

2 Problem Description

The problem of locating a transit line or network is concerned with maximising riders' accessibility while minimising rail line construction costs at the same time [20–23]. Accessibility of a transit line is modelled in two ways: in one of the approaches stations are positioned in a manner that ensures maximal service coverage to demand points surrounding the assigned transport corridor. This problem is known in the literature as the maximal coverage shortest path problem [24]. Another approach is to locate the stations so that total travel distance between demand regions and the nearest station located on a line is minimised; in this case the problem is known as the median shortest path problem [25].

For the majority of the work available in the literature the focus has been mainly on objective functions that concern the system's patrons or operators. Little attention has been directed towards modelling the impact that the design of the proposed rail line is likely to cause on the neighboring population in terms of noise.

The problem examined in this paper is concerned with the location of the stations forming the rapid transit line. In order to find optimal locations for the network line, the problem is formulated to minimise the total noise levels reaching receiver points; these receiver points represent surrounding residential zones.

2.1 Measuring Noise Levels in Rail Lines

To assess the effect of rail noise exposure at residential buildings surrounding the rail system, some studies adopt the equivalent noise level assessed over a 24 hour period measure; this is calculated from the sound exposure levels and number of different train types [13]. It is, however, reported in the guidelines published by Environmental Protection Agency (EPA) in Australia that the continuous equivalent noise level (L_{Aeq}) measured over a certain period corresponding to daytime, night-time or the noisiest one hour duration, should be deployed [26].

When it comes to noise estimation from rail-lines, a number of steps needs to be followed. These are based on guidelines published by both EPA and the Department of Transportation [26,27]. The steps are summarised as follows. First, the railway needs to be divided into segments. For each segment, the number of receiver points that will be impacted by the noise need to be mapped. The angle of view of the receivers with respect to each track segment is then calculated.

The second step involves calculating the reference noise level (SEL) for each train that will be operating on tracks. The baseline SEL at a reference of 25m from the train (i.e noise source) is obtained from train manufactures. The baseline SEL will then need to be corrected to account for the number of vehicles in the train. A track correction also needs to be applied to account for the type of tracks and the associated ballast laid.

The third step involves accounting for the distance propagation impact. This will be determined based on the location of the reception point with respect to the tracks. The height of the track below/above the reception point needs to be considered. Ground propagation and air absorption are corrected for. The presence of any barriers around the tracks, separating the track line from the reception points, will also need to be considered in the distance propagation measure. The angle of view from the tracks with respect to the receiver points is also considered in the noise propagation calculations.

The fourth step involves consideration of noise reflection effects due to façade of the reception points (assuming the receiver is a building).

In the fifth step, the SEL is converted into the equivalent continuous noise measure $L_{Aeq,T}$ over the duration of the assessment ($T = 6$ hours usually for nighttime and T = 18 hours for daytime) using the following equations, **Eq. (1) – Eq. (2)**:

$$L_{Aeq,6} = SEL + 10\log_{10} Q_{night} \quad (1)$$

$$L_{Aeq,18h} = SEL - 48.1\log_{10} Q_{day} \quad (2)$$

where Q_{night} and Q_{night} represent the total number of trains predicted to pass the receiving points during the night and day time respectively. The unit of measurement for the equivalent noise level is the A-weighted decibel (dB(A)).

2.2 Mathematical Model

The mathematical optimisation model proposed is a Binary Integer Programming (BIP) model that attempts to find the most suitable rail line configurations associated with the least noise pollution, as measured at the surrounding population. The objective function and constraints formulated to address the problem are described next

2.2.1 Notation

The notation adopted in the proposed model is presented in **Table 1.**

Table 1 Notation Set

Notation	Description
O	Set of potential origin stations
D	Set of potential destination stations
$k \in O \cup D \subseteq K$	Set of all potential stations
$r \in R$	Set of noise-sensitive receivers
P	Maximum number of stations on a transit line
N_{kr}	Noise levels resulting at receiver point $r \in R$ due to train passing potential station $k \in K$
z_k	Binary variable, which equals 1 if station k is selected, and 0 otherwise
x_{ik}	Binary variable, which equals 1 if potential stations i and k are connected, and zero otherwise

2.2.2 Objective function

The objective function captures the maximum noise disruption that is caused at each potential station location and is formulated as shown in **Eq. (3)**:

$$\text{minimise} \quad \sum_{k \in K} \max_{r \in R}\{N_{kr}\} z_k \quad (3)$$

In particular, the final equivalent continuous noise measure is mapped onto the noise parameter N_{kr} (i.e. $L_{Aeq,6} \rightarrow N_{kr}$).

2.2.3 Constraint Type 1: Origin & Destination Stations

The start and end of the transit line is determined by the choice of the origin and destination stations. **Eq. (4)** is defined to locate an origin station, while **Eq. (5)** defines the location of a destination station

$$\sum_{k \in O} z_k = 1 \quad (4)$$

$$\sum_{k \in D} z_k = 1 \quad (5)$$

2.2.4 Constraint Type 2: Connectivity

There needs to be a constraint defined to ensure that all selected stations are connected. Two types of equations are formulated: one is for stations that are either the origin or destination station, where these require to be connected to 1 other station. In particular, **Eq. (6)** is formulated for connecting the chosen origin station with another interim station on the line. **Eq. (7)** on the other hand is defined to link the chosen destination stations with other interim stations on the line.

The second type of connectivity constraints is associated with interim stations (not origin or destination stations), given that these require to be connected to 2 other stations. This is achieved through **Eq. (8)**

$$x_{ij} = z_i z_j \quad \forall i \in O, \forall j \in K / O \cup D \quad (6)$$

$$x_{ij} = z_i z_j \quad \forall i \in K / O \cup D, \forall j \in D \quad (7)$$

$$\sum_{i<k} x_{ik} + \sum_{j>k} x_{kj} = 2z_k \quad \forall k \in K \setminus O \cup D \tag{8}$$

2.2.5 Constraint Type 3: Sub-tour elimination constraints

Only a single continuous tour, representing the route of the rapid transit, is to be produced as the final solution, as opposed to two or more disjoint sub-tours. The algorithm is prevented from creating sub-tours by introducing **Eq. (9)** in the model:

$$\sum_{j \in K} \sum_{\substack{i \in K \\ i \neq j}} x_{ij} \leq |S| - 1 \tag{9}$$

2.2.6 Domain of variables

The domain of the variables used in the model is given in **Eq. (10) – Eq. (11)**:

$$z_i \in \{0,1\} \quad \forall i \in K \tag{10}$$

$$x_{ij} \in \{0,1\} \quad \forall i, j \in K : i < j \tag{11}$$

3 Case Study and Discussion

In order to display the applicability of the model, a realistic case study is examined. The case study, a simplified representation of a future rail project to take place in Doha, Qatar, comprises a single track railway. For the purpose of this study, only 1 type of train is assumed to traverse the rails. The section of the train to be designed is assumed to be a straight line segment. Average speed of the train across the rail way system is set at 150 km/h. A total of 179 train passes are assumed during the day, while the number drops to 17 passes during the night. The area between the track and the reception point is assumed to be flat. The region under consideration, with residential areas, and potential station locations, is highlighted in **Fig. 1**. In particular, the potential station locations for the origin and destination nodes of the rapid transit line to be constructed are highlighted by the circulated zones in **Fig. 1**. **Table 2** displays the noise analysis conducted at each residential node.

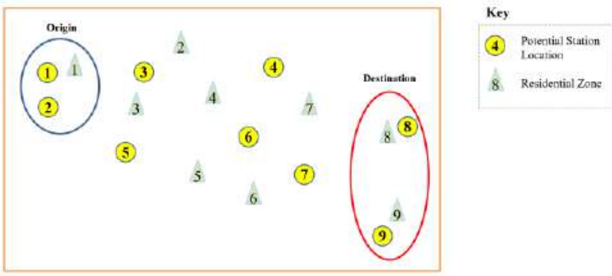

Fig. 1 Case study representation

The model is programmed in GAMS [28] and solved using CPLEX [29], on a desktop computer running on Microsoft Windows 10 operating system, with Intel core i7 processor at 3.4 GHz and 16GB of RAM. The computation time was recorded at 73 seconds, for the algorithm to reach an optimal solution with 0% optimality gap. The solution produced is given as follows:

2 → 5 →6 →7→9

where the origin of the rapid transit line starts at Node 2, and the destination node is at Node 9. The average noise pollution of the overall proposed rail line route is assessed to be around 68 dB (A).

Table 2 Noise level in dB (A) at each station

Residential Nodes $r \in R$	$(N_{1r}, \cdots, N_{9r})$
1	(91,83,63,43,51,47,34,20,20)
2	(64,62,91,80,72,71,55,42,20)
3	(71,72,93,73,101,61,53,42,20)
4	(51,53,73,84,65,96,78,61,45)
5	(40,56,61,43,82,94,81,64,53)
6	(31,43,45,52,65,82,92,66,51)
7	(23,32,51,74,54,81,91,64,55)
8	(20,20,32,53,45,55,71,101,83)
9	(20,20,33,41,43,62,81,92,103)

The solution yielded by the proposed model is contrasted with an approach that is based on selecting the route with the least overall cost; this can be achieved by minimising the travel distance and number of stations respectively. The results are displayed in **Table 3**. It is clear that some sort of trade-off exists between the two contrasted models. The mimimum noise model produces a solution that is 22% less noise intensive than that of the minimum construction cost model. The cost of construction associated with the minimum cost model is however 39% higher. It is important to note that this is only case specific and there can be instances where the solution that minimises the noise pollution due to the operations of the rail line is also the one that minimises the construction cost. What the test highlights however is the need to consider the trade-off between other factors impacting the design of rapid transit lines in urban regions.

Table 3 Noise level in dB (A) at each station

Model	Average Noise Level (dB(A))	Monetary Cost ($ AUD)
Minimum Noise Model	68	123,909
Minimum Construction Cost Model	87	75,444

4 Conclusion

In this study a novel mathematical optimisation model was presented, based on a binary integer programming approach, to minimise the noise pollution associated with the operation of an urban rapid transit line. The model optimises the locations of stations making up the rail line, through forming a continuous link between the selected stations, while minimising the noise levels measured at receiving points along the track. The proposed model can therefore act as a decision support tool to rail line designers at the initial planning phases of the project in order to reflect considerations for the sustainability of the rail track.

In order to test the applicability of the model, a realistic case example was examined. In addition, the solution yielded by the proposed model was also contrasted against one that was based on minimising the construction cost of the rail line. Results revealed that a drop of 22% can be achieved if noise is optimised, as opposed to construction cost. The solution produced by the cost minimisation model however yielded a track that was 39% cheaper. A trade-off was therefore realized between the two models for the case study considered.

The proposed model is formulated for new rail lines proposed in an urban region. With slight modification, the model can also be adopted to account for incorporation of one or more stations to an existing line. Future work will be focusing on developing a multi-objective optimisation model that accounts for social, environmental and economic aspects of rail line route design.

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Persuasive Effects of Immersion in Virtual Environments for Measuring Pro-Environmental Behaviors

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Abstract –

In this study, we investigated the effects of immersive vs. non-immersive virtual environment (VE) platforms (i.e., head mounted display (HMD) vs. laptop PC) on compliance with pro-environmental behaviors. We performed a detailed analysis of the effects of these VE platforms on other variables, such as task performance, sense of presence, and simulator sickness. We also explored the factors, such as participants' gender and immersive tendency that could have influenced the effects of VE platforms. In a between subject design, 100 participants were randomly assigned to interact with either a desktop or an HMD. The results showed no significant effects of VE platforms on compliance with pro-environmental requests, task performance, and sense of presence. However, the HMD elicited higher simulator sickness compared to the desktop display. In addition, we demonstrated there was a strong relationship between participants' immersive tendency and the presence that they experienced. Our findings provide empirical evidence capable of helping researchers select an appropriate VE platform when investigating the influence of behavioral interventions aim to promote sustainable behaviors.

Keywords –

Virtual environments; pro-environmental behavior; immersion; presence; simulator sickness; compliance

1 Introduction

To study occupant behavior in general and occupants' interactions with buildings, many studies used immersive virtual environments to collect occupant-related data [1-3]. For example, Heydarian et al. used immersive virtual environments to collect data on occupants' lighting-related behaviors and preference. They used the data to investigate the design alternatives aiming to meet occupants lighting preferences while increasing building's energy efficiency [2]. Saeidi et al. investigated the effectiveness of IVEs to be used as a tool to collect data on occupant behavior. They suggested that IVEs can be more valuable tools if they are used during the design stage of the building to define the main drivers of occupants' lighting behaviors in buildings [4]. Virtual environments (VEs) are also increasingly used for scientifically studying the effects of communication in different persuasive contexts (e.g., health, advertising, and education) on human behavior by enhancing the experimental designs in a controlled manner [5-7]. However, the VE systems that have been used across different studies vary in their dimensions specifically in their level of immersion, the degree to which a system can "deliver an extensive, inclusive, surrounding, and vivid illusion of virtual environment to a user [8]." Immersion is one of the main factors required to enable the users to perceive all aspects of the space to create lifelike impression [9]. Choice of an appropriate system for a specific application impacts the effectiveness of VEs [10]. VEs are mostly characterized based on their platforms (e.g., desktop/laptop PC, head mounted display (HMD), etc.). However, there is no guideline leading us to the selection of an appropriate platform. One of the main considerations in the selection of appropriate VE platform is the level of immersion, which is often linked to the sense of presence and simulator sickness (motion sickness experienced during an interaction with a VE) experienced by users of those environments. "Presence is defined as the subjective experience of being in one place or environment, even when one is physically situated in another [11]."

Studies have used different VE platforms varying from a simple desktop/laptop computer with standard monitors to more immersive environments like HMD, in which users wear the computer display on their head to be immersed, and later to a fully immersive environment, like Cave Automatic Virtual Environment (CAVE), in which users move around in a room where they are completely surrounded with computer projected displays.

Each platform has different characteristics and user interfaces. Selection of the VE platform could impact the behavioral responses of participants engaging with the VEs [5]. However, it is relatively unclear whether the level of immersion, sense of presence, and simulator sickness experienced through different VE platforms influence user performance and behavior. Often, the effects of VE platforms on performance and behavior appear to be overshadowed by other factors, such as task context and user characteristics (e.g., age, gender, and previous experience with VEs) [12,13].

Several studies have been completed to investigate this issue and compared various platforms with each other in different contexts. In this study, we investigated the influence of VE platforms on measuring compliance with pro-environmental requests. We compared a non-immersive VE (i.e., laptop PC) with an immersive VE platform (i.e., HMD). To explore the factors that could influence the effects of VE platforms, we conducted an experiment, in which we investigated the effects of sense of presence and simulator sickness on user experience while interacting with different VE platforms: a laptop computer with a standard monitor and a laptop computer with a head mounted display system (laptop PC vs. HMD) and the effects of these factors on compliance with pro-environmental requests and task performance. In addition, we examined other factors, including users' gender, immersive tendency, and previous experience with VEs that could impact the effects of VE platforms on compliance. Immersive tendency refers to individual differences in the proclivity to become immersed in a simulation and previous experience with VE, like playing video games, can influence the immersive tendency [11].

