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A Proposed Framework for Construction 4.0 Based on a Review of Literature

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Construction 4.0 is the adoption and adaptation of the Industry 4.0 framework for the construction sector. Industry 4.0 promises to revolutionize how ‘things’ are made by using physical and digital technologies in an integrated manner. Similarly, the authors envision that the Construction 4.0 framework can fundamentally change the way that assets are designed, constructed, and operated. The idea of the Construction 4.0 developed from the need of the construction sector to overcome the existing horizontal, vertical, and longitudinal fragmentation and to take a holistic approach to the improvements needed in the industry. In this study, a literature review of Industry 4.0 and its influence on the construction sector was undertaken. Based on this systematic literature review, the authors define the Construction 4.0 framework and provide its benefits and barriers to implementation. A key finding of the study is that building information modeling, and a common data environment form the key foundation for the implementation of the Construction 4.0 framework. In defining the Construction 4.0 framework, the paper described its components and how its implementation is likely to proceed. The authors envision that by adopting Construction 4.0, the industry can transform itself into a highly efficient, quality-centered, and safe industry capable of successfully delivering the demands placed on it by society.

Key Words: Construction 4.0, Industry 4.0, cyber-physical systems, digital ecosystem, Internet of Things, Internet of Services, BIM, CDE

Introduction

The construction sector must transform and modernize itself (Farmer, 2016; Gerbert, Castagnino, Rothballer, & Renz, 2017). This issue has been a constant calling from the proponents of the industry and something that the industry has been grappling with on an ongoing basis. The demands placed by the society on the construction sector are mounting, but the sector’s productivity and efficiency do not seem to be keeping in pace with these demands (Sawhney, Agnihotri, & Paul, 2014). This is not a localized problem, as is evident from the historical efforts of many countries to uplift their construction sector. For example, in the UK, several prominent studies have been conducted to highlight the problems of the construction sector and to derive a program for improvement of the whole-of-the-sector (Egan, 1998; Farmer, 2016; Latham, 1994). Similar efforts have also taken place in the US with several industry efforts documenting what is wrong and how to fix it (Tatum, 1986; Teicholz, 2013; Teicholz, Goodrum, & Haas, 2001; The Business Roundtable, 1983). Broadly, the construction sector faces broad-ranging and significant challenges such as resistance to change, barriers to innovation, low productivity, predictability, and profits, and skilled workforce recruitment and retention issues due in part to poor industry image (Farmer, 2016; Gerbert et al., 2017; Global Industry Council, 2018; Sawhney et al., 2014; The Business Roundtable, 1983; Witthoeft, Kosta, WEF, & BCG, 2017).

Teicholz (2001) developed the graph of productivity index for the construction industry and compared it to all non-farm manufacturing industries from 1964 to 1999, thereby documenting for the whole world to see the productivity stagnation in the industry. This has formed the motivation for the sector, and numerous efforts are now in place to change the status quo. Structurally these challenges result in an overall fragmentation of the construction industry (Fergusson & Teicholz, 2002). As shown in Figure 1, the lifecycle steps on a typical construction project are not tightly coupled, leading to vertical fragmentation. The project teams do not work in integrated fashion leading to horizontal fragmentation. Furthermore, these issues are repeated from projects to projects due to longitudinal fragmentation.

