Construction 4.0: A Roadmap to Shaping the Future of Construction

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Abstract –

The construction industry is forecast to grow from its already impressive size to unprecedented new heights. This significant expansion, along with the increased complexity and sophistication of construction projects, has placed more pressure on construction companies to maintain their vitality and grow in the modern market. As the fourth wave of technological advancements, known as Industry 4.0, continues to evolve, it becomes imperative for construction companies to adopt new technology to remain competitive – much like the Darwinian mantra, the companies must adapt or die. Although the construction industry is often labeled as conservative regarding potential advancements in technology, it has been experiencing a growing use of a wide range of 4.0 technologies. Using insights gained from the existing literature, this paper explores the current state of Construction 4.0 and discusses a four-layer implementation of Construction 4.0 in the industry. Seven Construction 4.0 technologies are first discussed, their integration throughout the project lifecycle is presented in a roadmap, their integration and connectivity with one another are outlined in an interaction roadmap, and the requirements necessary for achieving the 4.0 transformation are articulated. A case study is finally presented to showcase the proposed implementation plan.

Keywords –
Construction 4.0; Implementation; Roadmap; Integration; Interactions

1 Introduction

The construction industry sits at a crossroads. It is economically vital to the prosperity of nations, and a key player that affects our everyday lives. Yet, the construction industry lags behind other major industries in its adoption of technological advances [1]. Nassereddine et al. [2] noted that the complex nature of the construction industry and its heavy reliance of information require the adoption of new and emerging technologies. Challenges facing the construction industry span a multitude of reasons including the dauting decline in productivity, shortage in the workforce, low levels of research and development (R&D), and the inefficient and insufficient transfer of knowledge from project to project [3], add more pressure on construction to move from an industry that has resisted emerging technology to one that is embracing it. One industry that has been a source of innovation in construction is manufacturing [4]. From the many practices that construction has adopted from manufacturing, this paper focuses on the concepts of Industry 4.0.

Industry 4.0, a term coined by the German Federal Government to highlight the fourth industrial revolution [5], can be defined as "a new technological age for manufacturing that uses cyber-physical systems and Internet of Things, Data and Services to connect production technologies with smart production processes" [6]. Montgomery and Norman [7] noted that manufacturing has passed through three different revolutions before reaching Industry 4.0, namely, revolutions, mechanization, electrification, and digitalization. Schwab [8] explained that Industry 4.0 is the stage that enables the full integration between people and digitally controlled machines with the help of internet and information technology (IT). Lu [9] added that industry 4.0 supports the growth and evolution of various fields and industries. The automotive industry has greatly benefited from Industry 4.0, where manufactured cars are being 40% controlled by electronics [10]. The health sector has also taken full advantage of Industry 4.0 in creating new diagnostic methods and technologies to sequence genes [11].

The industry is said to transform the lifecycle process of products and production systems by increasing the connectivity and interaction among parts, machines, and humans [10]. This transformation is enabled and driven by nine fundamental technological advances, also referred to as pillars: autonomous robots, Augmented Reality, Simulations, the cloud, Big Data and analytics, the Industrial Internet of Things, cybersecurity, additive manufacturing, and horizontal and vertical system integration [12]. It should be noted that the technology itself is not powering Industry 4.0: while most of the nine pillars are not entirely new to manufacturing, it is the full integration of these building blocks and their connectivity across the borders that define Industry 4.0 [3].

The construction industry has also experienced a radical transformation and made great strides in changing its status quo and embrace technological advancements [13],[14],[15]. Influenced by the gains that resulted from the fourth industrial revolution, researchers in construction began investigating the potential of integrating Industry 4.0 into construction. While construction is often compared to manufacturing, the former is approaching and embracing Industry 4.0 from a different direction [12]. Recently, the term "Construction 4.0" emerged in the 21st century construction research corpus [16]. The interest in Construction 4.0 is fueled by the development of various technologies, the drastic change in the needs of owners, the shift towards mass customization, and the need for green construction and sustainability [16].