2 Background

A common assumption about virtual environments is that increased immersion is associated with higher experienced presence and it results in enhanced task performance and behavior change. However, research shows that there are conflicting views on whether the level of immersion impacts the user's experienced presence, performance, and behavior. For example, Gorini et al. [14] tested the effects of a VE platform (immersive vs. non-immersive) and narrative context (emotional vs. non-emotional) on the users' experienced presence. Their results suggested that both immersion and context have a significant role in generating an effective VR experience as they contribute to increasing the feeling of presence from different aspects. In another study, Grassi et al. [15] investigated the effects of different platforms (mobile phone, desktop PC, and HMD) as well as emotional context (amusement, sadness, fear, and neutral) on the sense of presence and the results showed that platform type did not impact the sense of presence while the emotional context did impact the sense of presence.

User characteristics (e.g., gender, immersive tendency, and previous experience with VEs) can also influence sense of presence. Sense of presence and performance in VEs is likely to increase when user is familiar with the VEs and has higher immersive tendency. However, other studies found no relationship between sense of presence and immersive tendency and VE experience. A study conducted by Nowak et al. [16], investigating causes and consequences of presence in the context of violent video games, showed that user's characteristics (previous game experience and gender) can predict presence. In another study, Schuemie et al. [17] exposed participants to a virtual environment for phobia treatment and they found no correlation between sense of presence and gender or experience with VEs. These findings suggest that a user's sense of presence in a VE might not be influenced only by the characteristics of the VR platform; but also by context of the task performed and the characteristics of the individual user (e.g., gender and previous experience with VEs) [18].

A review of the relationship between the level of immersion and performance in VEs revealed that a positive relationship exists between the level of immersion and behavioral responses and performance. For example, Kim et al. [5] investigated whether different VE platforms (desktop PC, HMD, and CAVE) induce different patterns of emotional responses in contexts including high- and low-stress tasks. The results of their study suggested that immersive virtual environments (either an HMD or fully immersive VE platform) were more effective than a standard desktop PC in eliciting emotional arousal.

Simulator sickness might also influence user's experience of VEs. For example, Kim et al. [5] investigated the effects of different VE platforms (desktop, HMD, and CAVE) on simulator sickness while completing stressful tasks. The results showed that HMD induced significantly more simulator sickness than the CAVE and the desktop.

In summary, the level of immersion in different VE platforms could influence the sense of presence and simulator sickness symptoms and might also impact user behavior and performance. However, these effects might be mediated by the context of the task and user characteristics.

Previous studies mostly focused on performance measures in contexts that involve navigation or visualization and behavioral responses in psychological settings. Less has been done to investigate behavioral responses in social contexts, in which people interact with each other to influence each other's behaviors and attitudes. In this study, we investigated whether different VE platforms with different levels of immersion elicit different behavioral responses to persuasive pro-environmental requests.

3 Present study

We conducted an experiment to examine the compliance with persuasive pro-environmental requests and performance, using an office related task across two representative VE platforms, which varied in their level of immersion but used the same technology to interact with the environment (an Xbox controller). As the VE platform with lower level of immersion, we used a standard laptop. As the VE platform with higher level of immersion, we used Oculus DK2 Head-Mounted Display to provide an immersive environment, in which a positional tracker would track the participants' head and neck movements (Figure 1). The virtual environment represented a single occupancy office space and was identical in both the desktop and HMD conditions.

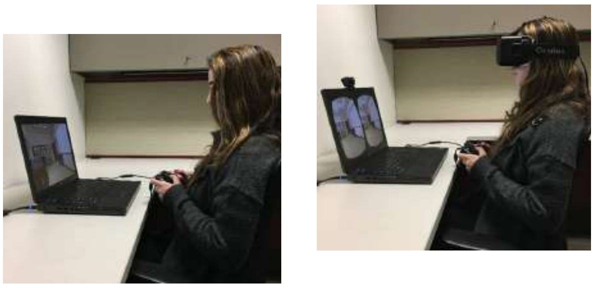

Figure 1 – Different VE platforms: laptop display (left); HMD (right)

We investigated the following dependent variables: (a) compliance with the pro-environmental request, (b) task performance, (c) presence, and (d) simulator sickness. Considering that research shows contradictory findings regarding the influence of the level of immersion as a characteristic of VE platforms on the sense of presence, behavior change, and performance, and these effects have not been investigated before in social contexts that aim to influence behavior, we could not hypothesize whether different VE platforms would generate different levels of presence or influence the compliance with the persuasive pro-environmental requests or task performance in the context of our study. Therefore, we investigated the following questions: (1) Do different VE platforms (desktop vs. HMD) influence the compliance with pro-environmental requests? (2) Do different VE platforms (desktop vs. HMD) influence the presence experienced by the participants during the experiment? (3) Do different VE platforms (desktop vs. HMD) influence the performance on the assigned task (reading a passage and answering some questions about it)? Considering that user characteristics can be another factor that influence the sense of presence, we also investigated the following questions: (4) Do different VE platforms influence the simulator sickness participants experienced while interacting with the environment? and 5) Do participants' characteristics (immersive tendency, previous VE experience, and gender) influence the presence that they experienced during the experiment? We also investigated the interaction between the sense of presence and effects of VE platform type on compliance with pro-environmental behaviors, as well as the task performance. The same for the interaction between simulator sickness and effects of VE platform type on compliance with the pro-environmental behavior and task performance.

3.1 Design

Pro-environmental requests included contents requesting participants to change the light level and temperature setpoint using the principles of reciprocation, which is a social influence method. A female avatar, representing the building manager, delivered the request since the adopted social influence method and delivery style were found to be among the most effective ones [19,20]. Participants were randomly assigned to one of the two experimental groups: laptop group, in which participants interacted with VE using a standard laptop without an HMD, and the HMD group, in which participants were immersed in a VE using an HMD. The only difference between these two groups was the platforms used for interacting with the VE.

3.2 Virtual Office Environment

The model was first generated in Revit© and then exported to 3D Max© to add materials, furniture, texture, lighting, reflection, and shadows in order to make it look more photo realistic. Then it was imported to Unity© game engine to program interactive options, such as opening/closing windows and turning on/off lights (Figure 2).

Figure 2 – Virtual Office

3.3 Procedure

As the first step of the experiment, participants were asked to complete a questionnaire covering general questions, including their age, gender, immersive tendency and previous experience with VE, and simulator sickness symptoms.

The Immersive Tendency Questionnaire (ITQ) was developed by Witmer and Singer [11] to measure the tendency or capabilities of individuals to be involved or immersed in a virtual environment. Simulator Sickness Questionnaire (SSQ) was developed by Kennedy et al [21] to measure the level of simulator sickness symptoms in a VE system. Prior to the main VE task, participants underwent training to become familiar with the virtual environments in which we showed them how to work with VE platforms and different settings in the virtual environment.

After the training session, we explained the experiment procedure to the participants. The procedure was as following: participants had to sit on a chair in an office and perform a very common office related activity: reading a document (two passages in this study). They were asked to read the passages very carefully as they had to answer comprehension questions about them. During the experiment, a female avatar representing the building manager would communicate with them (Figure 3).

Figure 3 – Pro-environmental requests delivered to the participant in the VE

Participants were told to pay attention to the requests carefully, as they would be asked what the requests were at the end of the experiment. However, it was noted that it was completely up to the participants whether to comply or not with the requests, and that they had to act as they would in their own offices. While participants were reading the passages, a request was delivered to them (30 seconds after starting the task). Two different pro-environmental requests were delivered to each participant: (1) “if I open the blinds for you to have natural light, would you please dim or turn off the artificial lights?”; and (2) “if I open the window for you to have a breeze and fresh air, would you please increase the temperature setting on the thermostat?”

The default lighting setting in the office room was the artificial lights on while the blind was closed and the default temperature setpoint was 73˚F. If the participants chose to comply with the pro-environmental request, they had to go to the light switch and lower the level of lights or turn them off while the blind was open. Likewise, if the participants chose to comply with the other pro-environmental request, they had to go to thermostat and increase the temperature setpoint. We observed the participants’ compliance with the requests in the assigned conditions (laptop vs. HMD). In addition, we assessed the participants’ performance by measuring the time that they spent on reading each passage and their reading comprehension (number of correctly answered questions).

After completing the virtual part of the experiment, the participants completed the post-experiment questionnaires. The first questionnaire assessed how participant’s values and attitudes resembled the environmentalists’ values and attitudes. The second questionnaire assessed the participants’ environmental setpoint preferences: preferences for lighting sources (daylighting vs. artificial lighting), lighting levels (amount of lighting), and temperature setpoint. As the last set of questionnaires, the participants completed two questionnaires investigating their sense of presence in the VEs: the Witmer and Singer Presence Questionnaire (PQ) [11] which measures the degree of presence and engagement that individuals experience in a virtual environment and the Slater, Usoh and Steed Presence Questionnaire [22], which focused mainly on psychological and behavioral response to immersion and involvement. Finally, participants completed the Simulator Sickness Questionnaire (SSQ). The participants had also completed the SSQ in the pre-experiment session so that their pre- and post-test scores could be compared to identify simulator sickness caused by interacting with VEs. The entire experiment took about 40 minutes.

4 Results

The results presented here are based on 100 participants (66 females and 34 males) recruited through the USC psychology subject pool who received course credits for their participation.

In order to analyze the data, we compared the compliance and other dependent measures including presence, task performance, and simulator sickness between the two types of VE platforms. We also investigated the effects of other factors, such as participants’ characteristics (i.e., gender and immersive tendency), on the dependent measures.

To examine the effect of the VE platforms on compliance with pro-environmental requests, we conducted an independent sample T-test (laptop PC vs. HMD) on the number of times participants chose to comply with the pro-environmental requests. There were no significant differences in the number of times that participants complied with the request in the laptop PC ($M = 1.30$, $SD = .81$) and HMD ($M = 1.20$, $SD = .83$)

conditions: t(98) = .61 , p = .54. These results suggested that the level of immersion does not influence the participants' decision regarding compliance with the pro-environmental request. We also checked the possible factors that might have impacted the compliance including participants' preferred source of lighting, preferred lighting level and temperature setpoint, and identification with environmentalists. Using linear regression analysis, the results showed no main effects of these factors on compliance: preferred source of lighting (β = -.05, p = .61), preferred lighting level (β = -.04, p = .67), preferred temperature setpoint (β= .01, p = .89), and identification with environmentalists (β = -.11, p = .26).

We also investigated the influence of VE platforms on task performance. As a measure of task performance, we computed the average time to read the passages in two different conditions (laptop PC vs. HMD). Using an independent sample T-test, the results showed that there were no significant differences in the average time that the participants spent reading the passages in the laptop PC (M = 57.97, SD = 15.63) and HMD (M = 60.04, SD = 17.86) conditions: t(98) = .53 , p = .25. In addition, we measured participants' reading comprehension by computing the number of correct answers to the questions that were asked about the passages. The results showed no significant difference in participants' reading comprehension in the laptop PC (M = 7.76, SD = 1.33) and HMD (M = 7.58, SD = 1.37) conditions: t(98) = .81, p = .51, suggesting that participants performed in the same way in both conditions.

We examined the sense of presence using the two presence questionnaires. Investigating the effects of VE platforms on presence using the questionnaire developed by Witmer and Singer, conducting independent sample T-test, the results showed no significant difference in the sense of presence experienced in the laptop PC (M = 89.10, SD = 15.25) and HMD (M = 91.90, SD = 18.22) conditions: t(98) = -.83 , p = .41. In analyzing the data from the Slater-Usoh- Steed Presence Questionnaire, using linear regression analysis, the results showed no significant difference in sense of presence experienced by different VE platforms: β= .14, p = .15.

Next, we investigated the interaction between the VE platforms and sense of presence (using the Witmer and Singer's questionnaire) by linear regression analysis. The results showed no interaction between the laptop PC (0) vs. HMD (1) dummy-coded variable and sense of presence measuring compliance (β = -.40, p = .56) and performance, both average time completion (β = .21, p = .75) and reading comprehension (β = .18, p = .79). The same results were observed for Slater-Usoh- Steed Presence Questionnaire: no interaction between VE platform and sense of presence measuring compliance (β = -.51, p = .15) and performance, both average time completion (β= .24, p = .51) and reading comprehension (β= -.29, p = .41).

Results of a mixed ANOVA on participants' simulator sickness symptoms before and after exposure to VE as well as within subjects effect and platform type and between subjects effects revealed significant interaction effects for simulator sickness (pre vs. post participation) and VE platform type (F(1, 98) = 8.24, p = .005). Accordingly, we conducted independent samples T-tests to examine the effect of VE platform type on participants' level of simulator sickness both before and after the experiment. The results showed no significant differences in the participants' level of simulator sickness before the experiment in both laptop PC (M = 154.32, SD =149.63) and HMD (M = 166.81, SD = 187.44) conditions: t(98) = -.37 , p = .71. However, there was a significant difference when comparing the participants' levels of simulator sickness after the experiment, such that participants experienced greater motion sickness in the HMD condition (M = 1073.89, SD = 276.56) than the laptop PC condition (M = 974.76, SD =198.59), t(98) = -2.06 , p = .04. We also investigated the interaction effects of VE platform type and simulator sickness on compliance and performance. The results of analysis showed that the interaction of VE platform type and simulator sickness did not have any significant effects on compliance with pro-environmental requests (β = -.12, p = .81) and performance, both average reading time (β = -.84, p = .1) and reading comprehension (β = -.29, p = .56).

We used the immersive tendency questionnaire to investigate if participants' characteristics influenced the sense of presence they experienced in VEs. We also tested the two experimental groups to ensure that there was not failure of random assignment (i.e., there were no significant differences between conditions in participants' levels of immersive tendency). Using independent sample T-tests, the results showed no significant differences between participants immersive tendency in the laptop PC (M = 67.62, SD = 10.54) and HMD (M = 69.76, SD = 11.40) conditions: t(98) = -.97 , p = .33.

Next, we examined if the participants' immersive tendency influenced the presence they experienced in the VE, as well as their performance and compliance with the pro-environmental requests using linear regression and correlation analyses. We used the presence data collected by the Witmer and Singer's presence questionnaire as this presence questionnaire as well as the immersive tendency questionnaire were both developed by Witmer and Singer. The results showed significant effects of immersive tendency on the sense of presence, meaning that participants with higher level of immersive tendency experienced higher sense of presence (β = .26, p = .01). A person, who is more likely to become immersed in a VE, will experience a greater sense of presence while interacting with a VE. These results suggested that participants, who had the ability to get deeply involved in an activity or a stimulus, such as books or movies showing a tendency to maintain focus on that activity, were more likely to experience higher presence in the virtual environment; participants' tendency to play video games was not an effective factor causing sense of presence.

The effects of immersive tendency on the sense of presence were independent of the platform type and no significant interaction effects were found for platform type and immersive tendency (β = .5, p = .38). No significant effects were found for immersive tendency on compliance with pro-environmental request (β = .09, p = .66) and performance: average time (β = .08, p = .45) and reading comprehension (β = -.06, p = .52). Also no significant effects were found for the interaction of platform type and immersive tendency on the compliance with pro-environmental request (β = -.30, p = .66) and performance, both average time (β = -.53, p = .43) and reading comprehension (β = -.94, p = .16).