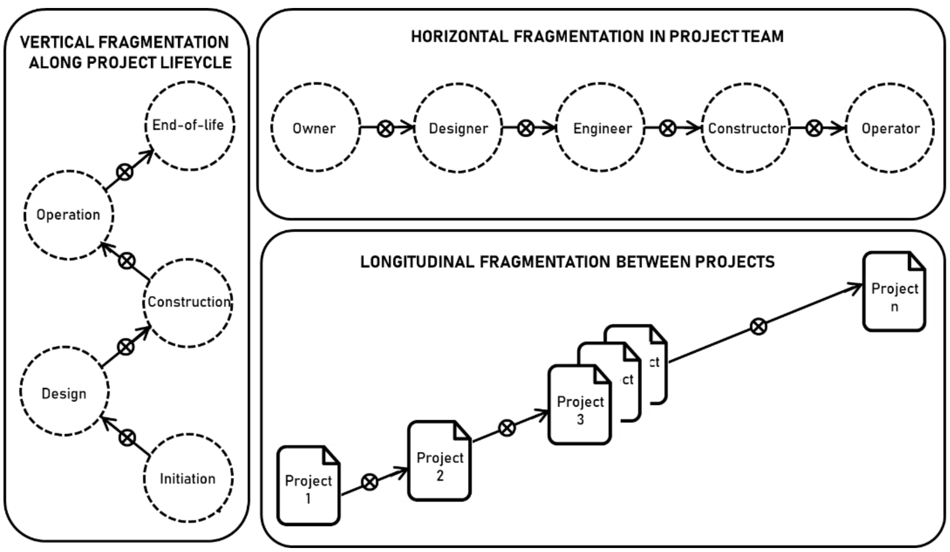

Figure 1. Fragmentation of the Construction Sector

Given this background, the industry needs transformational change (Farmer, 2016) to address these issues. The Industry 4.0 paradigm provides such a broad framework for the necessary change.

Research Objectives and Methodology

The objectives of this research were to define and describe the Construction 4.0 framework based on a detailed literature review of the Industry 4.0 concept. The study sought to establish the role of building information modeling (BIM) and a common data environment (CDE) in the Construction 4.0

framework. The benefits of the framework and barriers to its implementation were also identified and documented in this study. To successfully attain the research objectives the following four thematic areas were selected for literature review and analysis: (1) Industry 4.0 and its key components; (2) physical and digital technologies that support Industry 4.0; (3) role of BIM and CDE; and (4) Construction 4.0 definition, components, benefits, and challenges. The authors adopted the systematic literature review (Kitchenham, 2004) to study the four thematic areas, evaluate, and interpret the results. This type of review considers all available research relevant to a particular research topic or theme under consideration. Various search filters were adopted that yielded over 400 papers in the area of Industry 4.0, i.e., thematic areas 1 and 2. Of these papers, twenty papers that were highly cited and provided information about the two themes were selected for a systematic literature review. Similarly, ten articles were selected in the thematic areas 3 and 4. As this is a fast-emerging field, the search filters and selection of papers must be carefully done. Thirty research studies were analyzed and included in this study (due to lack of space, not all articles have been cited here).

Literature Review

Based on the systematic literature review, the research study documented the overview and definition of Industry 4.0, and its key components to identify its linkage to Construction 4.0. The information developed for Construction 4.0 is presented in the results section, whereas the literature review on Industry 4.0 is presented in this section.

Definition of Industry 4.0

The Industry 4.0 framework is based on the fourth industrial revolution that is currently ongoing. It relies on the use of cyber-physical systems and advanced digital technologies. As shown in Figure 2, the fourth industrial revolution allows deeper integration and handles complex real-world scenarios. The German Federal Government in 2011 released its vision for the future of the manufacturing sector under the broad umbrella term INDUSTRIE 4.0 (Roblek, Meško, & Krapež, 2016). This is now known as Industry 4.0, with an underlying thrust of the fourth industrial revolution. Industry 4.0 is a broad term consisting of a "confluence of trends and technologies" that are likely to reshape the way things are made (Baur & Wee, 2015). The German government describes Industry 4.0 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" (Kagermann, Wahlster, & Helbig, 2013; MacDougall, 2014). It will make manufacturing smart. Industry 4.0 has also been defined as "a new level of value chain organization and management across the lifecycle of products." (Hermann, Pentek, & Otto, 2016). The integration of machinery and devices with networked sensors and software that can be used to predict, control, and plan for better business and societal outcomes is a critical aspect of Industry 4.0 (Shafiq, Sanin, Szczerbicki, & Toro, 2015). In a way, Industry 4.0 improves manufacturing organizations, business models that they use, and their production processes with physical and digital technologies (Xu, Xu, & Li, 2018).

Key Components of Industry 4.0

Industry 4.0 has been made possible due to the evolution of embedded systems to more advanced Cyber-physical systems (CPS) (Vogel-Heuser & Hess, 2016). CPS consists of a set of technologies that connect the virtual and physical worlds to create a networked production environment in which intelligent objects communicate and interact with each other (Kagermann, Wahlster, & Helbig, 2013). As shown in Figure 3, the journey towards Industry 4.0 started with the embedded systems and their technological evolution towards CPS and further to provide an Internet of Things (IoT), Data, and Services (MacDougall, 2014). CPS helps create a virtual copy of the physical production environment that is called the 'digital twin.' In turn, the physical-digital-physical loop is created (Rutgers & Sniderman, 2018), which then becomes the production environment in the factory known as the Cyber-Physical Production Systems (CPPS) (Vogel-Heuser & Hess, 2016). CPPS results in a digitalized, smart, optimized, service-oriented, and interoperable production environment upon which other components of Industry 4.0 are built. Business processes and other technical processes of the production system are linked into the Industry 4.0 framework through the Internet of Things, Data, and Services.

