A Framework for Embracing Construction 4.0

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Abstract**—**This paper addresses the challenges of embracing Construction 4.0 and proposes a framework for its implementation. The paper provides a brief background on Construction 4.0, as well as outlines the benefits and challenges of embracing it. Based on the literature review and deductive analysis, the paper proposes a framework that could help the construction industry to embrace Construction 4.0. The framework entails that governments assume the ownership of embracing Construction 4.0 since the nature of the construction industry and the adversarial relationships among the stakeholders involved defeat the implementation of Construction 4.0 without the presence of a patron.

Keywords: AI, Autonomous Construction Equipment, Construction 4.0, Digitalization, IR4.0, Emerging Technologies

I. Introduction

In 2020, the value of the construction market including related materials and services reached around USD10.7 trillion worldwide [1]. However, globally, the construction industry has suffered from resistance to change, barriers to innovation, low productivity, as well as difficulty recruiting and retaining a skilled workforce. In addition, project teams tend to work disjointly, thus repeating the same problems in each project [2], [3].

Over the past decades, automation and technologies in general have played an important role in improving productivity, safety, and quality in many industries. Between 1947 and 2010, productivity increased in manufacturing almost sevenfold and in agriculture by almost a factor of sixteen due to automation, while productivity in construction has not significantly changed [4]. Unlike manufacturing and other industries, the construction industry has always been slow to benefit from the adoption of new technologies [5]. The construction industry has many characteristics that make it unique in a variety of ways compared to other industries. For example, the construction industry is more susceptible to economic fluctuations than other industries. This instability can be seen at both the construction firm (micro) and industry (macro) levels. Furthermore, the construction industry is more often affected during any recession or period of economic stagnation [6].

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In addition, each construction project is unique and tailored to specific customer demands—unlike in manufacturing, there is no continuity in production in the construction industry [3], [7]. In addition, each project is affected by its geographical area and its design. Taken together, these attributes of the construction industry could comprise the cause of the stagnation of the construction industry in terms of its benefiting from technologies. One possible reason for the slow innovation and technology embracing is that the application of robotics and automation is limited in the construction industry because the complication of the jobs to be performed is much higher than in other industries. Nagy et al [8] summarized implementation challenges into four categories: 1) New skills for human labour, 2) Organisational and workflow changes, 3) Management knowledge in technologies, and 4) The high initial cost of new technologies

Recently, Construction 4.0 has emerged as a promising concept that could revolutionize the construction industry and resolve the chronic challenges and problems of the industry.

This paper addresses the challenges to and opportunities of adopting Construction 4.0. The paper discusses the nature of the construction industry to gain a better understanding of what could be the root causes of the lag in the construction industry in terms of embracing new technologies in general and Construction 4.0 in particular. Finally, the paper proposes a framework for embracing Construction 4.0 in the construction industry.

This paper could help policymakers and stakeholders in the construction industry to embrace Construction 4.0 and benefit from the monetary (e.g., contractor profits) and non-monetary (e.g., safety and customer satisfaction) returns provided by Construction 4.0.

The paper is structured as follows: Section II addresses the methodology; Section III provides background information on the construction industry, Construction 4.0 technologies, and the benefits and challenges of embracing Construction 4.0; Section VI proposes a framework for embracing Construction 4.0; and Section V provides the conclusions.

II. Methodology

A qualitative approach using deductive analysis was employed to conduct this study since it is exploratory in nature. A relevant literature review was conducted to understand the challenges of adopting Construction 4.0 and to identify the available technologies that could contribute to improving the construction industry. Understanding the challenges is the first step in moving forward and surmounting them. The following terms were used in the literature review search: the Fourth Industrial Revolution (IR4.0) and construction; Construction 4.0; industry 4, digital engineering, design automation innovation, and construction; innovative technology and construction; digital transformation and construction; AI and project management; and emerging technologies and construction. A Scopus search was carried out for the keywords. The search was limited for the last five years. The analysis of the available technologies and the potential challenges of adopting Construction 4.0 in tandem with understanding the nature of the construction industry was the basis for developing the proposed framework for embracing Construction 4.0. The unique characteristics of the construction industry make it much more difficult to gain the full benefits of engineering innovation compared to other sectors. Construction takes place in a non-standard environment and the construction process involves several interrelated stages and many participants in different locations and phases. In this regard, there are various implementation challenges, including high implementation costs [9], significant staff training costs, and resistance to change [10]; and the underdeveloped level of technology [11,12]. Sacks et al. [13] reported that the transition of the Industry 4.0 paradigm in construction is far from finished because the principle of connectivity and system autonomy is missing in construction activities. They recognized that the Construction 4.0 initiatives lack the necessary implementation framework, which prevents it from becoming a unified, complete, and functional paradigm