Through a thorough literature review, this paper introduces a four-layer implementation plan and begins by discussing Construction 4.0 and seven of its most commonly cited technologies, namely: iBIM, AR, VR, robotics, 3D printing, AI, and drones. As a construction 4.0 approach is seen as a two-level integration effort: 1) integration of a Construction 4.0 technology throughout the construction project lifecycle and 2) integration and connectivity of Construction 4.0 technologies, each of those levels is examined in this paper. A roadmap for the integration of Construction 4.0 technologies across the project lifecycle is created and an interaction map of Construction 4.0 is developed. The requirements for achieving Construction 4.0 are also discussed. Finally, a case study is presented to highlight how Construction 4.0 can be realized by showcasing the four layers put forth in the paper.

2 Construction 4.0

According to the European Industry Construction Federation (FIEC), "Construction 4.0" is the counter part of industry 4.0 in the Architecture, Engineering & Construction (AEC) industry and it refers to the digitalization of the construction industry [17].

Rastogi [16] stated that the main goal of construction 4.0 is to create a digital construction site that monitors progress throughout the life cycle of a project by using different technologies. The adoption of Construction 4.0 will not only change the construction process, but it will change the organization and project structures, shifting the fragmented construction industry into an integrated industry [17].

2.1 Construction 4.0 Technologies

To understand the various layers of Construction 4.0, it is important to first understand the technologies that are enabling this transformation. While the existing research corpus discusses various Construction 4.0 technologies, this paper focuses on seven Construction 4.0 technologies that have been frequently cited. A brief introduction to each of these technologies is provided below:

Integrated Building Information Modeling (iBIM) is considered the higher level of traditional BIM and consists of three elements: (1) the integration architecture which defines major layers of iBIM and how they are interconnected, (2) the product model which defines the content and function of the object's behavior, and (3) the process model which identifies the interaction scheme and mechanism between model objects [18].

Augmented Reality (AR) is both an information aggregator and a data publishing platform that allows the user to (1) passively view displayed information, (2) actively engage and interact with published content, and (3) collaborate with others in real-time from remote locations [19]. AR is gaining increased momentum in the construction industry, and various use-cases are being explored and tested throughout the project lifecycle, such as promoting AR-enabled production planning [13] and enabling remote expert system [20].

Virtual Reality (VR) is a step further than AR on the spectrum of virtuality. VR creates a virtual and immersive experience for the user through headsets with 360-degree visions, allowing the user to experience a completely different environment. Li et al. [21] categorized the use of VR in construction into the hazard identification, which allows construction teams to sense, analyze, and extract potential dangers, and safety training and education, in which construction workers will train in a safe environment in comparison to on-site training, which might be expensive and hazardous.

Robotics uses machines that can perform or replicate human actions. While robotics has been widely used in manufacturing and aerospace, construction is following suit and is using robotics, mainly in the vertical construction sector [22]. This technology is heavily used in construction assembly work, especially for high rise buildings. SMART system developed by SHIMIZU in Japan, for instance, was used to construct more than 30 stories of an office building [23]. Additionally, different construction tasks such as painting, brick overlaying, and earthwork can be performed by robots [24].

3D printing, also known as additive manufacturing, is the process of creating a complex, physical 3D object from a CAD model. 3D printing has undergone 25 years of research and development, and as a result, the technology is currently used in different industries such as aerospace, automobile, and medical [25]. The construction industry is also exploring the use of 3D printing, mainly for small and medium-sized applications at the time being [26]. This technology is showing great potential for large scale implementations; however, a number of challenges such as layering effect which results in uneven surfaces with voids, tensile strength issues associated with the lack of steel reinforcement need to be overcome before the industry embrace this technology [27].