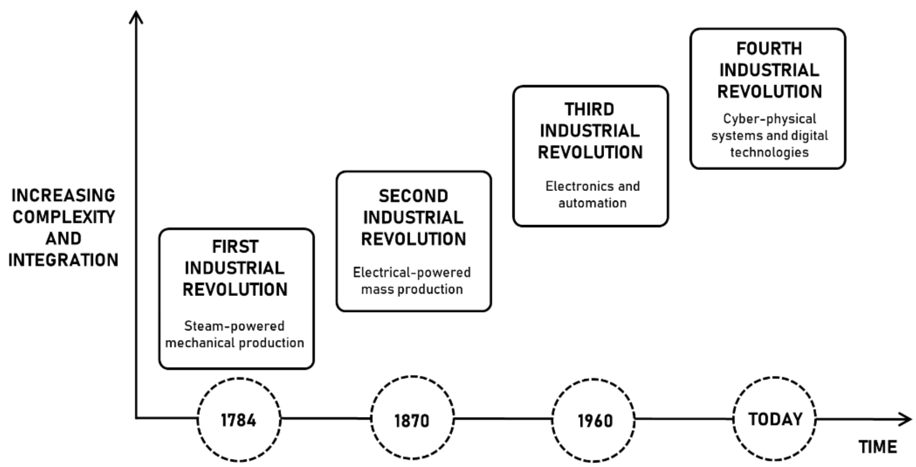

Figure 2. Fourth industrial revolution

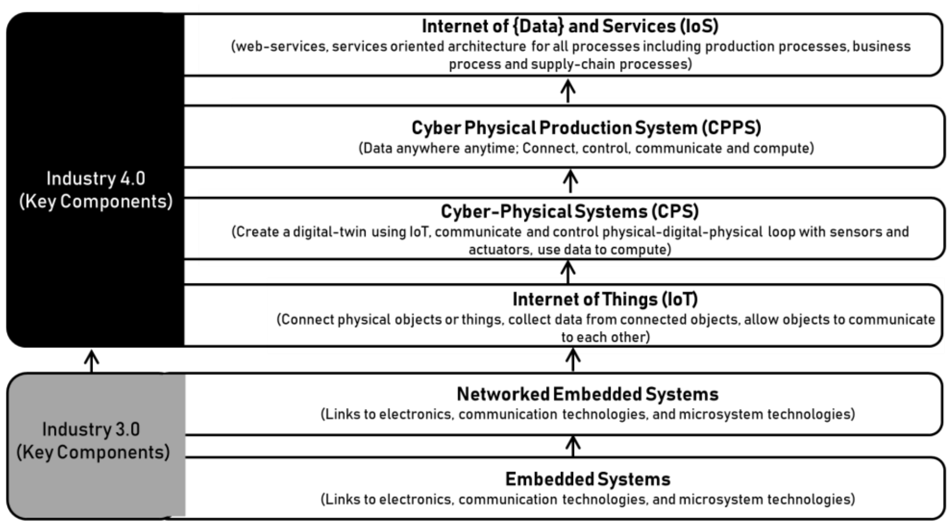

Figure 3. Fourth industrial revolution and Industry 4.0

The CPPS sits on top of the CPS layer and provides data about the physical world anywhere and anytime, and helps connect, control, communicate, and compute. CPPS provides an intensive connection with the surrounding physical world and its ongoing processes (Monostori et al., 2016).

Finally, the topmost layer is the Internet of Data and the Internet of Services (IoS). The IoS creates a service-oriented ecosystem and brings end-user of customer centricity to the system (Hofmann and Rüsch, 2017). IoS allows the digital tools that support end-user functions to be available as a service on the Internet (Alcácer and Cruz-Machado, 2019). Both internal and cross-organizational services are offered and utilized by participants of the value chain (Reis and Gonçalves, 2018). The IoS helps create networks incorporating the entire manufacturing process that convert factories into a smart environment (Kagermann, Wahlster and Helbig, 2013).