In addition, we used regression analyses to examine whether the participants' gender had any effects on compliance, presence, and performance or moderated impacts of VE platforms. There were no interaction effects of gender and VE platforms on compliance, presence, and performance (Table 1).

Table 1 – Gender main effects and interaction effects with VE platforms on compliance, presence, and performance

Dependent Measure	Between Subject Measure	Beta	t
Compliance	Gender (Interaction with platform type)	.20	.32
Presence (Witmer and Singer)		-.20	.33
Presence (Slater-Usoh- Steed)		-.06	.76
Performance (Average Reading Time)		-.01	.97
Performance (Reading Comprehension)		.20	.31

Note. †p< .1;*p< .05;**p< .01; ***p < .001

5 Discussion and Conclusions

Overall, the results of this study showed no significant differences in the participants' sense of presence and performance while interacting with two different VE platforms that varied in their level of immersion. In addition, there was no significant difference in participants' compliance rates in the laptop PC and HMD conditions. We also investigated the relationship between the occurrence of simulator sickness symptoms and VE platforms, compliance, and task performance. Results of our study showed HMD-based VE induced a higher level of simulator sickness. These results suggest that studies designed with the aim of minimizing simulator sickness symptoms may take advantage of using a laptop PC over an HMD [5].

We also found no relationship between participants' gender and their sense of presence, behavior and performance. In addition, we found no relationship between participants' immersive tendency and their behavior and performance. On the other hand, the results showed that there was a strong relationship between participants' immersive tendency and the presence they experienced. The participants with higher immersive tendency experienced higher sense of presence, however, these effects were independent of the type of VE platforms. We also found that individuals' tendency to become involved in situations and maintain focus on current activities can predict the presence that they experience in the VE and their previous gaming experience is not an influential factor.

This study provides findings about possible benefits and limitations of using immersive and non-immersive VE systems in a study examining the effectiveness of persuasive requests. However, there are limitations. For example, we only used two kinds of VE platforms. Although a laptop and a HMD are appropriate representations of non-immersive and immersive VE technologies, different types of VE platforms (e.g., fully immersive virtual environments like CAVE) can be addressed in future studies to continue to characterize the effects of these different VE systems on user behaviors. We plan to conduct future studies investigating the advantages and disadvantages of using different VE platforms in research on behavior change replicating and extending the findings using other behavioral contexts in buildings, such as security and comfort. Our study can also guide similar studies by comparing the effectiveness of different VE platforms and by investigating the potential factors that impact the effectiveness of these platforms.

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ESTIMATING CONSTRUCTION WORKERS' PHYSICAL WORKLOAD BY FUSING COMPUTER VISION AND SMART INSOLE TECHNOLOGIES

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Abstract –

Construction workers are commonly subjected to ergonomic risks due to awkward postures and/or excessive manual material handling. Accurate ergonomic assessment will facilitate ergonomic risk identification and the subsequent mitigation. Traditional assessment methods such as visual observation and on-body sensors rely on subjective judgement and are intrusive in nature. To cope up with the limitations of the existing technologies, a computer vision and smart insole-based joint-level ergonomic workload calculation methodology is proposed for construction workers. Accordingly, this method could provide an objective and detailed ergonomic assessment for various construction tasks. Firstly, construction workers' skeleton data is extracted using a smartphone camera with an advanced deep learning algorithm. Secondly, smart insoles are used to quantify the plantar pressures while the worker performs a construction activity. Finally, the gathered data is fed to an inverse dynamic model in order to calculate the joint torques and workloads. The aforementioned approach was tested with experiments comprising simulations of material handling, plastering and rebar. The results reveal that the developed methodology has the potential to provide detailed and accurate ergonomic assessment. Overall, this research contributes to the knowledge of occupational safety and health in construction management by providing a novel approach to assess the risk factors of work-related musculoskeletal disorders (WMSDs).

Keywords –

Construction worker; Occupational health and safety; Deep learning; Machine learning

1 Introduction

Workplace safety and health is an important issue in construction industry around the globe. One of the main reasons is the highly physical demanding nature of the construction tasks [1]. Repetitive and prolonged working could increase the possibility of fatigue, which in turn could result in decrease in attention and accidents in worst case scenarios [2]. In addition, fatigue might decrease construction workers productivity [3] and develop work-related musculoskeletal disorders (WMSDs) [4]. Considering the significant negative influences of physically demanding workload on construction workers, it is important to provide precise workload assessments for its mitigation. Manual observation is frequently used to estimate construction workers' physical workload based on workers' postures and external loads. However, due to the subjectivity of the observed data and inability to quantify the loads, the assessments appear to be not accurate enough. Additionally, it entails increased requirement of safety management staff on the construction sites. To get more objective and precise quantification of workload, biomechanical measurement devices were introduced to facilitate workload analysis [1]. Although these studies have proven the concept, they are intrusive in nature, requiring multiple sensors to be attached to the body of construction workers. As such, on-body sensors are uncomfortable to wear and could easily instigate irritation.

Considering the limitations of the aforementioned methodologies, this research proposes a blend of computer vision technology and smart insoles for workload assessment of the construction workers. The proposed methodology could provide a novel non-intrusive method to quantify the workload. First, a computer vision-based 3D motion capture algorithm is developed that could model the motion of various body parts while performing construction tasks using a RGB camera. Second, smart insoles equipped with multiple pressure sensors are used to capture workers' plantar pressure distribution. These pressure sensors would register the plantar pressure due to self-weight of the construction workers and other forces while carrying load, operating tools and performing related activities. Together with the 3D joint-model data from the developed motion capture algorithm and pressure data from the insoles, inverse dynamic modelling will be applied to calculate the joint-level torques. Subsequently, these torques will be used to calculate workload and plan ergonomic risks` mitigation strategies.

2 Literature Review

The purpose of this review is to provide an understanding of the previous research in this area as well as providing a rationale for the choice of workload assessment and data collection methods used in the present study. We begin with a review of the definitions and influences of workloads; three workload assessment methods, including self-report, observation and biomechanical analysis, are then reviewed and compared; this is followed by a discussion of the behaviour data collection methods used previously in the construction context.

2.1 Definition of Physical Workload

Workload refers to all of the factors that constitute a challenge which a worker has to surpass in order to perform a task, including physical workload and mental workload [5]. This research focuses on physical workload because: 1) physical workload has been proven to be one of the major risk factors of acute trauma injury and cumulative musculoskeletal disorders [6]; 2) it is more practical to provide a relatively objective and quantitative assessment of physical workload. It should be noted that physical workload can be assessed in two different ways namely biomechanical load and cardiovascular load [7]. Biomechanical load measures the workload as a set of torques applied on a human body resulting from the task which he performs, while cardiovascular workload is defined by the physiological changes in the human body as a response to an external task (e.g. heart rate, breathing frequency, core temperature). Biomechanical workload can be measured with non-intrusive methods such as observation and non-contact sensors (e.g. cameras). Besides, biomechanical load has more clear relation with external load and work postures [8]. Therefore, this research assesses physical workload from the biomechanical perspective.

2.2 Previous Workload Assessment Methods

The self-report-based workload assessment method focuses on workers' subjective ergonomic feelings and self-assessment on physical discomfort. For example, NASA-TLX (Task Load Index) scores workload from six aspects such as mental demand and frustration [9]. Borg RPE scale (Borg Rating of Perceived Exertion Scale) was developed to describe perceived work load [10]. Questionnaires and interviews are the main data collection approaches in these methods, making data collection time- and effort- consuming.

Observation-based methods are another kind of widely-used methods. Many workload assessment methods have been developed based on visual assessment of the work being performed and response of the worker to that work (e.g. work posture, external load, repetitive and duration). These methods include but are not limited to OCRA (Occupational Repetitive Actions, RULA (Rapid Upper Limb Assessment), and REBA (Rapid Entire Body Assessment). Although these methods are easy to use and can provide a rough workload assessment, they are prone to subjectivity and requires dedicated safety personnel. Additionally, these methods focus on different aspects of workload constructions (i.e. some of them do not consider work repetition). As a result, assessing the same workload with different methods may lead to different results [11].

Biomechanical analysis has also been applied in various cases to provide workload assessment. [12] applied biomechanical methods to explore the relation between work posture and workload during insertion of pin connectors. [13] determined low back pain risks with biomechanical analysis. Biomechanical methods have also been successfully applied in construction industries to facilitate determination of work-rest schedule using simulations [14].

Theoretically, biomechanics analysis can be applied to all parts of body while examining any work task [11]. Since biomechanical analysis require precise information of orientation of various body parts and their movements, traditional observation-based methods cannot be used. Traditionally, an integrated system of multiple cameras has been used for this purpose under laboratory conditions. As such, this approach could be used for actual construction sites where deployment of such system is not feasible [15,16]. Accordingly, researchers have adopted various other technologies to bridge this gap which are discussed in the following section.

2.3 Automatic Data Collection Methods for Workload Assessment

Posture data and biomechanical data are the data foundations of biomechanical analysis. This section reviewed and compared current posture and external load data collection methods.

2.3.1 Automatic Posture Data Collection

One of the widely-used motion capture sensor system is inertial measurement unit (IMU). If attached to key joints, IMU sensors are able to capture the location and acceleration of the joints, and the human body motion data can thus be retrieved [17]. The main disadvantage is the intrusiveness. IMU sensors are required to be tied tightly to human body, but from the view of application, workers may reject wearing sensors so tightly. Such sensors are feasible for short-period track but may instigate irritation if used for long-time [18,19].

With the development of computer vision, various video-based methods are proposed to collect worker's posture data. Compared with sensors, cameras are less intrusive and inexpensive. Several previous studies have applied vision-based methods in construction management, for example, RGBD sensors have been used to recognize workers action [20], whereas depth cameras have been used to capture worker joint angles [21]. The study also found that although depth camera is an efficient tool to collect posture data for ergonomic/biomechanical evaluation but is not appropriate for construction sites because it cannot work under direct sunlight and requires the subject to be in near vicinity. Other researchers extracted posture information based on RGB pictures from ordinary cameras. For example, [14] proposed computer vision-based framework to identify construction activities from 2D image sequences. [17] used ordinary cameras to capture worker's posture. However, the major limitation of these methods is that they can only provide 2D postures of construction workers, which cannot support 3D biomechanical analysis of construction workers.

A recent progress in computer vision shed lights on video-based joint level biomechanical assessment. A newly developed computer vision algorithm can estimate 3D human skeleton from 2D video frames, making it possible to collect joint angles just based on videos [22]. By combining the state-of-art computer vision algorithm, this research aims at developing an accurate, real-time, and non-intrusive ergonomic assessment method which is suitable for both indoor and outdoor environments.

2.3.2 Automatic External Load Data Collection

Most of previous methods didn't quantify the external loads and performed ergonomic assessments solely using posture related data. Insole-shaped plantar pressure sensor is an efficient tool to collect external load data, which can quantify the ground reaction forces from both feet non-intrusively [23]. Recently, [24] demonstrated the potential of applying smart insole to collect construction workers' plantar pressure in working status without interfering normal construction activities. Similarly, this research has used smart insoles to continuously collect the ground reaction forces for the calculation of external loads in order to perform biomechanical analysis. By combining computer vision-based posture data and smart insoles-based external workload,

This research provides an automatic workload assessment measurement methodology. Such method could provide relatively accurate and objective workload assessment for construction workers as compared to previously on-site adopted methods, which will help the managers to better understand the ergonomic risks and provide data foundation for ergonomic improvements.

3 Methodology

Figure 1 depicts the flowchart of the proposed construction worker's workload evaluation method. The first row in Figure 1 represents the input data, including anthropology information (age, gender, weight and height), RGB video from smart phone camera and plantar pressure data from plantar-shaped pressure sensors. Then joint capacity was calculated based on joint capacity prediction equation. 3D skeletons consisting of the xyz coordinates of key joints are generated from the RGB video frames based on a computer vision algorithm. External loads are calculated based on plantar data. Next, the 3D skeleton data and the external load data are used to calculate joint torques with biomechanical analysis. Finally, the workload is assessed by comparing the joint torques and joint capacity.

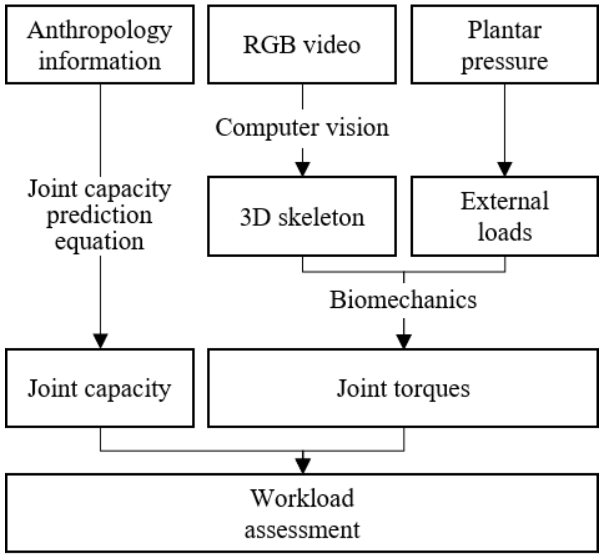

Figure 1. The outline of the automatic workload assessment method

3.1 3D Pose Capture from 3D Images

The workflow of the 3D pose estimator is shown in Figure 2. First, RGB images are collected from construction video clips. A deep learning architecture, named hourglass network (Newell et al., 2016) is trained to estimate the 2D coordinates of joints. Then the joint length ratio constrains are used to estimate the 3D coordinates of the various body joints [22].

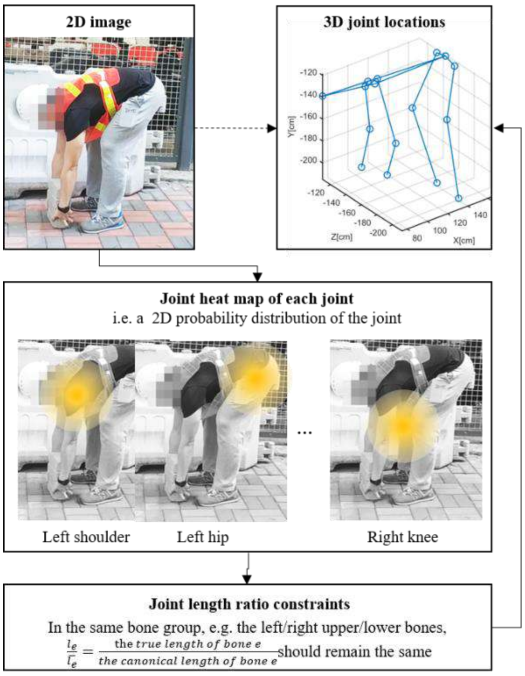

Figure 2. The framework of 3D pose estimator

3.2 Automatic External Load Assessment

A novel insole with plantar pressure sensors, named Moticon, is used to measure the total ground reaction force generated during the work task. This includes the worker's self-weight and external burden, as shown in Figure 3. The insole can be used in virtually any shoe. The commercial available smart insoles can transfer data wirelessly through ANT radio service. The size of external loads can thus be calculated by subtracting worker`s self-weight from the total reaction force generated. It is important to note that for most of the construction tasks, the external loads are usually applied at hands, resulting from the tools or equipment which a worker uses to perform the task.