Artificial Intelligence (AI) is a term used to describe a machine that replicates the human cognitive functions [28]. One of the main components of AI is machine learning, where a machine learns from a set of data using statistical methods. According to a study by McKinsey & Company, AI is starting to gain momentum in construction [29]. The study highlighted three main current AI applications: (1) project scheduling optimization which is achieved by continuously testing a large number of plan alternatives and selecting the better option, (2) image recognition and classification which can be used to identify issues related to safety on site and to collect the information for future learning, (3) enhanced analytic platforms which collect and analyze building machine data and building sensor data to predict any issues related to maintenance.

Drones, also known as Unmanned Aerial Vehicles (UAVs), are unpiloted small sized aircrafts that are remotely controlled. In early 2006, drones were mainly used for military applications [30]. In recent years, their use in construction and other industries has been on the rise [31]. The construction industry is mainly employing drones for inspection and monitoring during surveying, construction, and facility management [32].

2.2 Construction 4.0 Roadmap

The first level of the Construction 4.0 integration efforts takes a lifecycle view for the integration of Construction 4.0 technologies. A project moved from its early planning phase, to design, construction, and then facility management. A technology is used to its full potential when it is integrated throughout the construction project lifecycle, where applicable [33].

For instance, several studies including [34], [35], [20] identified potential use-cases of AR throughout the project lifecycle. The blue, solid bars of AR in Figure 1 reflect the AR applications that have been tested and used on construction projects and the green, hatched bars represent the potential benefits of additional AR use-cases that are being explored.

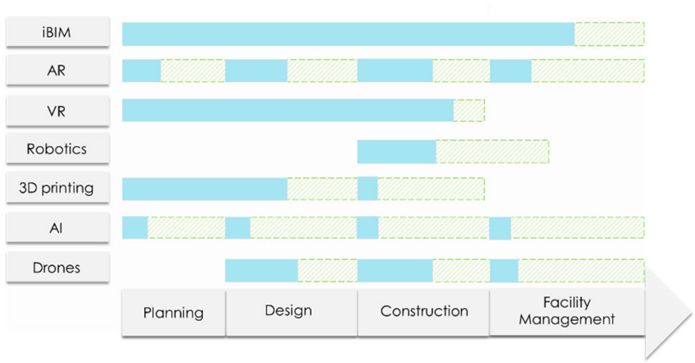

Figure 1. Construction 4.0 Envisioned Roadmap
(The solid blue bars represent the current use of a construction 4.0 technology
and the green hatched green bars represent the projected use of a construction 4.0 technology)

2.3 Construction 4.0 Interaction

The second level of the integration efforts demands an increased connectivity and interaction of Construction 4.0 technologies [36]. Aleksandrova et al. [37] noted that the full integration of digital technologies is a radical transformation in construction that creates a united digital ecosystem.

A scan of the literature on Construction 4.0 and its associated technologies was performed to identify current and future potential interactions. A map was then developed (Figure 2) to outline those interactions and illustrate potential synergistic efforts.

iBIM and AI can be thought of as core technologies of Construction 4.0 and the impetus to connectivity [37]. Copper [38] added that BIM and cloud-based common data environment (CDE) are central to Construction 4.0 framework: BIM carriers the simulation feature that is a core component for Industry 4.0, and CDE acts as the data warehouse for all information related to construction project over its life cycle. BIM and CDE establish a single platform that helps integrate all of the construction project phases and link the physical and cyberspace [3]. Thus, allowing the implementation of Construction 4.0.

Some of the interactions outlined in Figure 2 are extracted from the existing construction research corpus, while others are extracted from adjacent industries, such as aerospace and medical, and are interactions yet to come to construction. For instance, Wake et al. [39] discussed the interaction between 3D printing and AR technology in a healthcare environment. The authors used these two technologies on a patient with a kidney tumor. A 3D printing transparent kidney model with the ability to color the tumor zone was first created. Then, an AR kidney model of the patient was created. These models were used before and during the operation to aid in the robotic partial nephrectomy operation.