Results

With the advent of Industry 4.0, the built environment sector also has the opportunity to leapfrog to production that is more efficient and is driven by efficient business models and value chains (Craveiroa, Duartec, Bartoloa, and Bartolod 2019). Such a transformation is possible through the convergence of existing and emerging technologies that form part of the Industry 4.0 paradigm (Oesterreich & Teuteberg, 2016). This transformative framework is called the Construction 4.0 framework in this paper.

Description of Construction 4.0

The Construction 4.0 framework helps plan, design, and deliver built environment assets more effectively and efficiently by focusing on the physical-to-digital transformation and then digital-to-physical transformation (Dallasegaa, Raucha & Linderb 2018). Modeled after the concept of Industry 4.0, the idea of Construction 4.0 is based on a confluence of trends and technologies (both digital and physical technologies). No agreed definitions of Construction 4.0 exist in the literature (Maskuriy, Selamat, Ali, Maresova & Krejcar, 2019) except that currently, most studies refer to it as the 'counterpart of Industry 4.0' (Soto, Agustí-Juan, Joss, & Hunhevicz, 2019). Based on the systematic literature review, the authors put forward the following working definition of Construction 4.0:

> "*Construction 4.0 is a paradigm that uses cyber-physical systems, and the Internet of Things, Data, and Services to link the digital layer consisting of BIM and CDE and the physical layer consisting of the asset over its whole life to create an interconnected environment integrating organizations, processes, and information to efficiently design, construct and operate assets.*"

In Construction 4.0, the fundamental driver is the use of cyber-physical systems. CPS are technologies that bring the virtual and physical worlds together to create a truly networked world in which intelligent objects communicate and interact with each other (Griffor, Greer, Wollman, & Burns, 2017). The Construction 4.0 framework uses CPS as a core driver and links it with the concept of the Digital Ecosystem (Gartner, 2017). As shown in Figure 4, Construction 4.0 consists of three layers within which different components of the framework fit. Building information modeling (BIM) and a cloud-based Common Data Environment (CDE) are central to the Construction 4.0 framework (Oesterreich and Teuteberg, 2016; Cooper, 2018). This provides the digital layer in which BIM provides the modeling and simulation features that are a core component of the framework, CDE acts as a repository for storing all the data that relates to the constructed asset over its lifecycle (Maskuriy et al. 2019). In the other two layers, the following components exist (Tetika, Peltokorpia, Seppänena & Holmströmb, 2019):

- Industrial production (prefabrication, 3D printing, offsite manufacture, and onsite assembly)

- Cyber-physical systems (robots and cobots for repetitive and dangerous processes, and drones for surveying and lifting, moving and positioning, sensors, and actuators)
- Digital technologies (BIM, video and laser scanning, IoT, sensors, AI and cloud computing, big data, and data analytics, reality capture, Blockchain, simulation, augmented reality, data standards and interoperability, and vertical and horizontal integration)

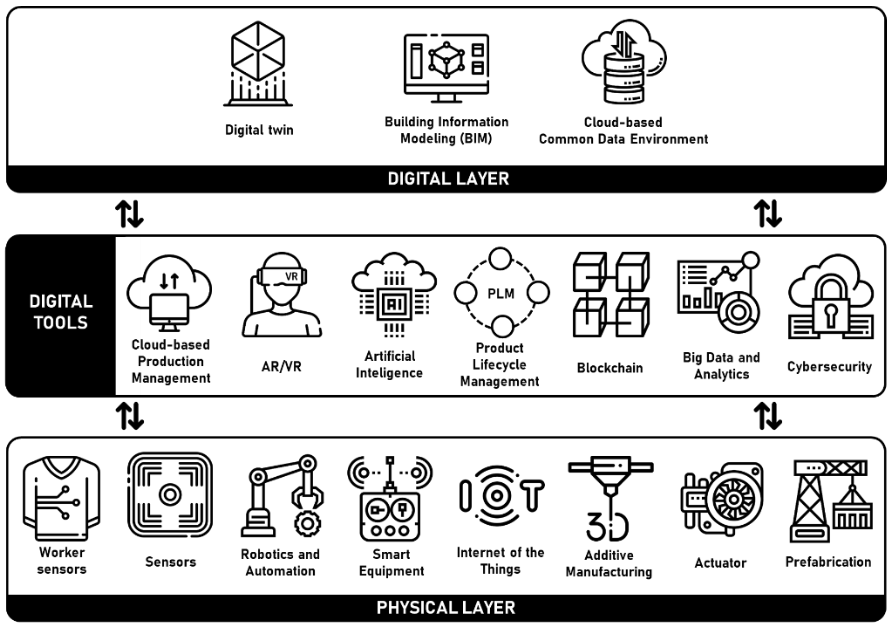

Figure 4. Construction 4.0 Framework

While Construction 4.0 is predominantly discussed in terms of technology, successful implementation will depend on the critical issues surrounding people, practices, and the environment.