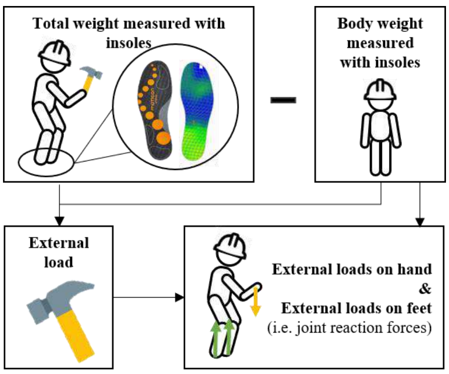

Figure 3. The calculation of external loads with smart insoles

3.3 Biomechanical Analysis

Inspired by biomechanics, this research simplifies the human body as a lever system, and then utilizes mechanics principles to analyse the internal load of each joint. The inputs of inverse dynamic model include: 1) a muscle-skeleton model, which simulates the muscles, tendons and skeletons with a lever system connected with hinges and dampers; 2) a motion file containing the time series of three-dimensional coordinates of the joints in muscle-skeletal model; and 3) external load data including the size and direction of ground reaction forces on both feet and the external loads on both hands. Based on the above data, the inverse dynamics model can be written as Equation (1).

$$M(p)\ddot{\boldsymbol{p}} + \boldsymbol{C}(\dot{\boldsymbol{p}}, \ddot{\boldsymbol{p}}) + \boldsymbol{G}(\boldsymbol{p}) = \boldsymbol{\tau} \tag{1}$$

where $\boldsymbol{p}, \dot{\boldsymbol{p}}, \ddot{\boldsymbol{p}} \in \boldsymbol{R}^N$ are the vectors of joint positions, velocities and accelerations, respectively ; N is the number of the degrees of freedom; $M(p) \in \boldsymbol{R}^{N\times N}$ refers to the mass of different body parts; $\boldsymbol{C}(\boldsymbol{p}, \dot{\boldsymbol{p}}) \in \boldsymbol{R}^N$ is the vector of centrifugal forces; $\boldsymbol{G}(\boldsymbol{p}) \in \boldsymbol{R}^N$ is the vector of gravitation forces; and $\boldsymbol{\tau} \in \boldsymbol{R}^N$ is the vector of generalized forces. 3DSSPP (Michigan University), a human body motion simulation software was used here to solve Eq.1.

3.4 Workload Analysis

The joint capacity in this paper is defined as Maximal isometric strength (MVIC) of each individual. MVIC can predicted with anthropology information including age, gender, weight and height [26]. Then workload equals to the ratio of joint torque to the joint capacity.

4 Experiment

Three main construction activities, including material handling, rebar, and plastering, were conducted during the experiment, as shown in Figure 4. The subjects wore smart insoles to capture the self-weight and any external load. A smart phone camera fixed on a tripod recorded the whole process. At the same time, a set of IMU sensors tied to the subject's main joints also recorded the location of the joints. The IMU sensor has an accuracy of up to 1 degree [27]. Experiments were enacted in both indoor and outdoor environments to demonstrate the feasibility of the proposed method.

Figure 4. The example frames during material handling, plastering and rebar

4.1 Experiment Data

Table 1 provides the raw data. The video data frequency is 25 fps (frames per second). The IMU data frequency is 30 fps. The insole pressure data is 50 fps. The 3D joint coordinates, ground reaction forces, and hand loads were calculated and synchronized.

Table 1 The information of experiment data

Activity		Material handling	Plaster	Rebar	Total
Duration [sec.]		22	19	114	155
Video data	No. of frames	550	475	2853	3878
	No. of joints	16	16	16	-
IMU data	No. of frames	660	570	3424	4654
	No. of joints	13	13	13	-
Insole data	No. of frames	1100	950	5706	7756
	No. of sensors	26	26	26	-

4.1.1 Posture Data

The video clips were first separated to frames at the rate of 1 fps (frame per second). Then the 3D pose estimator was applied on each frame to get the 3D coordinates of each joint. Figure 5 provides an example of the frame during material handling. Given a picture (Figure 5(a)), the 3D posture estimator estimates the 3D coordinate of 16 key joints. Figure 5(b) visualizes the 3D pose estimation results.

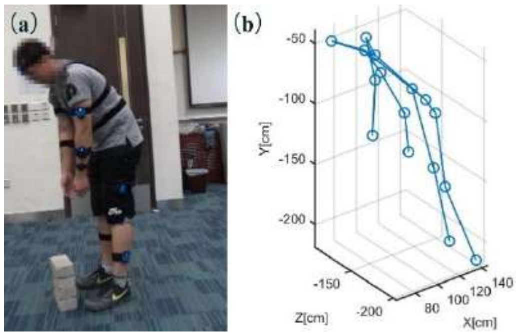

Figure 5. An example of the 3D pose estimation result

IMU sensors were used as the ground-truth to test the accuracy of the pose estimator. Figure 6 shows joint average of the estimation error of each frame. The results indicate that the average error of each joint was 4.10 cm.

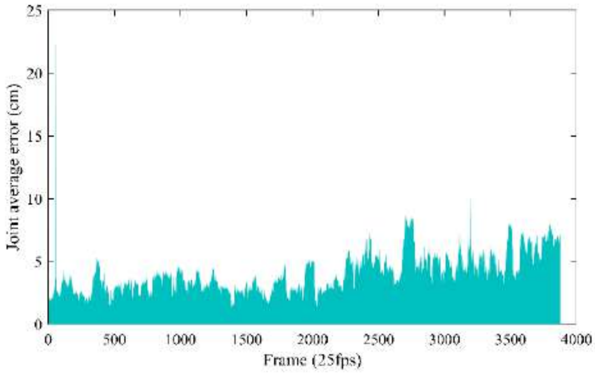

Figure 6. The error of 3D pose estimation

4.1.2 External Load Data

External load was estimated with the pressure data from the smart insoles. During the material handling experiment, the subjects were required to lift 0,1,2,3 or 4 bricks and hold them for 10 seconds. Each brick weights 2 kg, which equals to an external load of 19.6 N when g=9.8 m/s^2. The estimated external load resulting from the bricks was calculated as the difference between the ground reaction forces of consecutive liftings, as shown in Figure 7. The relative error is 5.99% by comparing the differences between the estimated external load and the ground truth external load.

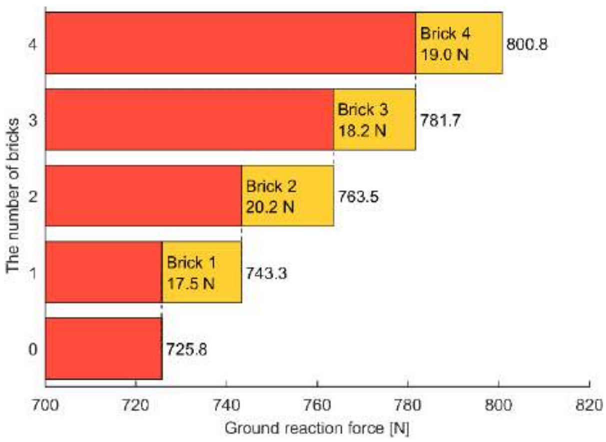

Figure 7. The measurements of external loads

4.2 Workload Assessment

Inverse dynamic modelling was applied to calculate the torque at each joint based on the posture data and ground reaction force data 3DSSPP was applied to facilitate the biomechanical calculations. The joint capacity was estimated according to the equations as suggested by The National Isometric Muscle Strength (NIMS) Database and the participant`s anthropometric information (age, gender, weight and height). Then, the workload was calculated as the percentage of maximum joint torque. Figure 8 delineates the joints` capacities, joints torques and resulting workload at each joint, which helps to assess the workload by illustrating the various body joints with different colors depending upon the workload percentage.

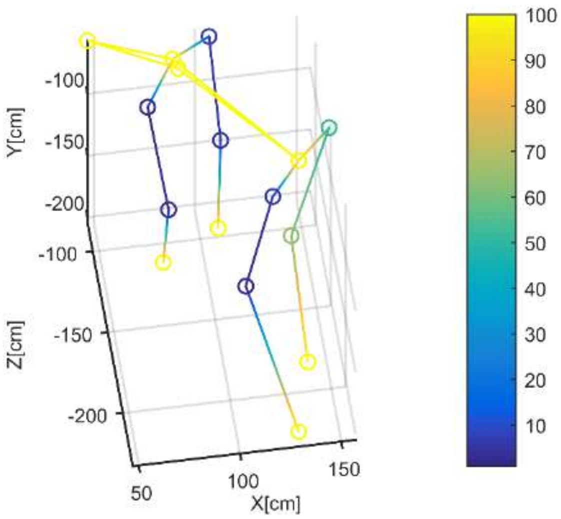

Figure 8. The visualization and calculation result of workload

Figure 9 shows the joint workload distributions during typical postures of the three construction activities involved. By comparing the join workloads of three construction activities, material handling was more likely to result in high joint workload than plaster and rebar. In all of the three activities, left hip and left knee had higher workload than other joints. The result suggested that the subject may need to reduce the workload of left legs by balancing the workload of both legs.

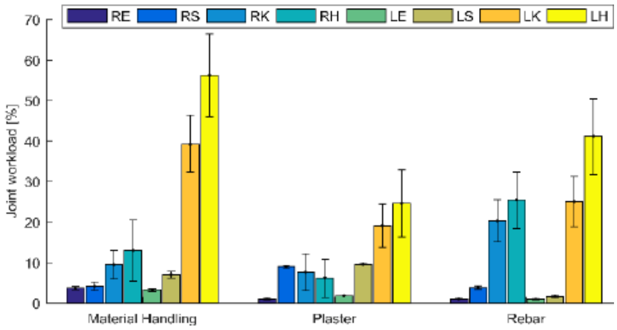

Figure 9. Joint workload assessment results

5 Discussion

Construction workers faced with high ergonomic risks, resulting in a negative influence on the workers' wellbeing and productivity. It is important, therefore, to assess the workers' ergonomic risk accurately. Observations, sensors, and depth cameras are three main posture data collecting methods, but are faced with challenges of low accuracy, uncomfortableness, and unsuitability to outdoor environments. This research intends to solve the issues by blending a video-based 3D pose estimation algorithm with smart insoles. The experiment results suggest that the method could 1) accurately collect construction workers posture and external load data, 2) automatically provide workload assessments without intrusiveness, 3) work well in both indoor and outdoor environments.

The methodology, however, has the following shortcomings and deserves further improvements.

First, the 3D motion estimation accuracy should be improved. Figure 10 provides two failure cases of the 3D posture estimation in an on-site experiment. The reason lies in visual obstacles. In Figure 10, the worker was squatting, and most of the body parts was invisible. The 3D pose estimation could be improved by adding more pictures with obstructions to the training dataset, so that the blocked body segment could be inferred.

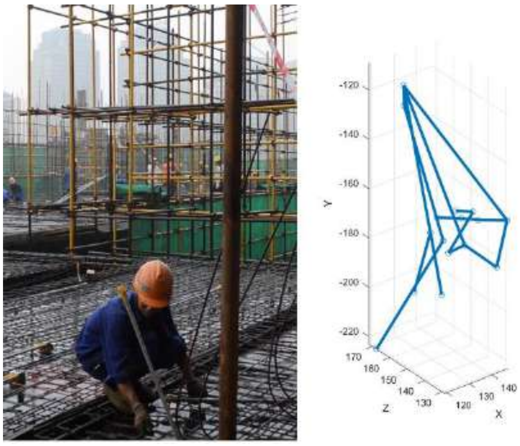

Figure 10. Failure examples of 3D pose estimation

Secondly, the current methodology can only be applied on frames containing only one worker. However, in most of the case, one supervision camera can record the activities of several workers. If the methodology could recognize all the workers within one frame, the efficiency could be increased a lot.

Thirdly, the pressure sensor data is not stable. Figure 11 shows the data from one sensor in the insole. It can be found that there exists sharp fluctuation in the first several frames. The reason might be workers' quick movements, which could lead to the unstable connections between pressure sensors and data receiver in the insole.

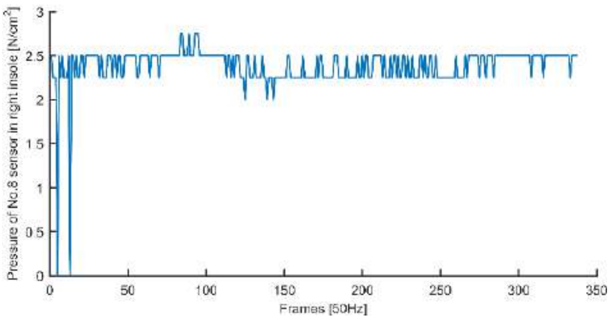

Figure 11. The data from one pressure sensor in the right insole

Finally, the methodology needs to be further demonstrated with real construction site data. Though the experiment demonstrates the feasibility of the methodology, the on-site experiment only records a ten-minute video for each worker. For data-based ergonomic improvement suggestions, it is necessary to take longer-period video records for more construction workers.

6 Conclusions

The research proposed a non-intrusive workload assessment approach for construction workers by merging computer vision, pressure sensors and biomechanics. The experiment results demonstrated the feasibility and accuracy of the approach. Development of such a system could equip the industry with a non-invasive tool for workload monitoring. Also, the approach provides detailed information about the posture and external load and associated patterns which could help understanding the relations between construction activities and workloads, which could serve as the data foundation for ergonomic improvements such as work-rest schedule and workstation design.

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Construction Equipment Collision-Free Path Planning Using Robotic Approach

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Abstract –

Path planning is crucial in constructability analysis and heavy construction equipment scheduling, particularly in industrial plants. The main purpose of construction equipment path planning is devising the shortest path between its initial and aimed location. This suggested path is supposed to be safe, and collision-free. The current planning practice, even in industrial projects whose sites are extremely congested, is manual based on the expert judgment. Thus, this sophisticated manual process is not only prone to errors, but also time-consuming. This research presents an automated path planning approach based on an obstacle avoidance technique in robotics to support the decision-making process. The proposed methodology finds the shortest path for the planar motion of any convex 2D object. It assumes continuous translational (i.e. X and Y directions) and discretized rotational motions for the object. Two case studies are also presented to illustrate and to validate the proposed methodology.

Keywords –

Construction Equipment; Collision-free Path Planning; Robotics; Automation in Construction

1 Introduction

Dams, bridges, roads, industrial plants, and other construction mega-projects heavily rely on the utilization of heavy construction equipment. Construction equipment planning and management is a sophisticated task due to its interrelationship with dynamic activities (i.e. workspace logistics, material delivery, and equipment allocation) [1]. Thus, improper planning and management of construction equipment would lead to unsafe, inefficient, and unproductive construction projects. Nevertheless, current construction equipment planning practice is manual and extremely depends on engineers' intuition, experience, and imagination and is proceeded by trial and error methods. Thus, this sophisticated manual process is not only prone to errors but also time-consuming. Additionally, complexity, uncertain nature and dynamic conditions of congested construction sites require frequent and short-term re-planning. Therefore, to maximize productivity, developing effective and flexible tools would be necessary to help engineers manage these pieces of equipment.