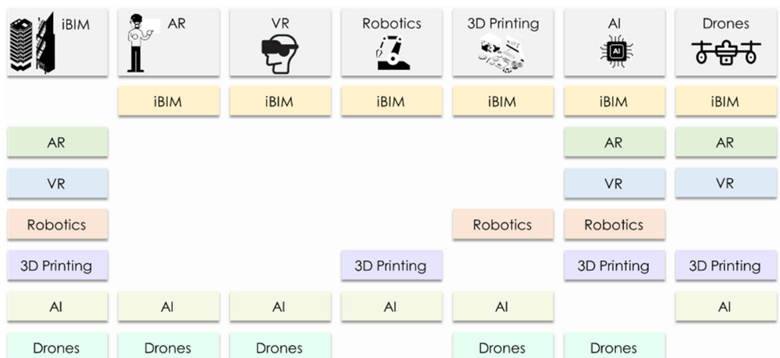

Figure 2. Interaction Map of Construction 4.0 technologies (graphics downloaded from https://www.freepik.com/)

2.4 Construction 4.0 Requirements

Embracing Construction 4.0 entails several challenges that have been discussed by construction researchers. Industries are normally averse to change, and therefore it is initially resisted until it can be perceived as a guaranteed opportunity. Several authors [38], [40], [41] noted that the construction industry is no stranger to the resistance of change.

Researchers pointed out that the multidisciplinary nature and uniqueness of the construction industry results in an unclear understanding of the value proposition of Construction 4.0 technologies. In the past construction companies often relied on a project-thinking approach when managing construction projects. The shift to Construction 4.0 requires a change of the thinking-approach and the processes. The development of digital technologies and their adaption to the construction company's needs is highly dynamic, tailorable, and expensive. Additionally, when new technologies are introduced, employees and workers will need extra training. Therefore, construction companies will generate a surplus value only if the new technologies are integrated within the company's processes and can be used across projects. The switch to Construction 4.0 requires a process-oriented mindset, as opposed to the traditional project-oriented approach. However, this mindset shift pushes construction companies to digitize their existing processes, posing an additional challenge for two reasons: (1) existing process have mostly been designed before current digital tools were available, and (2) not every process can be directly digitized. Therefore, all existing processes have to be re-engineered to accommodate the shift in the mindset and support the 4.0 transformation of construction companies.

Figure 3 shows a general process to implement new digital technologies in a construction company, as required for the transition to Construction 4.0. Prior to re-thinking a process, the actual process must be first recorded and analyzed to explore how and where the technology(ies) could be used. A thorough analysis and documentation of the "status quo" of the existing process is crucial to successfully manage the technological changes. Assessing current processes helps in identifying the relevant decision-making structures and cost relevant process steps. The process-oriented approach also forms the basis for the identification of waste and inefficiencies in the company, and thus, becomes a prerequisite for the application of Lean management in the company.

Once the existing process has been investigated, the potential for innovation and integration of technologies, along with efficiency enhancement analysis, is assessed next. This includes an application analysis of the different technologies of interest, as well as the digital tools that are already in use. The structural needs as well as the existing barriers to innovation have to be identified. The structural needs include the aforementioned aspects of implementing the various Construction 4.0 technologies in the construction companies. Other considerations for companies to think of are the high investments associated with adopting technologies, the need to additional human resources, and R&D investments, all of which poses a major financial barrier.

For a successful transition to Construction 4.0, a construction company needs a vision of the digitization change process which fits the company's needs. This is especially important since Construction 4.0 goes beyond technology alone. It includes a change in the mindset of the all people involved (from field personnel to management) as well as of the processes in consideration. Hence, a clear vision, which is supported by these people, is important. Only when these requirements are met, companies can make the transition from the traditional project-thinking to process-thinking.

This shift also changes the organization and infrastructure of many companies i.e. their partners. Another consideration to address is the long-standing problem of longitudinal fragmentation that renders stakeholders nearly powerless to pilot their companies through this change [42]. Over the past decade, the construction industry has made significant changes to its structure as organizational changes have already been applied to companies which implement Lean management. The importance of some traditional departments decreases significantly, whereas some new departments emerge.