Role of BIM and CDE in Construction 4.0

The Construction 4.0 framework provides a mechanism via which the industry can:

- Digitally model the built assets that already exist in our physical world;
- Design new assets in the backdrop of what already exists or plan for the retrofit and rehabilitation of existing assets using these digital models; and
- Once these assets are digitally captured and designed, use digital and physical technologies to deliver these physical assets.

It is important to note that BIM and CDE take on a central role in the Construction 4.0 framework. The CDE becomes the independent and application-agnostic repository of data of the constructed asset over its life. At the same time, BIM plays a crucial role in allowing design, construction, and other downstream processes to take place in a model-centric way. The resulting model provides a three-dimensional visual linkage to the asset under construction and after completion of the constructed asset itself. BIM and CDE, therefore, play an essential role in the development of the digital twin upon which other components of the framework rest.

Benefits of Construction 4.0 and Implementation Challenges

With the pervasive use of BIM, lean principles, digital technologies, and offsite construction, the industry is at the cusp of a transformation driven by Construction 4.0. The critical challenge is the fragmented state of our teaching, research, and professional practice in the built environment domain. The framework can overcome this fragmentation by describing Construction 4.0 in the context of the current state, emerging trends and technologies, and people and process issues that surround the proposed transformation.

Initial studies have attempted to envision the benefits of Construction 4.0 (Cooper, 2018; Dallasega, Rauch, & Linder, 2018; Oesterreich & Teuteberg, 2016). Based on these studies, the benefits of Construction 4.0 framework include: (1) adoption of a life cycle approach, (2) reduction of inefficiencies and waste; (3) horizontal, vertical and longitudinal integration; (4) improved cost and time performance; (5) significantly improved safety performance; (6) enhanced quality; and (7) improved image of the industry (Hossain & Nadeem, 2019).

The Farmer report documented the reluctance of the construction sector in embracing technology and summarized that the industry missed the Industry 3.0 transformation (Farmer, 2016). Based on an extensive literature review, the authors have developed a list of implementation challenges the sector faces while implementing the Construction 4.0 framework (Oesterreich and Teuteberg, 2016; Dallasega, Rauch and Linder, 2018; Alaloul, Liew, Zawawi, & Kennedy, 2019). Some of the identified challenges include (a) resistance to change; (b) unclear value proposition; (c) high implementation costs; (d) low investments in research and development; (e) need for enhanced skills; (f) longitudinal fragmentation; (g) lack of standards; (h) data security, data protection and cybersecurity; and (i) legal and contractual uncertainty.

Conclusions and Recommendations

Construction is a globally significant industry that employs millions of people and contributes massively to the GDP of individual nations and the global economy. However, it is conservative in its approach to innovation and suffers inertia in the face of the need to change. Unlike other industrial sectors such as manufacturing, automotive, and aerospace, the construction industry has failed to embrace the opportunities afforded by technology and advances in data management to enhance the efficiency and performance of the sector and the consistency and quality of its outputs. Despite numerous historical attempts to initiate and effect meaningful change, the industry still suffers from fragmentation and inefficiencies in the process, information flows, and collaborative working. The opportunities afforded by the concepts, principles, and components of Industry 4.0, translated into a strategic, tactical, and operational paradigm as Construction 4.0, have the potential to truly revolutionize the sector. In this paper, the authors have traced the links between Industry 4.0 and Construction 4.0. Using the systematic literature review approach, a description of Construction 4.0 and its key components was provided. As this is an emerging field, the research community must develop a clear research agenda for pursuing the various strands of the Construction 4.0 framework. It is also essential to consider the new skills required within the sector workforce for a successful application of Construction 4.0. It is incumbent on the construction industry to partner with technology innovators, academic institutions, and its’ researchers and educators to adequately prepare for the implementation of Construction 4.0.

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