Holistic Analysis of the Influencing Factors of Construction 4.0 Technology Implementation in the Construction Industry: A Twin Sustainable and Digital Transition Perspective

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Abstract. Construction 4.0 (C4.0) was begotten with emergent and disruptive technologies in the construction industry. Despite the promising benefits such as productivity and competitiveness, scholars and practitioners are still struggling with how to promote C4.0 technology implementation (C4.0TechIm) in construction. Previous discourses primarily lay in certain aspects of C4.0 without a holistic view of the influencing factors of C4.0TechIm. This study thus seeks to unveil the influencing factors of C4.0 technology implementation based on the twin sustainable and digital transition perspectives and guide future research needs. The authors reviewed the 77 relevant articles, identified a comprehensive list of 60 influencing factors, and used simplified analysis to quantify the factors. It is found that knowledge gaps exist in developing decision-making models that cover all the identified factors in an integrated framework. Practically, the results provide references to accelerate C4.0 technology implementation and offer strategies for maximizing potential benefits.

Keywords: Construction 4.0 · Construction firms · Sustainability · Digitalization · Factors

1 Introduction

As an engine for the promotion of productivity and competitiveness, a broad spectrum of disruptive technologies, such as Building Information Modelling (BIM), Internet of Things (IoTs), big data, and 3D printing [1], emerged in the construction industry under the aegis of Construction 4.0 (C4.0) [2].The conceptualized C4.0 in the construction industry heritages mainstream businesses' major attributes of the fourth industrial revolution (I4.0) [3]. It describes a new paradigm of autonomous and smart manufacturing in construction. Given its potential to provide construction firms with efficient, profitable business models and overall contribution to sustainability [4], C4.0 has gained prevalence within the business world and academic circles.

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Despite the long-standing interest and the plethora of advantages of C4.0, there are construction firms that still apply the conventional management concepts and processes due to the lack of experience and knowledge on integrated technology management and a holistic view of factors that affect C4.0 technology implementation (C4.0TechIm) in the construction industry. A review of the recent literature reveals that the discussions of C4.0TechIm have primarily centralized around (1) exploring the challenges and opportunities of C4.0TechIm [5, 6]; (2) discussing the relationships between I4.0 and construction performance [7] and sustainable innovation [8]; and (3) reviewing the status quo of C4.0 in the construction industry [6, 9]. It seems that although existing studies provided some insights on the drivers, motivations, barriers, or challenges of C4.0TechIm, the gaps remain in a holistic investigation of factors that may influence construction firms' C4.0TechIm so that top management of firms could effectively allocate restrained resources and deploy business strategies from a more sustainable manner. Against this backdrop, this study aims to investigate the key influencing factors of C4.0TechIm in the construction industry based on a sustainable and digital twin transition perspective. This study will provide a foundation for a broader and more holistic framework to facilitate the utilization of C4.0 digital technologies in the construction industry.

2 Research Background

2.1 Twin Sustainable and Digital Transitions in the Construction Industry

To overcome the overwhelming challenges such as environmental degradation, social needs, climate change, and low productivity in construction, sustainable and digital transitions tend to be the urgent need in the construction industry. It is with a view to coping with these challenges through sustainability practices and technology innovation that scholars and construction practitioners have endeavored to leverage digital technologies in the C4.0 era. As suggested by the European Commission, the twin green and digital transitions are equally important in the European Commission's political priorities that will enable long-term benefits for society [10]. The green transition target to achieve sustainability while the digital technologies are of gowning significance in transforming the socio-technical systems. Recent studies have shown that sustainable and technology transition can reinforce each other [4] while conflict might also exist between the due transition. For instance, C4.0 technologies can minimize resource and energy consumption and waste generation through automatic detection and data analysis across the entire supply chain and construction production [11]. On the other end, C4.0 might also bring some issues such as information security issues, poor quality due to fixed settings, and reduced employment, security of intellectual property and rights can prevail [12]. To unlock the potential of the twin transition and to prevent negative effects, more proactive and integrated management will be needed.

2.2 Construction 4.0 and Sustainability

By adopting a toolbox proposed by Bai et al. [4], this paper analyzed the potential connections between sustainable development goals (SDGs) and C4.0 technologies, as shown in Table 1. It is noted that prior to the analysis, we identified a list of 19 C4.0 technologies that are generally discussed in previous studies and connected them to the potential SDGs. These include laser scanner/3D scanner, sensor and actuators, unmanned aerial vehicles (UAV/drone), new materials, BIM, additive manufacturing (3D printing), light detection and ranging (LiDAR), artificial intelligence (AI), virtual reality (VR)/augmented reality (AR)/mixed reality (MR), Robotics, Big data, blockchain or distributed ledger technologies (DLT), Cloud computing, cyber security, cyber-physical system (CPS), global navigation satellite system (GNSS)/Global positioning system (GPS), geographic information system (GIS), remote sensing (RS), and Industrial Internet of Things (IoTs). Although there may be some overlaps, these 17 goals help construction firms to achieve sustainable development in the economic dimension (see SDGs 1, 8, 9, 10), environmental dimension (see SDGs 6, 7, 11, 12, 13, 14, 15), and social dimension (see SDGs 2, 3, 4, 5, 16) of sustainability [13].