In addition to the challenges associated with moving construction towards a process-thinking industry, the lack of global standards and framework for implementation is another roadblock. Furthermore, Construction 4.0 heavily relies on various Information Technology (IT) systems, and, therefore, concerns related to data and cybersecurity must be addressed and stringent security standards must be put forth. Legal and contractual issues need to be also discussed to allocate risks among stakeholders.

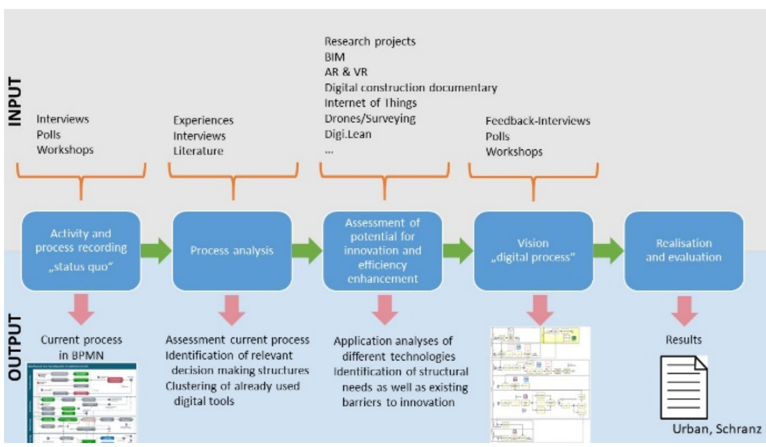

Figure 3. Process to implement Construction 4.0

3 A Case Study of the Two-Level Construction 4.0 Integration

To illustrate the two-level construction 4.0 integration, a case study where many of the previously discussed Construction 4.0 technologies act as a cross-linked system is presented.

Figure 4 shows a generalized data path for a future cross-linked system. All begins with a BIM model, which is created in a native modeling environment, like Revit or ArchiCAD. For a general use, the model is exported as an Industry Foundation Classes (IFC) file to a collaborative data environment on a BIM server. This export allows the model to be used in several of the previously discussed Construction 4.0 technologies. After exporting the model to a smartphone or tablet, the site supervisor and/or inspector (referred to hereinafter as user) can benefit from the visualization and interaction with the model on the smart device when e.g. inspecting a Heating, Ventilation, and Air Conditioning (HVAC) system. QR codes or RFID chips attached to a building component connect the smart device with the manufacturer's database of the building component.

This enables the user to access specific product data, which can be also transferred via BIM Collaboration Format (BCF) to the BIM server and, hence, back into the native BIM model. This two-way communication leads to a closed loop data transfer. Moreover, the manufacturer data, also referred to as semantic data, can be transferred to an .xml database that is then connected with the component's Globally Unique Identifier (GUID) in the BIM model. This information can be then retrieved by facility managers. This is especially valuable for maintenance- and safety-technical relevant data and leads to component-referenced manufacturer data.