III. Background

The construction industry has been known for lagging behind in terms of incorporating the latest technology in comparison with other industries. Many activities within the construction industry are still manual. The management tools are simple. The rigorous regulations including safety, technical, inspection, engineering, and environmental standards could be preventing innovation and agility in adopting new technologies [14]. Globally, construction has been suffering from many challenges including low productivity (profitability), poor quality, and delays in project schedules. Accordingly, the three imperative conditions to ensure a successful project for any customer—namely, completing a project within schedule and budget with high quality—are frequently not met.

Due to the importance of the construction industry on the economy, many countries have studied the challenges of the construction industry. For example, the UK released the Construction 2025 industry strategy with a plan to allocate around £75 million in research and development. Similarly, other developed countries such US, Canada, and China and developing countries such as India have conducted their studies to identify the challenges of the construction industry. Among the commonly identified challenges are the lack of innovation and delayed adoption of technologies [15].

3.1 Construction 4.0

The construction industry has always been learning from manufacturing industries [16]. Construction 4.0 emerged as a concept imitating Industry 4.0, referring to the Industrial Revolution 4.0 (IR4.0), which was well received by the manufacturing industry [17]. IR4.0 emerged as a concept from the German government in 2011 [5]. The essence of IR4.0 is to integrate physical and digital technologies [2] and was initially developed to support the manufacturing industry [5]. The German government defines IR4.0 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” [2].

Accordingly, the definition of Construction 4.0 derives from the foundation of Industry 4.0 but focuses on and relates to the construction sector. Therefore, Construction 4.0 is all technological changes related to the implementation of new work methods which are related to processes, materials, and markets. Construction 4.0, can be defined as “a paradigm that uses cyber-physical systems, and the Internet of Things, Data, and Services to link the digital layer consisting of Building Information Model (BIM) and Common Data Environment (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” [2].

Contemporary construction requires intelligent resources for process transformation, increasing productivity and safety. Construction 4.0 has introduced the following concepts to the construction industry [18], [2], [15]:

i. *Industrial production* involves the introduction of 3D printing as well as offsite manufacturing and prefabrication to reduce onsite construction challenges. For example, off-site production can improve quality, safety, and working conditions since the production is conducted in a controlled environment. Industrial production thus benefits from BIM and cloud-based CDE during production.

ii. *Cyber-physical Systems (CPSs)* involve the interconnection and integration of a smart system that includes physical and digital or cyber components. A CPS digitizes physical processes whereby the physical reality feeds the virtual real-time data, and the virtual makes decisions that inform the physical reality. Examples of CPS technologies include unmanned aerial vehicles (UAVs), augmented reality (AR), and the Internet of Things (IoT). Examples of CPS applications in construction are the use of robots for repetitive and dangerous processes, the use of drones for surveying and lifting as well as moving and positioning, and the use of sensors and actuators. CPS is at the core of Construction 4.0.

iii. *Digital technologies* refer to the digital transformation wherein the processes are digitized, such as with BIM and CDE. These digital technologies include video and laser scanning technology, artificial intelligence (AI), cloud computing, big data and data analytics, reality capture, blockchain, simulation, AR, and virtual reality (VR). In its 2019–2024 manifesto, the European construction industry federation (FIEC) states: “Construction 4.0: Accelerate the digital transformation of the construction industry.” The manifesto goes on: “Digital construction is an enabler for more efficient processes and elimination of errors and delays, as well as for a sustainable built environment” [19].

