Internet of Things (IoT) for Integrating Environmental and Localization Data in Building Information Modeling (BIM)

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Abstract –

Digital transformation is an ongoing challenge in construction. Whereas central storage and planning with Building Information Modeling (BIM) can be considered state-of-the-art, the integration of real-time data like environmental and localization data of workers in indoor work environments can provide further benefits for operations management in construction and facility management. This paper introduces the concept of permanent availability of up-to-date actual performance data sets through an Internet-of-Things (IoT) approach that integrates environmental and localization data in a cloud-based BIM platform. In this paper, we reflect on the usage of Internet of Things (IoT) technology and the lean and injury-free (LIFE) construction management approach, create a concept to implement the topics in existing systems, design and create a prototypical application, validate the prototype in field-typical work settings, and critically review the results.

Keywords –

Building Information Modeling (BIM), Bluetooth Low Energy (BLE), cloud computing, data visualization, facility management and operation, Internet of Things (IoT), Lean Construction Management (LCM), location tracking, real-time sensor data.

1 Introduction

The vision of Internet of Things (IoT) is to change the world as we know it. To name a few examples in construction applications, machines will be talking to each other to optimize production and assembly of materials, project coordination will be based on informed decision making, and smart systems will accurately predict and prevent risk of many kinds currently embedded in the harsh construction site work environment. Most construction enterprises, however, are still stuck with business processes that are as far removed from the IoT as paper based communication is from using a Fax or, more recently, E-Mail.

For years now, visionary construction companies have been connecting things, but if closely looked, they resemble nothing so much as digital islands. Often individual departments tackle and perform a specific task, but they do not make sure the information created is available everywhere in the organization. The result is a large disconnect, making operations inefficient at best, costly or life threatening at worst.

While the Building Information Modeling (BIM) method intends on supporting integrated or interdisciplinary delivery of construction projects, there generally is no connection between most of the architectural or engineering firms during the project design or planning phase with manufacturing or construction companies during the project execution phase. Furthermore, seamlessly connecting the early project phases with the operation and management (O&M) phase is important considering the true lifecycle costs of a project. An estimated 80 % of a building's cost occur during the O&M phase.

For these and more reasons, lean management in construction was examined. Koskela [1] developed the Transformation-Flow-Value (TVF) - Theory, saying that construction can be conceptualized with the transformation of resources and the creation of value and flow of materials and people. Ever since then, several lean production control theories have been developed for the construction sector [2]. Although they eventually developed to practical methods, tools for efficient (automated) data collection on construction sites and (near) real-time analysis are still missing.

It is therefore humans that enter field data in machines (e.g., tablets) that then process for most parts autonomously data to information. Humans again interpret the results and transfer information to valuable knowledge.

Proper construction project information management, from data generation to knowledge availability and sharing, is an essential key to the successful implementation of production controlling methods. Though a constant and reliable flow of information to assess work progress, constraints, and productivity is required.

The proposed concept envisions the support of lean and injury-free (LIFE) construction processes while facilitating higher task quality, on time project delivery, and safe value creation processes. It dates back to Teizer er al. [3] when this vision was first articulated in the proceedings of the 24th ISARC. This paper (1) reflects on the usage of Internet of Things (IoT) technology and lean management approaches for the building construction and facility management industry, (2) introduces a concept to implement both topics in existing systems, (3) implements a prototypical application, (4) validates the prototype in realistic indoor work settings, and (5) critically reviews the results.

2 Background

Aside a review on IoT-related technology and applications in construction, this review concentrates on the two use cases: (1) current practices for planning and assessing occupational safety and health in indoor work environments and (2) tracking trades to measure work progress in interior finishing tasks of building projects.

2.1 Construction safety and health planning and auditing

Construction safety and health planning, monitoring, and enforcement relies mostly on human experts applying knowledge on an as-needs basis. Most of the current safety-in-design (SID) review practices for general construction projects identify and mark the potential hazards on two-dimensional (2D) drawings [4]. Requirements for lighting, for example to carry out work at proper illumination levels, follow the safety and health standards set by the Occupational Safety and Health Administration [5] While such rules exist in most countries around the world, they differ minimally (Table 1).