The movement of mobile construction equipment is one of the principal causes of fatalities on a construction site. A collision-free path for construction equipment can reduce the risk of worker injury and fatality [2]. Such a collision-free path can decrease the probability of workspace conflict, enhance construction equipment management, and increase the productivity of the construction process. As a result, path planning analysis plays a pivotal role in constructability analysis and heavy construction equipment scheduling, particularly in congested industrial plants.

This research aims to present an automated path planning approach based on an obstacle avoidance technique in robotics to support the decision-making process. The main purpose of construction equipment path planning is devising the shortest path between its initial and aimed location. This suggested path is supposed to be safe, and collision-free.

The sub-objectives of this research are as follows: (1) developing and enhancing a methodology for finding the shortest path for the planar motion of any convex 2D object.; (2) using the method to determine the shortest collision-free path on a construction site for mobile construction equipment; (3) providing a visualization tool in CAD environment in order to present and evaluate the results and the whole process. Planners should be able to evaluate the user-defined variables and the final output. This research proposed a computer program to meet these goals and provides engineers with a computational, visual, and interactive way of decision making support systems. The proposed method is validated by some pilot case studies to prove that it can provide a visually effective and efficient result.

2 Literature Review

An effective construction equipment planning and control includes (1) site planning, and (2) heavy construction equipment movement control [1]. A lot of studies conducted to make these processes more efficient and flexible particularly by using computer-based automated solutions. For example, type and location optimization [3], resource allocation optimization [4], path checking [5], activity analysis and control [6] concentrate scholars' attention in recent decades.

Path planning is a sub-process in robots' motion planning and aims to find a collision-free path between the initial and goal configuration of the robot. The construction equipment path planning problem is potentially interchangeable to the path planning problem of mobile robots. A fundamental study conceded by Lozano-Pérez [7] proposed a method called "configuration space (C-Space)" to solve 2D motion planning problems for 2D convex mobile robot objects. The pivotal idea of this method is to reduce the dimension of the moving object's shape into one single representing point and to augment the obstacles to configuration space obstacles (C-Obstacles). The most significant advantage of this idea is that dealing with the intersection of a point and a set of obstacles is easier than the intersection of the moving object and the set of obstacles. Figure 1 (A) demonstrates how to convert an obstacle to the corresponding C-Obstacle based on a rectangular moving object without considering the rotations. The central point of the moving object is chosen as the representing point (B), and the obstacle is grown by the shape of that, creating a new area (C-Obstacle) (C). After the creation of the C-Obstacle, the problem of finding a collision-free path for the moving object is equivalent to finding a path for the representing point avoiding the generated C-Obstacle (D). If the moving object rotates, the shape of the created C-Obstacle would be changed. Previous work on construction equipment path planning employs various algorithms to search the created C-Space. However, the main focus is on two main search categories: (1) discretized (node-based) search algorithms (i.e. Visibility Graph [8], Gridding plus A*, GA, Dijkstra's Algorithm [9]), (2) continues (sampling-based) search algorithms. (i.e. RRTs [10], [11], PRM [12]).

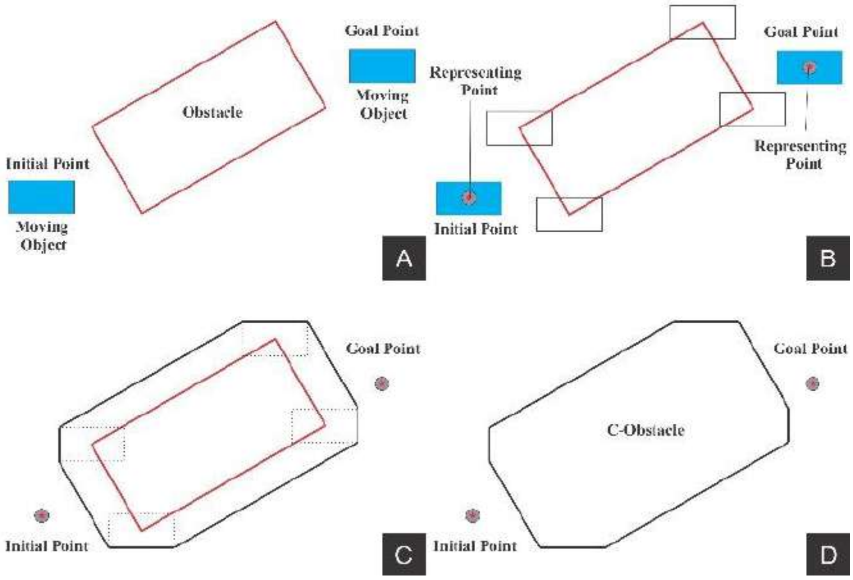

Figure 1- C-Space Generation Steps

3 Proposed Methodology

This research is based on the limitation enhancement of a research work done by Lei et al [13]. They neglected full discretization for rotation as the third degree of freedom for moving object. Mixed rotation-transition movement not only affects the optimality of the solution adversely, but also it restricts the developed system to 2D path planning. By exemption of this limit, this paper combined the robotic motion planning with the construction equipment path planning to reach a more flexible and developable methodology. Figure 2. Illustrates the proposed methodology which consists of several components. The system is developed in VisualBasic.Net employing MS Access database.

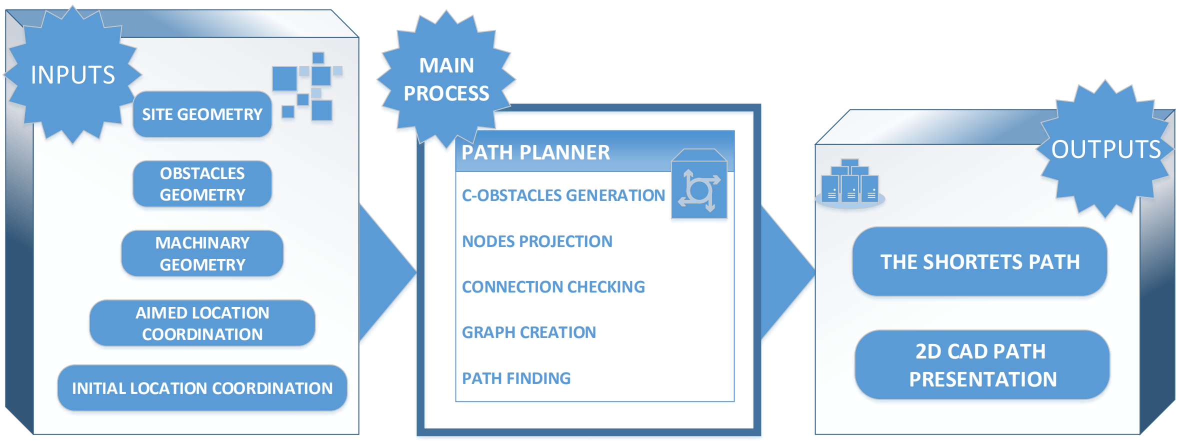

Figure 2- Proposed Methodology

3.1 C-Space Generation

As mentioned above, the shapes of the generated C-Obstacles would be changed as the moving object rotates. Therefore, the ideal modeling approach is to generate the C-Obstacles while considering the continuous rotation of the moving object. Nonetheless, in order to make the model computationally feasible and efficient, finite rotation steps are assumed. In this regard, for each rotation step of the moving object, the C-Obstacles are generated and kept on a separate corresponding rotational plane by their vertices. (Fig 3.) In this regard, it is needed to rotate the geometrical shape of the moving object by the 2D rotation matrix and proceed the augmentation process for each obstacle. Finding the shortest collision-free path for a convex 2D object through obstacles is now changed to finding the shortest collision-free path for the representing point through grown obstacles (C-Obstacles) between its initial and aimed location. Indeed, the moving object will avoid obstacles, if and only if the corresponding representing point is located out or on the perimeter of the C-obstacles.

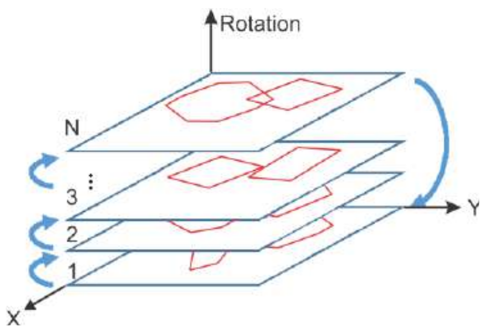

Figure 3- Discretized rotational planes in the generated C-Space

3.2 Corresponding Graph's Node Generation

Based on visibility graph, a collision-free path for a set of points and obstacles in the Euclidean plane is an array of feasible connections between the points (i.e. obstacles' vertices, start point, and aimed point) which starts from the initial point and ends to the aimed point. In fact, a visibility graph is a graph in which each node represents the representing point location, and each edge represents a visible connection between them. Two nodes will be connected, if and only if their connector segment does not have any intersects with any obstacles.

In order to implement this idea, it is necessary to introduce the nodes at the first stage. In this study, two types of nodes are introduced for each rotational plane: (1) Internal nodes; and (2) External nodes. Internal nodes initially consist of vertices of corresponding C-Obstacles for that rotation. Initial and aimed location of the representing point are two extra internal nodes which are added to their corresponding rotational planes. External nodes are introduced in this study to complete the full-discretized modeling of the moving object rotation. External nodes within any rotational planes are those nodes that are added from other rotational planes via continuous projection. The continues projection process proceeds in the negative and positive manner for clockwise and counter-clockwise rotation of the moving object for the amount of a single rotation step, respectively. During this process, each individual internal node within each rotational plane is projected to the next successive rotational plane negatively/positively. By so doing, the object ability to rotate around the representing point is investigated. For example, an internal node N(x,y) within plane j positively projected to plane j+1 and added to it as an external node N'(x,y), given that the projected node will not be placed inside of new plane's C-Obstacles. For the next step, N' would be projected to j+2. The positive projection will be continued unless projected nodes are placed inside the planes' C-Obstacles. In that case, the projected point will not add to that plane, and the positive projection process will be stopped for N(x,y). Right after that, N(x,y) will be negatively projected to plane j-1 to obtain N''(x,y). Similarly, the negative projection would be continued unless projected nodes were placed inside the planes' C-Obstacles.

make an inter-plane connection if they have the same coordination (i.e. X, Y). It is necessary to define a metric to assign a weight for any connections. In this work, the distance and length of motion is simply used. Finally, each connection and its weight treated as the corresponding weighted graph's edge.

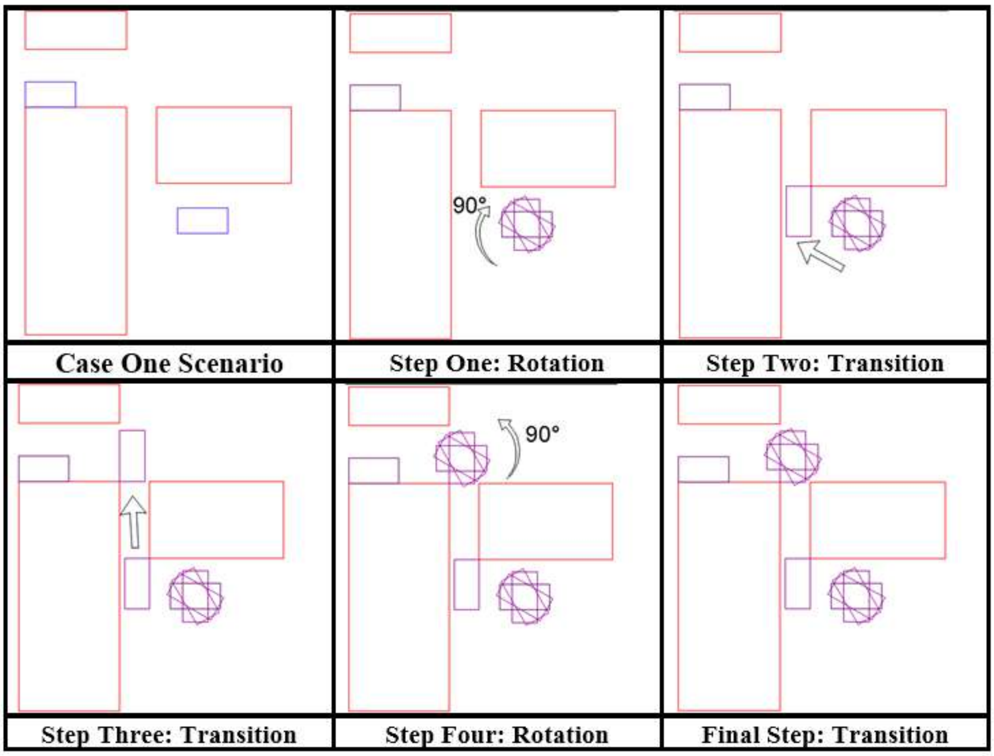

Figure 4- The shortest path in case one

3.3 Corresponding Graph's Edge Generation

When two nodes are connected, it implies that there is a feasible motion between the two positions represented by the nodes. This research proposed two types of connections between nodes: (1) in-plane connections; and (2) inter-plane connections. For instance, a connection between two nodes from the same rotational plane j represents that the moving object can transit without any rotations from one node to the other using a straight line; and a connection between two nodes from two successive rotational planes (e.g. j and j+1) implies the rotation of the moving object. This rotation is equal to one single rotation step.

Two nodes within the same rotational plane will be connected if the segment connector does not collide with the existing C-Obstacles. The connection for two nodes from successive layers is checked to guarantee that the rotation to the amount of a single rotation step will not collide with the existing obstacles. Hence, two nodes will

3.4 Path Finding

Dijkstra's algorithm is employed in this study to find the shortest path in the generated corresponding graph. The principal idea of Dijkstra's algorithm is to calculate the minimum cumulative weight of connections to reach any nodes such as the aimed node from the initial node in a weighted graph G= (V, E). [14]

4 Case study

4.1 Case One

Case one presents an illustrative example in which a moving object is supposed to move through three obstacles in five steps. (Figure 4) In each step the moving object is able to either transit or rotate, but there is no mixed movement for it. The proposed path is safe and collision-free.

4.2 Case two

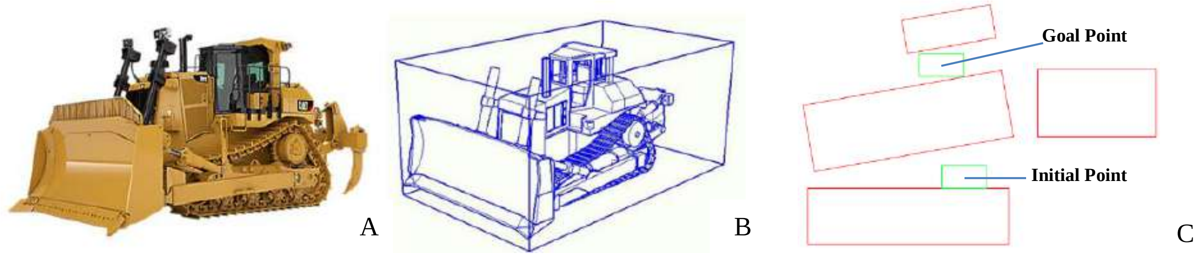

Figure 5- (A) CAT-D9 dozer; (B) Boundary box envelope; (C) A congested scenario

To apply the proposed methodology in finding the shortest collision-free path between initial and aimed location of construction equipment, it is needed to simplify that machinery to a 2D convex. Hence, a boundary envelope is used to guarantee that the mobile construction equipment will avoid obstacles. The boundary for a CAT-D9 dozer (Figure 5(A)) is shown in Figure 5(B); it is a box that completely encloses it. In other words, no points of the dozer will be placed outside of the boundary box.