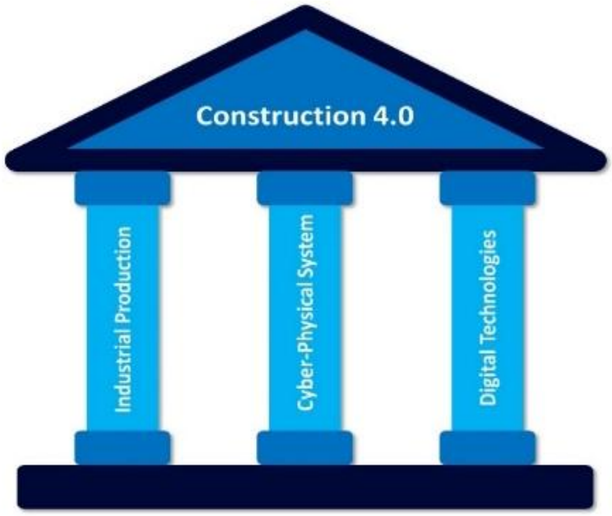

Fig. 1: Construction 4.0 pillars

There are several disruptive Construction 4.0 technologies that are available in the market that could benefit the construction industry as follows::

1. *Autonomous construction equipment* includes self-driving machines like forklifts, diggers, trucks, and other similar equipment that can operate without a driver. This available technology could provide higher productivity, lower operation costs and improve safety.
2. *Drones*, both fixed-wing and rotary, can perform land surveying and topographic mapping, equipment tracking, remote monitoring and progress reporting, security surveillance, personal safety, and structure inspection. Drones can be equipped with various devices, sensors, and GPS along with capabilities to collect and transmit real-time data [20].
3. *Robotics* entails robots performing tasks such as painting and bricklaying. For example, a semi-automated masonry (SAM) system is capable of lifting a brick, applying mortar, and placing the brick in place, while the mason has only to monitor and clean up the excess mortar. The Fastbrick robot can lay 1 000 bricks in an hour. The Theometrics robot can navigate a construction site based on input from the BIM or CAD drawings to perform the measurement task [21]. The TyBot provides a rebar-tying robot that moves to identify each intersection of rebar, ties it, and then moves on to the next intersection [21].
4. *IoT sensors* can be employed to monitor activities such as welding, with the sensors collecting environmental data to trigger the appropriate actions by the welding machine.
5. *VR* could help in determining constructability during project planning.
6. *BIM* is mostly associated with design and preconstruction, while benefits could be reaped throughout the project life cycle.
7. *Radio Frequency Identification (RFID)* technology could be used to monitor the workforce at the site and manage inventory.
8. *Industrialized building systems (IBS)* involve manufacturing in a controlled environment, either on-site or off-site. The construction of China’s Wuhan–HuaShenShan Hospital, which was completed in 10 days, is an excellent example of an IBS or modular construction technology.

3.2 Benefits and Challenges of Embracing Construction 4.0

Construction 4.0 could benefit the construction industry in more than one aspect, as outlined below [3], [15]:

1. *Cost-saving*: Autonomous construction equipment and robotics could improve productivity and reduce waste and workforce, which should result in the lowering of construction costs. This could solve budget overrun, a common problem in the construction industry.
2. *Time-saving*: Robotics, 3D printing, prefabrication, and autonomous equipment could accelerate construction execution schedules as a result of improving productivity. This could solve delays in project completion, which is another common problem in the construction industry.
3. *Better quality*: Construction 4.0 provides technologies that monitor and control the execution of design, which should improve quality. Robots and automation should result in work that is more precise and uniform compared to that of experienced workers.
4. *Enhanced safety*: Construction 4.0 could mitigate safety risks. For example, prefabrication where the work is performed in a controlled environment could improve safety. In another example, using UAVs to perform work at heights could mitigate safety risks.
5. *Cost control*: Real-time site data obtained using AI could help to monitor productivity and work progress and subsequently improve cost control.
6. *Improved customer satisfaction*: Smart project management tools and the digitization of repetitive and tedious tasks allow project teams to focus on customers’ needs.
7. *Attract high talent*: The construction industry is known for being a harsh working environment and behind in adopting new technologies. Replacing workers with robots in performing some challenging physical tasks may encourage workers to join this sector. With its involved technologies, Construction 4.0 could help to attract and retain talent.
8. *Sustainability*: Reducing waste and rework as a result of introducing automation and robotic technology should optimize resources that augment sustainability.