Current practices for planning safe work execution during construction visualize the required equipment based on expert opinion and experience. Figure 1 illustrates a result for planning the floorplan of a building project with essential lighting equipment. The dots indicate the lighting spots fixed at the ceilings of each room. The size of the lines indicate the expected brightness level according to how frequently the hallways are traversed.

Table 1. Required minimum illumination levels by area of operation [1 foot-candle (USA) = 10.7639 lux (International)] [5,6]

Area of operation (Examples)	Luminous flux [lux] OSHA (USA)	Luminous flux [lux] BG Bau (Germany)
General areas	32	--
Corridors, exits, stairs, and walkways	53	--
Landside work areas	53	20-30
Tunnels and underground work areas	53	60
Social rooms (eating, changing, and restrooms),	107	100-200
First aid stations	323	

Figure 1. Worksite lighting assessment process (example: manual drawing) [modified, 7]

The manual planning tasks require a certified engineer's or competent personnel's time. Although human errors in the planning phase can occur and safety plans are less often (if at all) updated once construction is in underway, work spaces are still required to be frequently checked upon. In essence, current construction safety planning and monitoring processes in many construction organizations apply the minimum but complex legal framework of rules and regulations. For this reason, many construction companies have shifted to self-regulated (stricter) safety best practices to ensure that work environments are kept safe. In this task though, the personnel is mostly using manual measurement devices and reporting.

Previous studies show that (a) the safety and health process remains a key issue in construction and (b) there is limited focus on the current status of construction sites due to the lack of suitable controlling and tracking functions in existing information management methodologies. The collection of actual data (e.g., safety and health or progress) is a crucial step towards informed management systems and serves as a prerequisite for further successful production planning and controlling. While current progress on projects is often compiled manually which is very time consuming and prone to human error, it leads to overall lower product quality and decreases the chances for successful risk mitigation. There is a need to compile and integrate tracking and forecasting information as feedback and input for successful identification, preparation, and execution of single working steps.

2.2 Digital progress tracking for Lean Construction Management (LCM)

Construction research has been increasingly focusing on discovering synergies between the adoption of lean and injury-free practices and information and sensing technologies [8]. Information and communication technologies (ICT) are in particular beneficial to lean and injury-free practices when they improve the flow of construction processes by identifying non-value or risk adding activities that can be eliminated. Other examples are cycle-times that can be shortened, rework, variation and errors that can be omitted [9].

Lean management and the adaption of technology is not new to construction. Several practical field applications exist, for example, Radio Frequency Identification (RFID) for pipe spool tracking [10], Global Navigation Satellite System (GNSS) for earth hauling operations [11], and wireless Real-time Location Sensing (RTLS) for tracking repetitive travel patterns of workers [12]. Even commercial solutions exist that allow personnel in the field to carry out inspections, for example, progress and quality reporting, and other documentation tasks.

The digital transformation remains an ongoing challenge in construction and facility management applications (see an example of current methods in Figure 2). While centralized cloud-based data storage and planning with BIM can be considered state-of-the-art, research by Sacks et al. [9] and Cheng et al. [13] outlines that much stronger ties between lean, safety and health, BIM, and digital technology are needed.

Figure 2. In-field manual trajectory planning for maintenance tasks relies on paper-printed building layouts

The focus of the proposed concept (Figure 3) is on tightening the planning, execution and control processes by planning digitally first (as-planned conditions), executing projects with mobile information at hand in real-time (in-field conditions), and reporting actual data on progress and quality (as-is or actual conditions). The methods for planning, supplying, and reporting data are based on building information modeling software, mobile field communication devices, and cloud-based information management solutions. Most of which exist commercially, but yet have to be bundled together in effective manner for practical use. These enable rather than reduce the capacity of construction personnel to understand, collect, and communicate high quality information quickly. The potential to make high fidelity information available that previously has neither been recorded nor analyzed has to be evaluated in studies.