Additionally, case two presents a more congested scenario with four obstacles (Figure 5(C)). In this case, a complex environment considered to challenge the proposed methodology. However, it is designed to be trackable for any individuals to easily validate the shortest path.

As shown in (Figure 6(A)) rotational planes and their C-obstacles are generated. Meanwhile, in-plan and inter-plane connections are made afterward (Figure 6(B)). The final result is shown in Figure 7 as below.

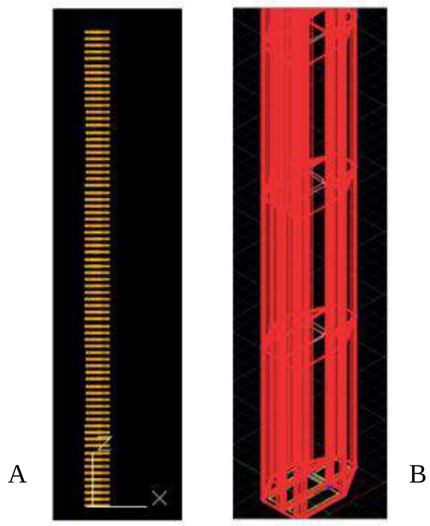

Figure 6- Case two; (A) Rotational Planes; (B) Connections and corresponding graph

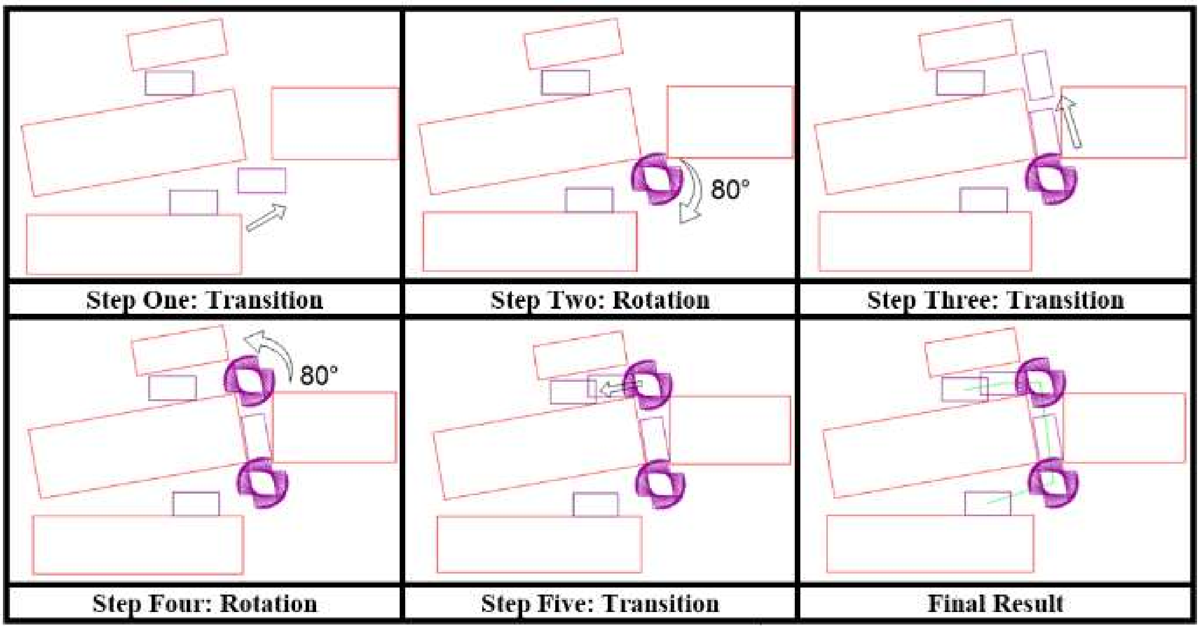

Figure 7- The shortest path in Case Two

5 Conclusion

Path planning is crucial in constructability analysis and heavy construction equipment scheduling, particularly in industrial plants. The main purpose of construction equipment path planning is devising the shortest path between its initial and aimed location. This suggested path is supposed to be safe, and collision-free. The current planning practice, even in industrial projects whose sites are extremely congested, is manual based on the expert judgment. Thus, this sophisticated manual process is not only prone to errors but also time-consuming. This study presents an automated path planning approach based on an obstacle avoidance technique in robotics to support the decision-making process. This research enhanced the limitation of the other scholars' efforts. However, the proposed system only considered the shortest path, but it can consider ease of operation, machinery movements, and other constraints in future studies. This research work will be further extended into heavy lift path planning of mobile cranes.

6 Acknowledgment

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Utilization of Virtual Reality Visualizations on Heavy Mobile Crane Planning for Modular Construction

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Abstract –

Many kinds of industrial projects involve the use of prefabricated modules built offsite, and installation on-site using mobile cranes. Due to their costly operation and safety concerns, utilization of such heavy lift mobile cranes requires a precise heavy lift planning. Traditional heavy lift path planning methods on congested industrial job sites are ineffective, time-consuming and non-precise in many cases, whereas computer-based simulation models and visualization can be a substantial improving tool. This paper provides a Virtual Reality (VR) environment in which the user can experience lifting process in an immerse virtual environment. Providing such a VR model not only facilitates planning for critical lifts (e.g. modules, heavy vessels), but also it provides a training environment to enhance safe climate prior to the actual lift. The developed VR model is implemented successfully on an actual construction site of a petrochemical plant on a modular basis in which heavy lift mobile cranes are employed.

Keywords –

Heavy Lift Planning; Virtual Reality (VR); Modular Construction; Automation in Construction; Mobile Crane

1 Introduction

Effective management and planning of resources are pivotal tasks in construction projects management. In recent decades, many industrial projects are constructed using industrialization/ prefabricated offsite construction methods, particularly modularization methods. Modules (e.g. pipe racks or vessels) are offsite prefabricated elements that assembled in module yards and shipped to the site for installation [1]. A set of modules constructs a larger structure. During the installation process, heavy mobile cranes are employed as the main lifting machinery. This heavy and large construction equipment is highly expensive and required precise planning and control due to safety concerns and the extensive impact on the project schedule. For example, the rental cost of a heavy lift mobile crane may reach $1,500 per hour [2]. Moreover, not only these resources force highly expenses (e.g. mobile crane rental cost, skilled crew, and mat cost) to a project, but also they are just available for a restricted period of time.

Proper use of these heavy mobile cranes can reduce costs and make the construction process faster. In contrast, inappropriate crane operation can lead to overruns, delays, and safety issues. Heavy lift path planning is one of the most significant elements in heavy mobile crane planning and management. Traditional heavy lift path planning methods on congested industrial job sites are ineffective, time-consuming and non-precise in many cases, whereas computer-based simulation and visualization can be considerable improving tools.

With tremendous development of graphical computer aid modeling and also novel interactive hardware, a definite opportunity is provided in architecture engineering and construction (AEC) industry to facilitate the training process and effective learning in virtual environments (i.e. virtual reality, augmented reality and mixed reality) through that. A lot of research has been done in this area, and scholars tried to examine the effectiveness of the application in the construction industry. Additionally, there are also many untapped opportunities in the construction planning process.

The objective of this research is to provide a Virtual Reality (VR) environment in which one can experience a simulated lifting process in an immerse virtual environment. Providing such a VR model not only facilitates planning for blind or critical lifts (e.g. modules, heavy vessels) but also provides a safe training environment prior to the actual lift. Moreover, using VR technology make it possible to provide useful extra information, and by so doing, operators, planners, and engineers will have the opportunity to obtain a common understanding and would be capable to cooperate to improve the plan.

2 Related Works

Throughout the recent decades, computers have played a significant role in construction. Scheduling and many other planning tasks are done with the support of computers. In the recent years, other applications have been also investigated particularly in construction operation visualization. Visualization aims to verify trustworthiness and to provide presentable insights about the modeled system. For instance, four-dimensional (4D) computer-supported design CAD technology presents a visualization of the advancement of construction by linking three-dimensional (3D) computer models of the project and construction schedules [3]. 4D models barely enable users to envision a construction schedule previously developed. However, they are not able to simulate the construction activities [4]. More recently, more pioneer computer-based technologies are employed to facilitate the visualization process. Immersive virtual technologies, such as VR technology, enable multiple design solutions to be evaluated digitally, which leads to a faster design process and more optimized end products. The first industrial use of VR was introduced when virtual prototypes started to be used in the design process. VR is a virtual prototyping technology that provides a three-dimensional scene that can be manipulated in real time and used collaboratively to explore and navigate the 3D model. By simulation of the construction process, VR makes users to get a better understanding and perception about the actual environment. As illustrated in Figure 1, there are many potential application areas for VR systems [5]. Various conducted research in the case of VR technology applications has confirmed that VR can bring vital value improvement and cost declines to the construction process [6].

Management of heavy construction equipment is a sophisticated task due to highly dynamic activities such as work-space logistics, material deliveries, and resource allocation. However, construction equipment management suffers from some deficiencies in different levels of site planning and their movements. Studies indicate that construction site planning highly depends on individuals' experiences, imaginations, and intuitions. Even though 4D visualization enhanced communications and mutual understanding of various stakeholders, there is no effective tool to analyze, evaluate, and anticipate ongoing challenges and future difficulties [7]. Furthermore, in modular industrial projects, heavy mobile cranes are employed for on-site module

Figure 1- Potential Applications of VR in Construction [5]

installation at their set locations. Efficient planning is essential to decrease errors, accidents, additional costs, and schedule delays [8]. An effective crane planning in these kinds of projects includes many tasks (i.e. crane type selection, crane location optimization, lift sequencing, lift path planning). Heavy lift path planning is a pivotal subtask in heavy lift planning. Many scholars proposed computer-based solutions to optimize or enhance the process by automation [8]–[10].

In order to increase the construction productivity, investigations are conducted to link these novel visualization technologies to crane planning and management. Some scholars employed the VR technology to provide a virtual environment to train cranes operators with neither dangers or expenses. For instance, overhead crane [11] and bridge crane [12] operator training systems based on virtual reality are discussed. Some other efforts are made to evaluate and enhance safety conditions in this regard [13]–[15]. However, authors have not found any specific investigation in the application of VR technology in heavy lift planning process of mobile cranes.

3 Development of VR-Based Heavy Lift Planning Simulator

The objective of our approach is to unify a virtual environment for different use cases in lift planning and execution of heavy lifts of prefabricated modules in industrial projects. Using an interactable virtual environment (VE) would enable users to have more profound experiences. Virtual reality (VR) is a mixture of digital processing, computer graphics, multimedia technology, sensor technology, and other computer-based information technologies. Thanks to VR technology, users are able to freely navigate any simulated 3D models in a VE.

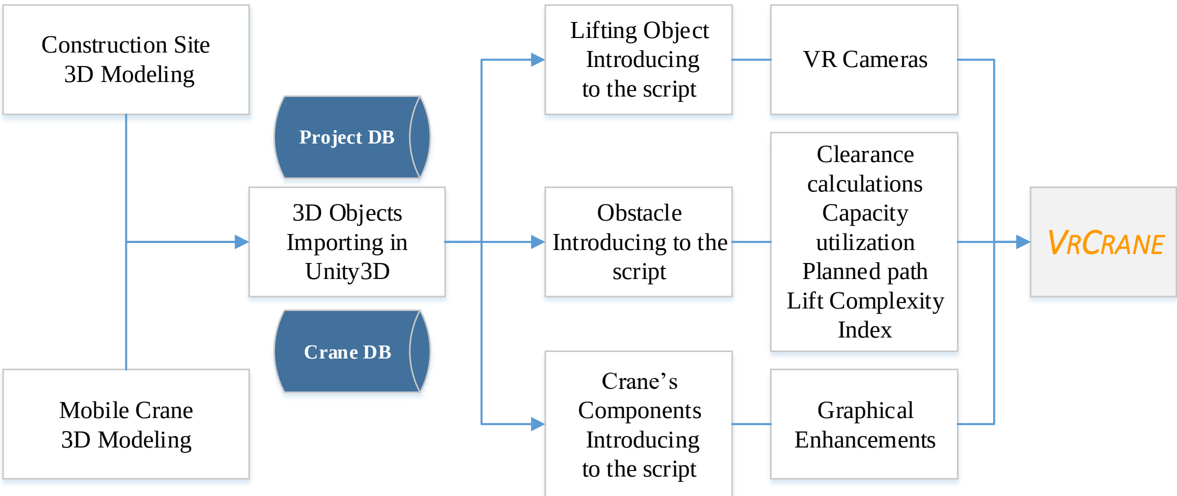

Figure 2 - VR-Crane Development System

Moreover, they would be capable to actively interact with the VE. Navigation is one of these interactions. Navigation includes the ability to move around and explore the simulated objects in a virtual environment. Similarly, interaction is the ability to control and affect the VE and also be affected by it. For example, the ability to move objects in a VE is an interaction between the user and the VE. The most significant advantage of VR models to other forms of VE such as personal computers (PC) displays is providing a lifelike three-dimensional and 360° experience via a wearable display-headset with a higher degree of virtual immersion.

In this research, a prominent VR headset, Oculus Rift is employed which consists of several parts. A head-mounted display (HMD), an Xbox Controller, and Oculus Rift Constellation sensor, an optical-based tracking system developed by Oculus VR, are the main parts of the VR device. The VR device needs to be supported by a high-performance graphical process unit (GPU). Thus, the user can experience a more realistic environment than simple 3D-glasses.

This paper presents the overall concepts of VrCrane, a VR simulator for heavy mobile cranes (see Fig 2). Authors proceeded five main steps in order to achieve a VR tool which facilitates the lift planning for heavy mobile cranes. In this regard, a 3D model of the selected crane and the construction site is required. It is possible to use BIM models or a raw 3D model and a manual database. Hence, a pilot BIM model of an industrial plant is employed which has both information and 3D model. Moreover, it is required to make users able to control mobile cranes' every possible degree of freedom. Therefore, Uinty3D as a handy and free game engine is used to simulate its every six degrees of freedom. These degrees of freedom are controlled by the Xbox controller (see Fig 3). Various types of virtual cameras equip the simulated model to make users experience the lifting operation as an operator, a signalman, or through other views which is easily possible in a virtual environment (i.e. bird view, plan view, dynamic view, etc.). Extra real-time calculations and information presentations (i.e. capacity usage percentage, clearance color-coding, risk evaluations, etc.) for virtual operators and others would increase the common understanding and facilitate the communication process among all decision makers and other key stakeholders (Fig 4). In addition, a life-like experience of a heavy lift would reveal the underlying challenges which were previously concealed during typical 2D lift planning.