The above-demonstrated capabilities and advantages of Construction 4.0 should thus encourage those who are in the industry to advocate for Construction 4.0 technologies. Both contractors and customers can enjoy the benefits of Construction 4.0, and the construction industry could overcome its persistent challenges, which have remained unresolved for decades.

At the same time, there are many challenges that may hinder the embracing of Construction 4.0 as follows [22], [23], [24], [3], [5], [2], [15]:

1. *Cost*: Deploying new technology requires a high initial investment with high uncertainty of the return on the investment. In addition, there are other hidden costs associated with training and maintenance that could discourage investment in unproven technology. The construction industry is extremely competitive, and a significant number of contractors are small and medium-sized, making them fragile when taking any kind of risk.
2. *Adaptation to new technology*: The new technology requires new skill sets to deal with it. Introducing new

technology requires retaining the workforce to invest in their training. Changing a given business model is usually encountered by resistance and fear of failure. This could be considered a risky step, especially in a fluctuating industry like the construction industry.

3. *Lack of standards and specifications*: Many engineering standards mandate certain procedures to execute a given activity. These procedures are developed based on the conventional method and in many cases not cater to alternative innovative methods.
4. *Resistance to change*: Workers typically prefer traditional methods and proven solutions instead of unproven modern methods. In fact, the construction industry is globally known for being conservative and resistant to change.
5. *Lack of skills:* Many aspects of Construction 4.0 require different skills and functions that are not commonly available within the workforce of the construction industry.
6. *Fragmentation*: Successful implementation of Construction 4.0 entails coordination among the various stakeholders to at least exchange the relevant data. However, the temporary relationships among the stakeholders disallow the necessary coordination.

In addition to the above challenges that are directly related to the construction industry, various technical challenges remain within Construction 4.0. Interoperability is one such challenge. There is still a lack of a unified standard protocol for data communication. Each technology provider has its own platform, which creates challenges in connectivity and exchanging data among various technologies. The essence of Construction 4.0 is bringing together all components to work in sync [25].

The use of IoT in construction technology, including BIM, smart communication, sensor, big data, augmented reality, location services, and remote operation throughout the construction process, has had a significant impact on the monitoring of the construction process, particularly in lowering the risk of construction error, defects, and avoiding construction delay. safety and efficiency.[26]

IV. Framework For Embracing Construction 4.0

Though BIM has become a common tool within engineering offices and some customers demand for this technology to benefit from it during the facility operation. However, Construction 4.0 goes far beyond BIM. BIM could enable many other construction technologies during the project construction phase. Construction 4.0 could improve contractors' performance during construction and prevent many of the common challenges that contractors encounter during the execution of a project. At the same time, contractors alone—even if they are willing—cannot adopt Construction 4.0 due to the challenges addressed in Section III. Therefore, embracing Construction 4.0 entails collective efforts among the stakeholders. However, due to the fragmented nature of the construction industry and the adversarial relationship among the main stakeholders—the contractor, customer, and engineering office—developing a collaborative relationship to adopt Construction 4.0 might be unrealistic. In addition, the lack of business continuity among the main stakeholders makes the shift from conventional business practices to a new paradigm challenging. Construction 4.0 cannot spread naturally within the industry unless one of the stakeholders acts as the advocate. Accordingly, the government as an independent entity that has a direct interest in improving the construction industry should assume the responsibility in embracing Construction 4.0. In addition, governments are the customers for public projects.

Governments can impose Construction 4.0 technologies throughout the project cycle. Using BIM could be a mandatory requirement during the design. In addition, the following measures could be implemented:

1. Allocate some points in contractors' prequalification evaluation criteria that cater to embracing Construction 4.0 technologies such as autonomous machines, IoT, and digitized project management systems.
2. Develop a web-based platform to communicate and collaborate with the contractor and other stakeholders and mandate that all communications and transactions are performed using the platform. The platform could even be used for submitting invoices and providing project progress reports.
3. Provide preferential treatment in the contracts awarded to those contractors who intend to use Construction 4.0 technologies in their technical proposals.
4. Mandate that contractors upload as-built details in the BIM for each facility.