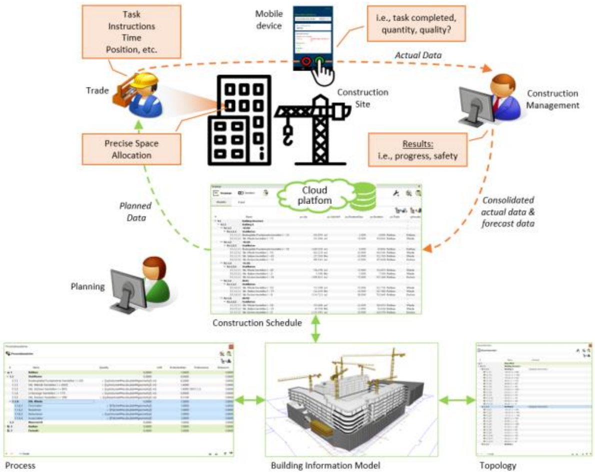

Figure 3. Overview of the proposed IoT system architecture: Digital project planning, cloud-based mobile field instructions, and actual as-is data recording and feedback processing [2,14]

2.3 Internet of Things (IoT) approach to connect physical work environments with digital information

The IoT foresees a future in which digital and physical things or objects (e.g., mobile devices, machines, and tools) can be connected by means of suitable information and communication technologies, to enable a range of applications and services (Figure 4) [15]. Challenging characteristics of IoT in construction involve suitable and scalable (mostly wireless) sensor networks and devices with robust and secure architectures, open data formats and interfaces, and dependencies that are operable in the harsh and dynamic work environment. They need to tackle rather large number of spontaneous events, creating and sharing knowledge from big data, while maintaining the privacy of humans [16]. Economies in many countries, e.g. in Germany, have established the term "Industry 4.0" referring to fourth industrial revolution (after mechanization, mass production, computer and automation, cyber physical systems) [17].

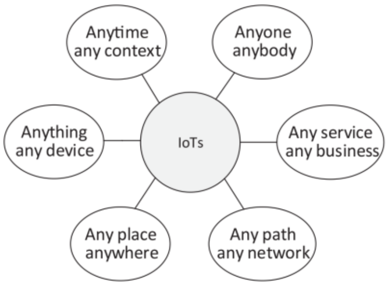

Figure 4. Definition of IoT [15].

3 Method, Experiments, and Results

While Figure 3 shows already the architecture of the authors' approach and the associated components, this section focuses on the technical description of the developed IoT system.

The authors implemented the proposed concept with components regularly used in research laboratories. Each "worker" (test subject) in the validation is equipped with sensor-enhanced personal protective equipment (PPE). In our case, sensors mounted on a hard hat collect environmental data (e.g., illumination levels) from the surrounding work environment and associate the location (e.g., ID of the work station) to each reading autonomously (Figure 5).

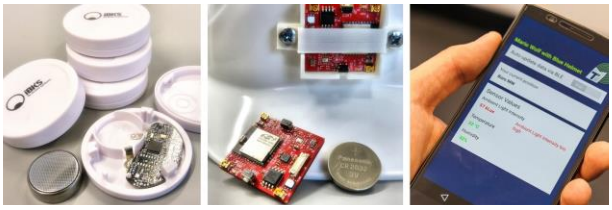

Figure 5. BLE beacons (left), BLE sensor on hard hat (middle), and mobile app (right)

The authors enable the collection of relevant data with Bluetooth Low Energy (BLE) based sensory equipment and the internet capability of smart devices (i.e., smartphones). Specifically constructed 3D-printed casings housed Avnet's Visible Things Bluetooth Smart Sensors [18]. These sensors allow the collection of various data sets related to environmental conditions, for example, temperature, humidity, and lighting.

The casings were mounted to the side plates of regular hard hats. It ensures the structural integrity of the hard and allows the casing to be used as an optional and easy-to replace add-on feature like it is already very common for the installation or the removal of face or hearing protection devices. The authors implemented a simple location tracking based on BLE beacons (Accent Systems iBKS105) utilizing the EddyStone Protocol and RSSI measurements for distance estimation. Details to the robustness of BLE location tracking can be found in Neges et al. [19].

Combining the traceability of the worker's location (case study 1) and the environmental data (case study 2) enables the IoT-platform to monitor key safety-related figures like time spent in low or high temperatures or the lack of adequate lighting at a work station. For example, work stations in the basement of a building under construction generally offer one of the poorest working conditions throughout a construction project. Accidents in such spaces lead to high number of minor injuries (e.g., spraining an ankle) that cause high costs to the industry (i.e., due to the absence of workers from work for a few days). While such instances also lower the productivity, such costs must be avoided through novel methods, such as rule checking during safety-in-design reviews as well as real-time site monitoring [4].