Table 1. Potential connections between SDGs and Construction 4.0

No	Goal	Connections with Construction 4.0	Sample enabling Construction 4.0 technologies
1	No poverty	Construction technologies can bring access to information and potential economic opportunity that provide more basic infrastructure and building assets with better services to the poor people and prevent them from poverty. I4.0 technologies have the potential to increase the resilience of infrastructure and alleviate unexpected economic losses during disasters	IoT, robotics, big data, BIM
2	Zero hunger	C4.0 technologies can promote fair distribution systems and decrease living costs for poor people so that they can afford more food costs	IoT, GIS
3	Good health and well-being	C4.0 technologies provide more high-quality and cheap building assets and enable the digitalization of construction activities, it promotes healthy lifestyles and effective healthcare services and improves safety and working environments for construction workers, local communities and the public	IoT, GIS, BIM

(*continued*)

Table 1. (*continued*)

No	Goal	Connections with Construction 4.0	Sample enabling Construction 4.0 technologies
4	Quality education	Some C4.0 technologies, such as VR/AR, could be used for education to provide a 3D demonstration to students for better understanding in a virtual environment	VR/AR/MR, BIM, GIS
5	Gender quality	C4.0 technologies decrease labor demand, providing more equal opportunities for both males and females to succeed at every level and in every function	Robotics, CPS
6	Clean water and sanitation	C4.0 technologies could help to provide affordable and sustainable equipment in architecture to access clean water and sanitation	IoT, CPS
7	Affordable and clean energy	Sustainable energy would be enabled with C4.0 technologies to increase energy quality and save costs for users	IoT, BIM, sensors
8	Decent work and economic growth	C4.0 technologies would create decent and fulfilling jobs and contribute to economic growth directly and indirectly	AI, BIM, big data
9	Industry, innovation and infrastructure	C4.0 technologies would promote investment in scientific research and innovation to upgrade conventional infrastructure for sustainable construction	AI, BIM, GIS, Robotics
10	Reduced inequalities	C4.0 technologies could help to bridge the unconnected to reduce the digital development gap and inequality within and among countries or people	AI, BIM
11	Sustainable cities and communities	Sustainable, green, and smart cities and communities would be built with the assistance of C4.0 technologies	GIS, GPS, remote sensing, BIM, big data
12	Responsible consumption and production	C4.0 technologies could facilitate collaboration and improve project consumption patterns and transparency in construction supply chains	CPS, Cloud computing
13	Climate action	C4.0 technologies can help reduce building energy leading to a reduction of waste and carbon dioxide	Sensors, CPS, BIM
14	Life below water (sustainable use of marine resources)	C4.0 technologies can contribute to more sustainable use of materials, including the sustainable use of marine resources	AI, new materials

(*continued*)

Table 1. (*continued*)

No	Goal	Connections with Construction 4.0	Sample enabling Construction 4.0 technologies
15	Life on land (sustainable use of land resources)	Saving land resources such as wood in C4.0 could halt land degradation and biodiversity loss	AI, GIS, new materials
16	Peace, justice and strong institutions	With decreased poverty and hunger, C4.0 could promote peace and justice in societies and ensure responsible firms or construction supply chains	IoT, blockchain
17	Partnerships for the goals	C4.0 could connect different stakeholders to achieve sustainable development goals	Blockchain

3 Research Methods

To achieve the research aim, the authors (1) conducted a systematic literature review and identified the influencing factors of C4.0TechIm; (2) performed a simplified analysis to comprehend the gaps in the current body of knowledge of C4.0TechIm; and (3) proposed future research directions for C4.0TechIm. The research processes are detailed next.

3.1 Identification of Relevant Papers

The research started by collecting relevant papers on C4.0TechIm in the construction industry by conducting electronic searches in September 2021, following the steps of Zhang et al. [14]. Keywords search was executed under the "Title, Abstract, Keywords" field by using Boolean operators to combine the relevant keywords of C4.0TechIm such as "Construction 4.0," "Industry 4.0," "construction industry," and "Building Information Modeling" and the "article or early access or review" document types were selected. After screening out those irrelevant articles, a total of 77 articles remained for further investigation. They were categorized into three major groups: (1) **Type A** articles that only offer theoretical discussions or insights about one or more factors affecting C4.0 technology implementation without developing any actual applicable models, frameworks, or decision-making tools. This group of articles was included in matrix X; (2) **Type B** articles that provide little (if any) theoretical discussions about the factors affecting C4.0 technology implementation, while heavily focused on developing actual models, frameworks, or decision-making tools based on mathematical/ computational algorism. This group of articles was included in matrix Y; and (3) **Type C** articles that provide both theoretical discussions and developed models, frameworks, or decision-making tools. This group of articles was recorded in both matrices X and Y.