4 Conclusions

By the development of virtual environments such as virtual reality, augmented reality and mixed reality in architecture engineering and construction (AEC) industry, it is an indisputable need for stakeholders and planners to use a better approach for their labor-intensive and error-prone activities particularly in heavy lift planning. Provided a virtual reality environment in which the user can experience lifting process in an immerse virtual environment not only facilitates planning for critical lifts (e.g. modules, heavy vessels) but also provides a training environment to enhance safe climate prior to the actual lift in a safe, fast, and low-priced manner.

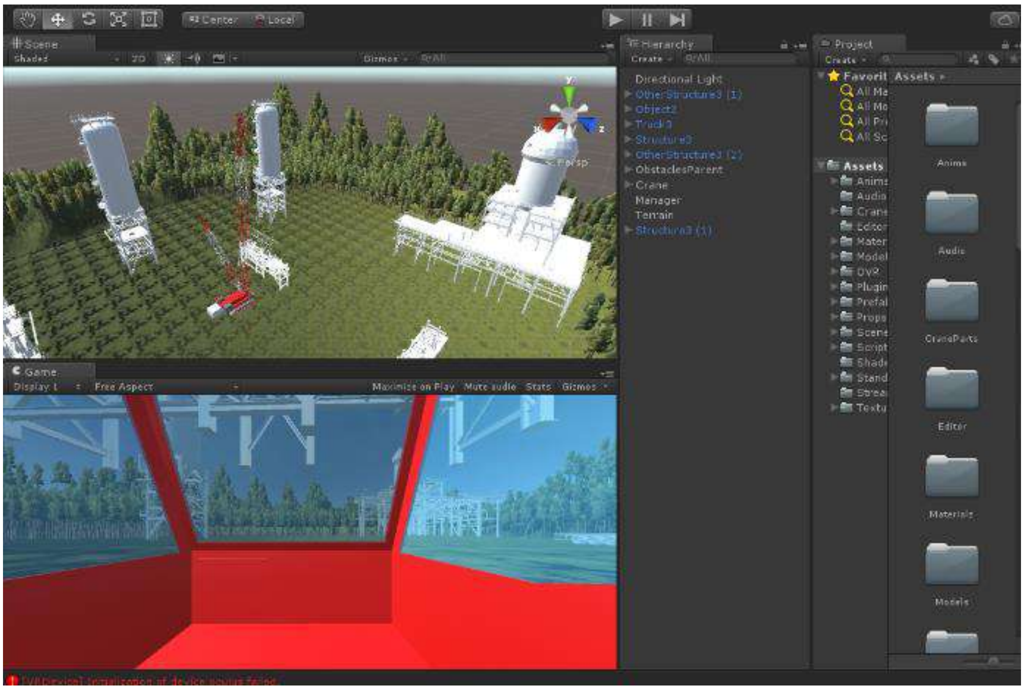

Figure 3- Simulation Environment in Unity3D

Figure 4- Users are experiencing the virtual lift operation

5 Acknowledgment

Sincere supports from PCL Industrial Management Inc. and TECNOSA R&D Center are greatly appreciated. The writers are also thankful to those who participated in this study and supported the research project.

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Automation of the Execution of Monolithic Reinforced Ceilings

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Abstract

The development in numerical control, 3D technology, as well as new materials, have a great potential in respect of automatic construction, while at the same time they contribute to freeing people from hard physical labour, improve quality of performance, and minimise the volume of waste. Vertical components are erected automatically, while possible horizontal structures are engineered using prefabricated materials. The presented *stropotronic* technology, using automatic formwork that moves together with the robot embedding materials, was applied to construct monolithic reinforced ceilings. Owing to its high early strength (over 20 MPa just after 1.5 h from reaction with water), concrete using rapid setting calcium sulphoaluminate (CSA) cement assures self-supporting strength in a very short time. The robot continuously places reinforcement and extrudes concrete while moving together with the formwork perpendicularly to the ceiling span. Automatic formwork moves very slowly under the ceiling constructed to assure continuous support for the setting concrete at the width of approx. 1.5 m, namely until the slab becomes self-supportive across the span between supports. The example of a section of the ceiling with composite inserts (main bars of steel, distribution bars of glass fibre) presents the results of preliminary analysis of the applied CSA cement-based concrete, progress of works related to material embedding, and the conclusions.

Keywords –

automation in construction, production organization, JA-WA system, stropotronic, CSA cement

1 Introduction

Current automated construction systems using large-size 3D devices apply 'wet' technology with nozzles forming the material to build walls, whereas ceilings are assembled of prefabricated materials, [2, 3, 7, 11, 13, 22]. The *JA-WA* system (Polish: ***J**ednostronna **A**plikacja* – ***W**ędrującym **A**utomatem*) represents the technology of single-sided material application using mobile automatic devices, [14-16,18]. For construction of ceilings (Polish: *strop*), a prototype '*stropotronic*' technology is proposed. The method allows construction of monolithic concrete ceilings reinforced with rods directly at the buildings constructed, with automated control of the equipment, according to a predefined numerical algorithm.

By standard, monolithic ceilings are placed on a prepared formwork placed in the space, relying on temporary supports, or on the floor. After stabilization of the formwork and placement of reinforcement inserts, the concrete mix is usually transported from the central concrete plant, and pumped at the site to the place of embedding, levelled, and mechanically compacted using manually operated power tools or manually. Following the period of concrete curing, the formwork can be removed, usually after several days, sometimes even later.

In the proposed *stropotronic* technology, ceiling construction is entirely different, and the time for supporting the formed part of the slab with the formwork totals just about 1.5 hours. The equipment is controlled by the operator, involving automatic formwork placement and a robot using the system for component mixing and embedding, according to the following principle. With the progress of works, automatic formwork and a robot placing reinforcement and coatings to secure against water evaporation and preparing the concrete mix for extrusion, as well as forming the external layers of the ceiling section, move on the rail scaffolding supported on the ground.

Precise operation of automatic equipment, appropriately to the results of analyses of the existing conditions and the calculation algorithm, with simultaneous continuous monitoring and control of the works quality, permits the application of rapid setting CSA (calcium sulphoaluminate) cement that takes about 30 minutes to begin, and with rapid early strength build-up. As a result, the support of the fresh ceiling with mobile formwork is only required for a short time, until the fresh concrete achieves the necessary strength to guarantee self-supporting properties of the executed section of the structure.

CSA cement, as applied in *stropotronic,* is a mineral, hydraulic binder with rapid early strength build-up (e.g. over 30 MPa after 8 from reaction with water), small contraction, and high resistance to sulphates. Main CSA components include: anhydrous *calcium sulphoaluminate* ($4CaO\ 3Al_2O_3 \cdot SO_4$), dicalcium silicate ($2CaO \cdot SiO_2$), and gypsum ($CaSO_4 \cdot 2H_2O$). When CSA cement is mixed with water, a quick reaction occurs between the anhydrous *calcium sulphoaluminate*, gypsum, and i calcium hydroxide, involving dynamic heat generation and intense generation of ettringite, mineral that allows achieving high early strength, with full strength guaranteed by the manufacturer to be achieved after 3 - 7 days, [4, 5, 8-10, 21]. Due to immediate binding of such cement, it requires specialist (very efficient) execution.

2 *Stropotronic* technology for monolithic ceilings

The *stropotronic* kit includes:

- analytical algorithms for equipment control with monitoring of ambient conditions, [2, 14-16],
- the robot forming the ceiling, namely placing the reinforcement and protective coatings, as well as composing the components, and embedding the concrete mix,
- mobile formwork moving with the operating area, supporting the freshly made ceiling until it achieves self-supporting strength,
- scaffolding rail that supports the system equipment (mobile formwork and the robot) and transmitting load onto the ground, [14-16],
- intermediate material resource to assure logistic stock of materials to guarantee continuity of work, [12, 17, 19-20].

3 Analytical algorithms, robot forming the structure, and mobile formwork

During the works, appropriately to the changing conditions and rapid CSA cement-based concrete strength build-up, the control, monitoring, and quality control of the automatic mobile formwork, the robot embedding the materials, and the material stock are assured. Depending on the ambient thermal conditions and calculation results, the automatically controlled kit of equipment allows for real-time coordination, continuous preparation, and embedding of materials at strictly defined times, with the necessary production intensity. Keeping of the preparation and embedding times preconditions correct curing of the monolithic concrete structure, and the appropriate time of supporting the freshly made ceiling. Hence, the necessary efficiency of works execution and the equipment movement velocity are controlled.

According to Fig. 1, embedding kit A, executing ceiling 1, connected to mobile formwork B, continuously moves with the works section in direction 2.

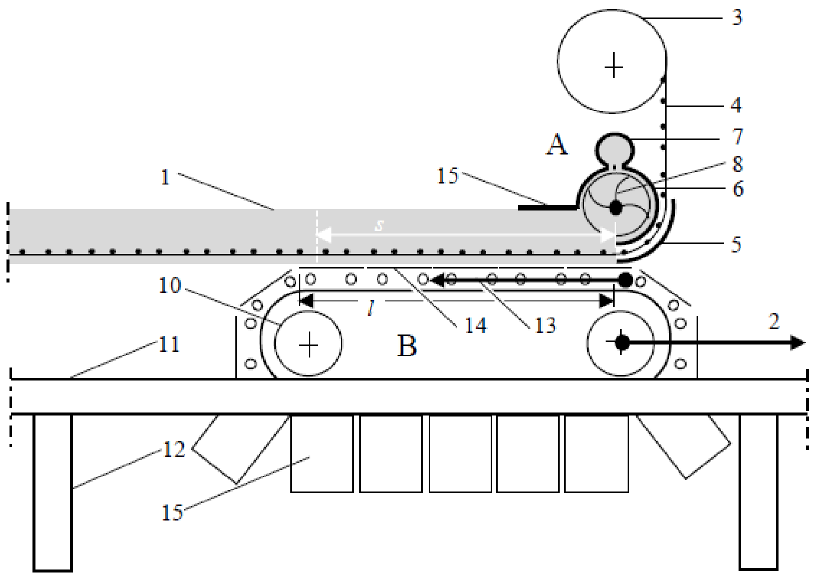

Figure 1. Diagram of the embedding kit - A and mobile formwork – B, description in the text

In the embedding kit A, the reinforcement mesh 4, unfolded from roll 3, for formed ceiling 1, is input between the front plate 5 and embedding kit casing 6. Concrete mix supplied with hose 7 is distributed across the ceiling span, extruded and compacted using carrier 8. Top plate 9 forms and smoothens outer surface of ceiling 1.

Mobile formwork B moves in direction 2 with the progress of the works, on wheels 10, on track 11, supported on supports 12. At the same time, particular formwork disks 14 move in the opposite direction 13. End parts of the formwork disks (over the tracks) are tilted. When the formwork plates move under, such end parts 15 on hinges tilt from the vertical, which allows for moving of formwork disks between the tracks and the supports.

The formwork supports freshly formed ceiling on section *l*, in the early period of (CSA cement-based) concrete curing for a time longer than until the fresh concrete achieves the parameters to guarantee its self-supporting properties in its entire cross-section at the span between the supports, as indicated below.

4 Properties of the applied CSA cement

During The first tests involving aluminous cement were conducted in the 1930's, including in France and in Poland by Stefan Bryła, [9, 10]. In 1966, in the USA, Alexander Klein proposed the application of calcium sulphoaluminate as the source of aluminium ions, and then patented the technology involving mixed Portland and expanding cements based on calcium sulphoaluminate, [1, 8-10,].

At present, CSA cement on calcium sulphoaluminates is manufactured with grades 42.5, 52.5, 62.5, 72.5, 82.5, and 92.5 (in this case, the values indicate compressive strength values achieved after 7 days). CSA cements stored in dry places in sealed packaging have the use by dates of 12 months. Major manufacturers of rapid setting cements are located in the USA and China. It is assumed that in the early period of CSA hydration, 80% ettringite is formed still before the hydration phase, and hence cement does not show strong expansion, and it can be classified as non-shrink cement. According to [19], after 28 days, in the conditions of very dry air, the contraction totals approx. 0.076 mm/m, while in the wet environment swelling of 0.2 mm/m occurs (acc. to ASTM C 845-96 [1], the limit for non-shrink cement totals up to 0.5 mm/m).

According to [4], CSA cement achieves compressive strength of f_{ck} = 20 MPa just one hour from its mixing with water, while after one day – 45 MPa, with full strength of 50 MPa, as guaranteed by the manufacturer, achieved after seven days. Later on, strength build-up occurs similarly as in Portland cements, and increases with time, totalling 62 MPa after 28 days. Further strength increase was investigated by Oreworld Cement Manufactured (OCM). As compared to compressive strength after 28 days, increase of 25% was recorded after one year, with further increase in strength of further 33% reported after five years [4].

Pursuant to the tests performed by the OCM, the proportions of tensile strength vs. compressive strength are similar as in Portland cements. Tensile strength after seven days totalled 4.1 MPa, with tensile strength at break of 5 MPa.

In order to achieve the intended strength parameters, CSA concrete preparation and laying must occur at outdoor temperature of from 7ºC to 32ºC (at lower temperatures, the setting process occurs at a much slower rate, while at higher temperatures, with additional hydration heat, ettringite may become decomposed). At the temperature of 20ºC, according to [4], setting occurs just after 15 minutes or up to several minutes later. With citric acid used as a retardant, the onset of setting time can be elongated by 15 minutes.

The onset of CSA cement setting, usually occurring after just several minutes, requires non-standard execution of the works. The setting and curing processes occur almost immediately after the addition of water, much quicker than in the case of Portland cements. In most frequent cases, when performing urgent and short-lasting repairs, concrete teams trained and equipped with the suggested equipment perform works according to the predefined works organisation. Concrete must not be vibrated after it has started to set, and the surface must be secured against evaporation. During the work, tools must be systematically cleaned, usually not less frequently than every 30 minutes. Standard pumps and pipelines must also be cleaned at similar time intervals.

5 Concrete Mix tests

At the laboratory of the Department of Geomechanics, Civil Engineering and Geotechnics of the AGH University of Science and Technology in Krakow, preliminary compressive strength tests f_c, were performed on concrete on CSA Rapid Set® cement, with setting onset of t_{pw} = 32 minutes. Concrete Mix was applied available in 25 kg bags, [8]. The water, dry mix, and ambient temperatures totalled 20ºC. With water/cement proportion of w/c = 0.5, the test involved three cubic samples each, with dimensions of 100 x 100 x 100 mm, in each of 9 concrete age times, counting from the time of mixing with water. The results of the compressive strength tests performed according to EN 12390-1 [5] (on walter+bai ag DB 3000 press with control module NS19) have been presented in Table 1.

Table 1 Strength values for Rapid Set® fresh concrete pursuant to tests and calculated according to equation (1)

Test of concrete aged t, h	1.5	2	3	4	8	24	48	72	168
Average strength from tests $f_{cm(t)}$, MPa	24.9	27.3	29.9	31.5	35.1	37.9	40.2	41.5	44.3
Characteristic strength values, acc. to (1) $f_{ck(t)}$, MPa	20.9	23.3	25.9	27,5	31.1	33.9	36,2	37,5	39.3

In the case of application of CSA cements, where fresh concrete in the ceiling needs to be immediately deprived of formwork, the *ja-wa* system requires information on the characteristic concrete compressive strength $f_{ck(t)}$ already at the age of $t \geq 1.5$ h.