One of the authors' objectives was to provide the workers with easy-to-use tools for detecting whether a work station is safe or unsafe to work in. The first case study located the workers in the work stations assigned via Building Information models (BIM). For the mobile implementation of the Android 6.0.1 application, the test subjects used their private cell phones as a communication center for both the data capturing and the relaying of the data to the cloud platform.

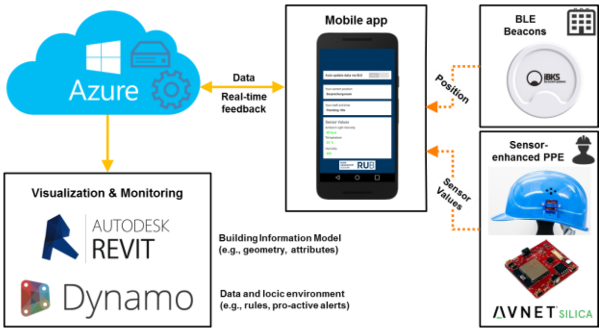

Figure 6. IoT including sensors for data collection, cloud platform data storage, processing, and communication

The backend for the storage of said data was tested on several IoT platforms. For example, the first use case on location tracking of trades used the IoT-platform of PTC Thingworx. The second use case on construction safety and health applications used Microsoft's IoT-platform Azure. Connected to Autodesk Revit with the programming interface of Dynamo to process real-time data (Figure 6), the Azure cloud only saves refined data, usable for further analysis.

3.1 Case study 1: Tracking trades by room

The first preliminary test of the developed IoT concept focused on tracking several trades in a building construction project. Assigning and coordinating the right work station, the times to begin and end work, etc. for a multitude of trades that are concurrently present inside a building project is critical to achieve a continuous production flow. Enabling methodologies like BIM and LCM improve project understanding by visualization the bottlenecks between tasks, the requirements of the processes and their dependencies.

The aim of the first case study was to provide a continuous progress monitoring function (Figure 3). The particular focus was set on testing the feasibility of the developed IoT approach for tracking the location of trades assigned to interior finishing tasks.

The proposed approach used an nD-BIM for planning the project topology (i.e., work station/location) of resource-loaded processes (i.e., name, dependencies, quantity, cost, required resources) [14]. It linked the geometric information to an automatically derived construction schedule (i.e., duration, quantity, trade). The IoT-platform relying on wireless location tracking and reporting technology (e.g., Bluetooth Low Energy (BLE) sensors, mobile devices and a cloud database made the information of directives, prerequisite work, and resources available to authorized users.

To that extent, the authors enabled the collection of relevant data with IoT-functional equipment, stored the data in an IoT-platform and connected it to a BIM system to seamlessly integrate real-time data. The use case tested a lightweight infrastructure solution for indoor tracking of personnel of three trades.

The validation had the goal to avoid spatial overlap of the trades. BLE beacons installed at the work stations (mounted inside the rooms at a wall, ceiling, or door frame) transmit their signals as soon as a worker enters the work station. The smartphone enables the connection to the IoT cloud-based platform for further data processing. Time recordings per second or higher become feasible. Knowing the presence of workers at a lower frequency might offer an opportunity to comply with potential privacy regulations that are present in many countries. The same technology works for asset tracking, including tools and materials. In such a use cases, smaller BLE beacons are installed or embedded inside the tools' casing or material, respectively.

Combining the traceability of the personnel's location and timestamp enabled the IoT/BIM-platform to collect and visualize actual presence and duration of trades by work station (Figure 7). As ethical concerns are important to construction organizations and the workers themselves, tracking what tasks the trades were performing while being at the work station is not possible (unless further technology is implemented) and subsequently was not monitored.