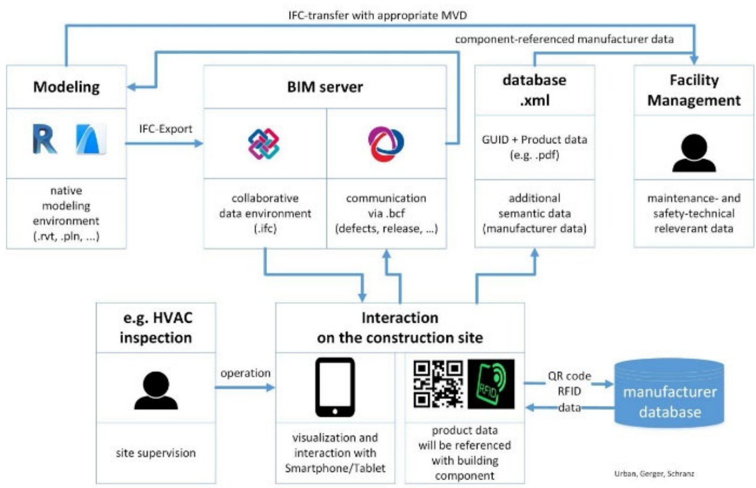

Figure 4. On-site inspection: closed-loop data transfer in a generalized form

For example, the BIM model normally contains the general specifications for a required fire protection flap. After the installation of the fire protection flap, the specific product data can be transferred into the BIM model. Then, the correct maintenance requirements for this product are available for the facility management. Another option is the usage of an IFC transfer with an appropriate MVD (Model View Definition) directly from the BIM model.

This closed-loop data transfer not only works during the construction phase, but also in the later operation and maintenance phase. Each time one or more building components are replaced, the new product data is transferred into the central BIM model.

Another technology that can be considered is Augmented Reality (AR). The authors worked on different use-cases for AR in Construction 4.0 [34], [43]. AR is one of the emerging technologies which has a great potential to transform the construction industry. The aforementioned closed-loop data transfer can be used with several AR use-case, e.g. for monitoring the progress of the construction site, visualizing augmented drawings or construction systems in the field, as well as conducting on-site inspection. In one of the research projects of the authors, AR-AQ-Bau [44], a specific AR use-case for on-site inspection has been developed. In this case, the BIM model was also exported to a BIM server and then an AR model was created using the game-engine Unity. The site supervisor can use this AR model to control the HVAC system on the construction site. The control can happen before the HVAC system is built, to check for instance, whether there is enough space for movement in front of inspection hatch. After the HVAC system is installed, the site inspection can monitor and check if everything is built correctly. This process or application not only works for HVAC but for the whole construction. In the AR device, the site inspection marks every defect or deficiency in the construction. Hence, the position of the defect in the building is stored in the AR model. Additionally, a description (text or audio) of the defect as well as photos can be added. All this information is then transferred back into the BIM model via BCF. On one hand, this helps to keep a record of all defects in a building and, on the other hand, improves the repair of existing defects. Additionally, the AR tool for site inspection is also very invaluable for the facility management during the operation phase.

The scan of QR-codes or RFID becomes easier with AR devices. After scanning the tag, the AR devices can be connected with the manufacturer's database and can retrieve the specific product data of the built-in component. This data is then transferred to the BIM model or another specific database (as described before).

4 Conclusions and Future Work

The fourth wave of technological advancement (Industry 4.0) and the digital transformation at its helm are pushing industries worldwide to embrace newer technologies to continue to remain competitive. Although the construction industry is not leading this change, it is not an exception to the digital revolution. The unique nature of the construction industry provides fertile ground for research on digitizing the industry and the term Construction 4.0. This research builds on the existing construction research corpus and discusses four layers of Construction 4.0 implementation. The first layer consists of the understanding the technologies associated with Construction 4.0. This research discussed seven frequently cited technologies, namely: iBIM, AR, VR, robotics, 3D printing, AI, and drones. The second and third layers defined the two-level of integration needed to implement Construction 4.0. The second layer presents a roadmap that outlines the integration of each of the seven technologies across the construction project lifecycle. The roadmap is a depiction of the current state-of-practice of the technologies and an outlook into future developments. The third layer offers insights into how the seven technologies can be connected and integrated together. An interaction matrix is developed to outline the relationships between the different technologies. It should be noted that the two-level integration cannot happen across the board, but rather only when applicable. The implementation of these three layers is only enabled when the fourth layer is realized. The fourth layer encompasses a set of requirements that construction companies must consider. At the core of these requirements is the necessary shift to process-thinking. Construction stakeholders must have the right mindset to pilot their companies through the disruptive Construction 4.0 storm. Finally, a case-study is presented to discuss the four-level implementation outlined in the paper. Future research efforts can extend on the seven technologies discussed in the paper and introduce additional elements of Construction 4.0. Additional research is also needed to verify the interactions between all the Construction 4.0 technologies.

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