When analysing the strength of samples tested (3 samples each, at 9 times, from 1.5 h up to 7 days; at the aforementioned laboratory of the Department of Geomechanics, Civil Engineering and Geotechnics of the AGH University of Science and Technology), major differences of the results, with standard deviation of s = 1.38, occurred for samples with concrete age of 8 h (from mixing the components with water). Average strength of three samples totalled $f_{cm(8)}$ = 35.1 MPa. *t*-Student was applied to check whether EN 1992:2008 Eurokod 2, [6], condition of 95 % samples in the lot achieving the characteristic strength, has been met. For sample strength of δ = 4 MPa lower than average $f_{cm(8h)}$, the value of test statistics $t_{obl} = (\delta/s)\sqrt{n-1}$, following substitution totals t_{obl} = 4.099 and is higher than *t*-Student distribution quantile of $t_{(0.95,\,2)}$ = 2.920. Therefore, the following was assumed that the characteristic concrete compressive strength $f_{ck(t)}$ at age t totals:

$$f_{ck(t)} = f_{cm(t)} - 4 \text{ MPa}, \quad \text{for } 1.5 \text{ h} \leq t \leq 168 \text{ h}, \tag{1}$$

$f_{cm(t)}$ - average concrete compressive strength at the age of t hours.

Table 1 present the results for fresh CSA-based concrete compressive strength determined in the tests, as well as calculated pursuant to equation (1).

According to Article [21], creep results of samples aged t_o = 1,5 h during the curing time of concrete CSA Rapid Set®, with the load of k_σ = 0,40, have indicated that deformations in creep-testing machines were lower than calculated according to EN 1992:2008 Eurokod 2, [6]. On day one, average sample deformation values in creep-testing machines totalled 0.74 deformation values calculated acc. to Eurocode 2, and the proportion decreased with time to 0.53 on the 7th day of the test.

6 The ceiling slab structure

It was assumed that the analysed ceiling slab is unfinished, free-supported at the edges, made of reinforced concrete. Main reinforcement is made of A-III ribbed steel, and distribution bars - of glass fibre composite rods. The solution allows rolling a long section of the prefabricated mesh (owing to its high elasticity and shape memory of the composite rods as distribution rods).

Three phases have been defined in the behaviour of the load-bearing structure. State I, or self-supporting ceiling slab (without an external load), state II – planned layers in the ceiling, and state III – corresponding to target behaviour of the load-bearing structure with full operational load.

6.1 State I – self-supporting ceiling slab

According to the tests, CSA-based concrete of age t = 1,5 h (from mixing with water) was characterised with strength $f_{cm(1.5)}$ = 24.9 MPa, cf. Table 1. After calculation acc. to equation (1), characteristic strength totalled $f_{ck(1.5)}$ = 20.9 MPa.

Pursuant to calculations according to EN 1992:2008 Eurocode 2 for unfinished slab, free-supported at the edges, with axial distance between supports of 3.3 m, thickness of 0.15 m, loaded with own weight q = 3.6 kN/m², for concrete C 16/20, with agglomerate of 0.8 cm, with cover of 1.5 cm (C_{dev} = 1.0 cm, C_{dur} = 0.0 cm), and reinforcement of A-IIIN grade ribbed steel (RB500), with calculated elasticity limit of f_{yd} = 435 MPa:

- reinforcement cross section area:

$$A_{s1I} = 2.01 \text{ cm}^2.$$

- bend deflection:

$$f_I = 0.07 \text{ cm}.$$

The following was assumed:

- main reinforcement φ = 0,8 cm, with spacing of 5 cm, and value A_{s1p} = 10.05 cm².

6.2 State II of planned layers in the ceiling

In the above conditions, pursuant to laboratory tests and calculations according to (1), it was assumed that CSA-based concrete with age t = 24 h has characteristic strength of $f_{ck(24)}$ = 33.9 MPa. For C 25/30 concrete grade, with constant load q = 5.1 kN/m²:

$$A_{s1II} = 2.01 \text{ cm}^2, \; f_{II} = 0.11 \text{ cm}.$$

Therefore, reinforcement as in section 6.1, namely φ = 8 mm, with spacing of 5 cm, and value A_{s1p} = 10.05 cm^2 , are bigger than required for state II.

6.3 State III of slab bearing strength with operational loads

In the conditions as in section 6.1, it was assumed that CSA-based concrete with age t = 168 h has characteristic strength of $f_{ck(168)}$ = 39.3 MPa. For C 30/37 concrete grade, with constant load of 5.6 kN/m^2 and variable load of 2.0 kN/m^2:

$$A_{s1\mathrm{III}} = 4.81\ \mathrm{cm}^2,\ f_{\mathrm{III}} = 1.00\ \mathrm{cm},$$

$$f_{\mathrm{I}} + f_{\mathrm{II}} + f_{\mathrm{III}} = 1.18\ \mathrm{cm} < f_{\max} = 1.32\ \mathrm{cm}.$$

Therefore, the applied reinforcement as in section 6.1, namely φ = 0.8 cm, with spacing of 5 cm, and value A_{s1p} = 10.05 cm^2, are bigger than required for state III with target load, and the final slab deflection is lower than permissible.

7 Time limits for concrete mix embedding

In the *stropotronic* technology, automatic mixing of components with water, and their direct transport and dynamic extrusion embedding (mechanical compacting of the concrete mix with pressure exerted by the carrier blades) occurs in one continuous production process. Any portion of the mix that has water added into it at a specific moment features two important process times to be noted. One, ‘the latest time’ after which no vibrations from the dynamic extrusion of fresh material embedded can affect the cement during its setting time, and the other, ‘the earliest time’ to assure that the time of supporting the freshly formed section of the ceiling has been long enough, and concrete age assures the necessary compressive strength and the structure can start functioning as a self-supporting structure from that time onwards.

7.1 The latest time of concrete mix embedding

According to the conditions of correct workmanship, after t_{pw} – onset of cement setting, the concrete mix must not be moved or exposed to vibrations, initiated here by the machine upon material compaction, as this might cause damage to the bonding crystals formed. Therefore, it must be assured that the formed mix is no longer exposed to vibrations transferred by the material laid from the added and mechanically compacted mix still before the onset of CSA cement setting. Because of intense attenuation occurring in the pressure-densified fresh mix in our solution, the vibration zone is small, and already at a small distance a, totalling up to a few cm from the surface of direct exposure to compacting machine blades, the harmful impact is limited.

Therefore, in reference to each portion of the mix, at a time shorter than until the onset of CSA cement setting, components must be mixed with water, transported, and embedded, with such a quantity of material added so that the operating zone of the machine is moved away to the distance a, in order to eliminate the negative impact of vibrations. This can be written as:

$$t_{pw} \geq t_m + t_{tw} + t_a \tag{2}$$

t_{pw} – time interval from mixing components with water until the onset of CSA cement setting time, t_{pw} = 32 minutes,

for concrete mix portion (mixed with water at time t) duration:

t_m – component mixing, t_m = 2 minutes,

t_{tw} – transport and extrusion (in the most unfavourable case, with mix transport to the most remote embedding location, namely at the section of 3 m) t_{tw} = 9 minutes,

t_a – construction of a ceiling section with length a = 8 cm, in minutes.

After transforming the equation (2) and substitution of values, the construction time of section a = 8 cm of the ceiling must meet the following condition: $t_a \leq 21$ min.

7.2 The earliest time of formwork removal

Automatic machine forms the ceiling section on consecutive mobile formwork discs that move underneath, continuously under the freshly placed concrete mix, cf. Fig. 1. Characteristic compressive strength $f_{ck(t)}$, as above, depends on age t – of the analysed portion of concrete. According to section 6.1, a slab of reinforced concrete automatically formed on formwork discs achieves self-support function in the span between the supports, namely state I, at the age of CSA-based concrete totalling t_{I}. Therefore, the earliest time of removing the formwork supporting the ceiling in the span between the supports corresponds to the age of concrete totalling t_{I}. When analysing the embedding process, one can write it as:

$$t_{\mathrm{I}} \geq t_m + t_s \tag{3}$$

t_{I} – age of concrete upon the ceiling slab becoming self-supportive (without an external load) in the span between supports – state I, t_{I} = 90 minutes,

t_m – as above, component mixing time (t_m = 2 minutes; here, during the mixing, the material is transported to the nearest place of embedding; hence, the time t_{tw} – transport and extrusion was omitted)

t_s – applicable period of supporting the ceiling slab in the span between the supports with mobile formwork, in minutes.

After transformation of equation (2), the applicable period of supporting a ceiling slab section in the span between the supports with the mobile formwork (corresponding to the earliest time of the ceiling becoming self-supportive in the span between the supports) can be specified with the equation:

$$t_s \geq t_{\mathrm{I}} - t_m. \qquad (4)$$

Due to the short time of component mixing t_m, the assumption is that $t_s \geq t_{\mathrm{I}}$.

7.3 Maximum speed of machine and mobile formwork movement

The automatic machine moves in the time t_s (namely period where concrete achieves the strength to assure self-supportive ceiling in the span between the supports) at the section with the length of:

$$s = vt_s \qquad (5)$$

v – ceiling construction speed, corresponding to the moving speed of the automatic machine, cm/min.

In order to meet the condition of ceiling support in the span between the supports for the applicable time interval t_s, it is required that l – the width of formwork discs supporting the curing concrete (cf. Fig. 1) is not lower than s – length of the ceiling section constructed in such time interval t_s, hence:

$$l \geq s. \qquad (6)$$

In equation (5), following the substitution for s and transformation, velocity v of machine movement when constructing the ceiling must meet the following condition:

$$v \leq l/t_s\,. \qquad (7)$$

In the case analysed, when freshly constructed ceiling is supported by formwork discs at the section l = 1.5 m, and with value t_s = 1.5 h, the moving speed of the machine is low, and totals $v \leq 1.0$ m/h (namely $v \leq 1.67$ cm/min).

Similarly, efficiency Q of embedding concrete mix in m^3/h can be calculated using the equation:

$$Q \leq hbv, \qquad (8)$$

h and b – respectively, thickness and width (span) of the ceiling section constructed, m.

In the case of a ceiling with slab thickness of h = 0.15 m, span b = 3.3 m and machine and formwork movement velocity as above, $v \leq 1$ m/h, concrete mix embedding efficiency totals $Q \leq 0.45$ m^3/h (namely 7.52 dcm^3/min).

8 Conclusion

The prototype *stropotronic* technology for construction of monolithic concrete ceilings with mesh reinforcement:

- envisages numerical control of an integrated sequence of machinery in charge of: intermediate material stock – dosing, mixing, and transport of components – placement of reinforcement and extrusion of the concrete mix – support of the formed structure during concrete curing for the required period of time;
- applies the system for material preparation and feed, including a robot embedding the reinforcement mesh of main steel rods and distribution rods of glass fibre, as well as concrete mix on rapid setting CSA cement, as well as simultaneously moving mobile formwork to support the constructed structure during concrete curing time, until the ceiling slab achieves self-supporting properties (across the span between the supports; after the formwork has been removed from the ceiling constructed, the self-supporting slab must not be exposed to external loads for 24 hours).

  Owing to numerical control, and as a result of precise operation of the robot embedding the materials, and mobile formwork, it is possible to apply the CSA (calcium sulphoaluminate) cement-based concrete which, after mixing with water, is characterised with:
- very short time to the onset of cement setting (approximately 0.2 to 0.5 h);
- next, immediate concrete hardening and rapid increment in its early strength, e.g. compressive strength f_{cm} – average test values were over 24 MPa, 37 MPa, and 44 MPa, respectively after 1.5 h, 24 h, and 168 h, while characteristic values $f_{ck(\mathrm{t})}$ calculated according to the proposed equations totalled, respectively 20.9 MPa, 33.9 MPa, and 39.3 MPa;
- ceiling slab made as above achieves state I of self-support (across the span between the supports) after 1.5 h, state II allowing for execution of planned layers in the ceiling – after 24 hours, while state III of complete load bearing capacity adjusted to target loads is achieved after 168 hours.

  According to the calculation algorithm, the conditions of timely works execution in respect of each concrete mix portion are continuously controlled in the aspect of:
- the latest embedding time,
- the earliest formwork removal time,
- through control of material preparation and embedding efficiency, as well as robot and mobile formwork moving speed.

Characteristics of *stropotronic* technology include:

- liberating people of hard physical labour, including the need to prepare labour-intensive formwork in difficult site conditions;
- adjustment of the equipment and progress of works to the properties of materials applied; here: rods of glass fibre and CSA cement;
- limited involvement of technical means, namely low weight and low capital intensity of the solution.

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About the IAARC Community and Annual ISARC

The International Association on Automation and Robotics in Construction is the world's leading network of professionals and researchers in architecture, engineering, construction, and facility management (AEC/FM) who feel that the practice, education, and research of automation and robotics in construction have to transform in order to respond to the world's existing and future challenges. What historically has been organized by leading academics around the world has turned in 1990 to the world's leading International Organization for Automation and Robotics in Construction (IAARC).

By then a number of international symposia had already been convened and since 1984 the International Symposium on Automation and Robotics in Construction (ISARC) is IAARC's annual flagship event where both practitioners and researchers, industry and academic leaders meet. While ISARC has steadily grown over the past years it has always been presaging most of the innovations that have prominently emerged in the construction and infrastructure industries. Topics including 3D reality capture (i.e., laser scanning, drones), augmented/mixed/virtual reality (AR/MR/VR), artificial intelligence (AI), information modeling, 3D printed, automated heavy equipment, lean construction, supply chain management, prefabrication, and modularization have all been researched under the IAARC umbrella.

While the IAARC members come from all over the world, most are from the various industry and academic sectors in construction. Their common tie is to work together to drive innovation in safety, productivity, efficiency, and quality performances in an industry often pointed to lag behind others. The proclaimed goal of IAARC is to improve processes and people in the construction industry by advancing research and education on technology and innovative practices.

Even IAARC's open source intellectual property (IP) approach is innovative. Over 4,500 ISARC proceedings are all freely available on the IAARC website, with a new set added every year. Numerous innovations first researched within the IAARC community eventually emerged as commercial technologies, processes, and products, though in some cases it has taken decades. The recent uptake in interest of the AEC/FM community in transforming an entire industry through information and communication technologies (ICT) has considerably shortened the path of commercializing scientific research. Research-to-product (R2P) as well as rigorous prototype testing of integrated, practical, or operative solutions result in novel intellectual property (IP).

Other IAARC success stories involved innovative and forward thinking principles and methods like real-time automated material tracking, digital site layout planning, robotic platforms for automated assembly, human-machine interfaces, laser scanning for point cloud data acquisition and as-built modeling, internet-of-things (IoT), wearable sensing and actuation devices for safety and health monitoring, and many more. These are just a few of the topics that are presented at the annual ISARCs. Contributions of the most recent ISARC have proven that research and development on automation, robotic and digital technologies go hand-in-hand. They are about transforming the way we design, construct, or operate the built environment. It is therefore worth attending an ISARC where academic and industry leaders meet to bring much needed change to our industry! For more information, please visit http://www.iaarc.org.

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