Figure 7. BLE-beacon positions planned in BIM (top) and real-time work station occupancy visualization by trade (bottom)

3.2 Case study 2: IoT for personalized real-time construction safety and health audits

A second preliminary use case to test the developed IoT concept focused on measuring the brightness level at work stations. The experimental setup was similar to the first case study. In addition, the authors designed a Dynamo script (Figure 8) that allowed to visualize the results in real-time in Autodesk Revit (Figure 9). Furthermore, the authors created a mobile application that enables a worker to generate personalized feedback in real-time. The user interface displays the lumens flux value and indicates in red color whether it is safe to remain at the work station (Figure 10).

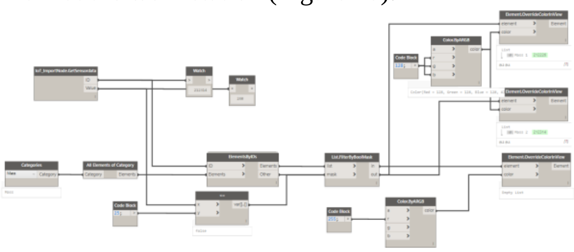

Figure 8. Dynamo script to transfer the results from the IoT-platform and visualize it in Autodesk Revit

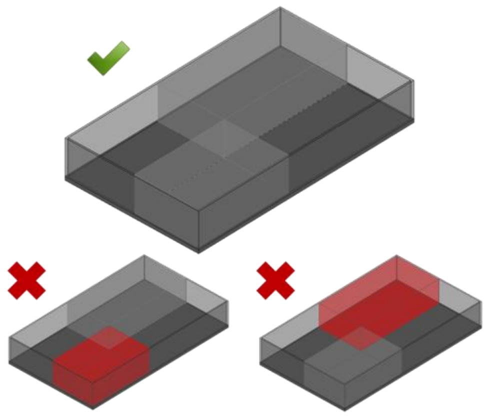

Figure 9. BIM visualizing two work stations (top) to be monitored in a (proposed on- or off-site) safety and health command center that overlooks the safety and health compliance for the construction site(s). Real-time alerts appear upon a test subject (worker) entering two work stations with insufficient lighting (middle).

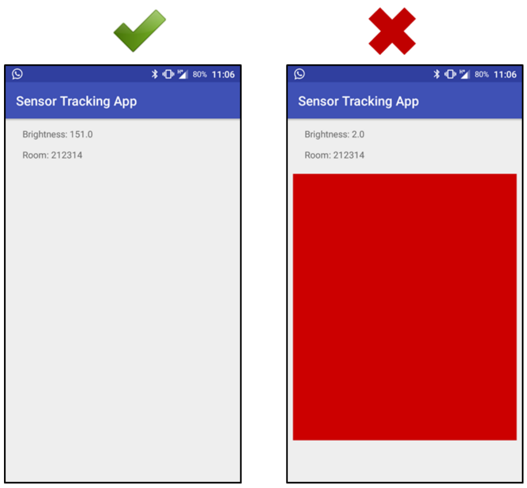

Figure 10. Personalized real-time feedback for the test subject (worker) on a mobile device indicating brightness levels 151 lux (left) and 2 lux (unsafe work environment unless further temporary lighting is provided) (right)

3.3 Path forward

While both experiments were conducted inside an existing building, the results present two important early findings: (a) the developed approach might extend its usefulness from construction to operation and management applications and (b) more tests in realistic construction environments are needed (and are planned). While the future research focus might be on the latter, investigations need to focus on the reliability of available data sensing infrastructure, data mining, and communication approaches.

4 Conclusions

Proposed is an Internet-of-Things (IoT) approach that integrates environmental and localization data in a cloud-based BIM platform. The design of a prototype system consisting of BLE beacons, sensor-enhanced personal protective equipment (PPE), Building Information Modeling (BIM), and IoT platform was successfully applied in two relevant case studies for construction and facility management and operation. The mesh of the technologies were successfully tested in laboratory-like, controlled work settings.

Preliminary evaluation of the results indicate the possibility to collect and visualize actual project data in real-time. The validation shows the potential for the implementation of connected, digital, and smart technologies in construction engineering and management as well as facility management and operation processes.

Future work will include the implementation of the author's improved BLE tracking algorithm [19], as well as advanced sensory equipment and communication over the LoRaWAN standard. After finishing the new prototype (called SmartHat 4.0), the authors will conduct a field study on an actual construction site.

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