Governments are empowered in imposing legislations that promote the adoption of Construction 4.0. In addition, governments can mandate the use of Construction 4.0 technologies in public projects. Initially, there could be a premium for adopting Construction 4.0 technologies, but the indirect return could exceed the premium by many factors. Examples of indirect benefits include improving the final product quality, mitigating safety risks, creating jobs with higher skill sets and developing the construction industry, which is important in any economy. The agenda of the private customers in general are short-term and have no driver to demand contractors to adopt Construction 4.0 technologies that come with premium and unproven returns. The success of public projects in embracing Construction 4.0 technologies will encourage the private sector to demand Construction 4.0 technologies. Governments can also introduce incentives for adopting Construction 4.0 technologies such as tax allowances for engineering offices and contractors who are embracing Construction 4.0.

Engineering standards should also be updated to cater to the use of Construction 4.0 technologies—for example, revising the engineering standard that mandates quality testing using a conventional device to allow for an alternative IoT device if such is available in the market. Governments are usually able to influence the organizations responsible for engineering standards to revise these standards to serve a national agenda.

Governments in collaboration with technology providers could launch training for construction workers to supply the construction industry with qualified workers who can utilize the new technologies. The construction industry is a workforce-intensive industry, and the shortage of construction workers in both developed and developing countries remains an issue [27], [28]. Construction 4.0 technologies entail more advanced skills, and much manual work is performed by machines. This should make the construction industry more attractive to job seekers.

The technology providers should also offer a full solution rather than focusing on selling their products. The Business Service Model (BSM) where the Original Equipment Manufacturer (OEM) offers services rather than products could be essential, especially in the construction industry. For example, the OEM of autonomous painting machines should consider offering painting services either directly or through a specialized vendor. In this case, the OEM or the vendor will be a subcontractor. It is to the advantage of the technology providers to promote their technology. This model will thus serve both the OEM and the contractor. The OEM will be able to expand its revenues from more than one stream, and the contractor will overcome the usual hesitation to invest in new technology. In addition, contractors will avoid the risk of underutilizing expensive technology, maintenance, and know-how (training). BSM is essential, especially in the construction industry where business fluctuation is the norm and utilization continuity cannot be guaranteed. This approach is in line with circular procurement, which has been adopted by many countries, especially in the European Union [29]. One of such circular economy strategies is BSM.

Furthermore, technology providers have also the opportunity to develop a cloud-based solution for project management that can be licensed to contractors. A customized solution could be a platform that is capable of digitizing project management activities.

V. Conclusions

The construction industry is an important sector in any economy and represents a sizable contribution to the GDP. It is also a large employer sector since construction is a labor-intensive industry. This is why governments pay attention to this sector and endeavor to improve it.

Over the past decades, manufacturing and other industries have benefitted from emerging technologies affecting both productivity and quality. However, the construction industry has lagged in adopting new technologies. Accordingly, the chronic issues of the construction industry including low productivity, delays, safety risks, and poor quality have remained. In 2011, IR4.0 appeared as a disruptive model in manufacturing that employs cyber-physical systems and digitization. Subsequently, Construction 4.0 emerged mimicking IR4.0 in the manufacturing industry. Construction 4.0 has the potential to reshape the construction industry and bring it into new frontiers where cost control, project scheduling, and quality can be significantly improved. In addition, the manual aspect of the industry could be reduced significantly via machines.

Nevertheless, the nature of the construction and the fragmented relationships among the industry stakeholders constitute major barriers to embracing Construction 4.0. Many analyses in the literature tend to implicitly place the responsibility for the failure to embrace new technologies on the contractors and the nature of the industry. The fact that contractors, unlike manufacturers, cannot be proactive in embracing innovative concepts and technologies is overlooked. Indeed, contractors are merely executors of customer requirements in compliance with the engineering design, specifications, standards, and procedures.

This paper discusses Construction 4.0 and the available related technologies. The paper demonstrates the benefits that Construction 4.0 could provide to overcome persistent challenges in the construction industry, as well as the challenges and benefits of adopting Construction 4.0. Finally, the paper proposes a framework for embracing Construction 4.0. The proposed framework suggests that governments should take the lead in driving Construction 4.0 in the construction industry, both directly and indirectly. Governments are customers for public projects, and these projects usually represent a signification portion of the construction industry in any country. Imposing Construction 4.0 technologies in public projects should thus push stakeholders within the construction industry to adopt Construction 4.0. In addition, resolving the other barriers to embracing Construction 4.0, such as cost and standards, can be carried out with governmental influence.

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