3.2 Identification of the Influencing Factors of C4.0TechIm

In this step, the 77 articles were carefully reviewed to generate a list of influencing factors of C4.0TechIm. This involves identifying and recording the factors by assigning value 1 (when the factor was mentioned by the article) or 0 (when the factor was not mentioned by the article) to the matrices X (covering types A and C articles) and Y (covering types B and C articles). In the developed matrices X and Y, the rows denote the identified factors, and the columns denote the selected articles. Matrix X covers types A and C, and matrix Y cover types B and C. When an article mentioned a corresponding factor, it was labeled as 1; otherwise, it was marked 0. In this, Article *j* mentions factors *Fi*, *Fi* + *2*, to *Fn*; as such, a value of 1 was recorded in the *i*th, *i* + *2*th, and *n*th rows of the *j*th column, while 0 was given for the other cells. To this end, knowledge gaps in the current literature can be identified by comparing these two reference matrices (i.e., X − Y).

3.3 Simplified Analysis

This study utilized the simplified analysis to calculate a score for each influencing factor of C4.0TechIm by adding all cells in the raw in the corresponding reference matrix, as shown in Eq. (1). In addition, Eq. (2) is utilized to obtain the normalized score:

$$Score_i = \sum\nolimits_{x=1}^{f} W_{i,j} \tag{1}$$

$$Normalized\ Score_i = \frac{Score_i}{Maximum\ Score_i\ in\ the\ matrix} \tag{2}$$

whereby $Score_i$ represents the number of frequencies mentioned for factor *i*; and $W_{i,j}$ denotes the value for the corresponding factor *i* (0 or 1) and article *j* in the same reference matrix. The *f* means the last value of *j*, which should be 77 in this study. In this way, the normalized score falls between 0 to 1.

4 Results and Discussions

After reviewing the 77 collected articles, a list of 60 factors was identified, covering a wide range of influences from the external environment, project-related factors, and organizational factors, to technology competence and technology challenges. Afterward, two reference matrices, X and Y were developed, of which 74.03% (57) articles were categorized as Type A, 13.0% (10) articles were grouped into Type B, and 13.0% (10) articles were grouped into Type C. Therefore, matrix X covers 67 articles (including types 1 and 3), and matrix Y covers 20 articles (types 2 and 3). This indicates that the scholars emphasized more on the theoretical discourses than the developed models of the influencing factors of C4.0 technology implementation. Table 2 presents the normalized scores in simplified analysis. It is found that the top five factors that provided theoretical insights (X) of C4.0TechIm were F19, F27, F18, F30, F29, and F52. Similarly, the top factors that provided actual models, frameworks, or decision-making tools were F18, F30, F29, F52, F20, F28, F34, and F33. These factors can then be regarded as important factors of C4.0TechIm. By calculating the differences of the normalized scores of Matrices X and Y (See the last column in Table 2), the gaps in the literature can be identified. The results show that the largest gaps exist in F19, F27, F53, F26, and F39. Although many existing studies have overly stated these factors in terms of their significance and impact of C4.0TechIm within construction firms, many studies fail to incorporate, address, or validate these factors in developed models. As documented above, it seems previous works lack comprehensive and holistic inclusion and consideration of these influencing factors in an integrated analysis framework. As such, scholars are recommended to holistically consider and incorporate the identified 60 factors in future prediction models, decision-making tools, and frameworks to understand their effects on the organizational C4.0TechIm better.

Table 2. Differences between the results from social network analysis and simplified analysis.

Code	Factors	Matrix X	Matrix Y	X − Y
F19	Availability of resources	1	0.6	0.4
F27	Quality, safety, health, and risk management	1	0.6	0.4
F53	Data-related issues	0.675	0.3	0.375
F26	Integration and interoperability	0.525	0.2	0.325
F39	Perceived overall organizational performance improvement	0.325	0	0.325
F54	Uncertainty about the cost efficiency	0.6	0.3	0.3
F22	Corporate strategy and management policy	0.675	0.4	0.275
F43	Synchronization of procurement and improved supply chain management	0.225	0	0.225
F1	Level of awareness, acceptance, and applications in the industry	0.725	0.5	0.225
F11	Project size, complexity, site nature, scope, delivery method	0.4	0.2	0.2
F18	Availability of capabilities	1	0.8	0.2
F30	Improved project efficiency and productivity	0.975	0.8	0.175
F12	Lack of legal framework and contract uncertainties	0.25	0.1	0.15
F15	Level of stakeholder collaboration and coordination	0.25	0.1	0.15
F55	Security of intellectual property and rights	0.25	0.1	0.15
F35	Energy efficiency	0.425	0.3	0.125
F56	Uncertainty about the time efficiency	0.125	0	0.125
F37	Improved facility management and service	0.2	0.1	0.1
F46	Improved estimation method	0.1	0	0.1
F47	Better project delivery	0.1	0	0.1
F2	Level of standardization	0.6	0.5	0.1
F7	Governmental initiatives or incentives	0.3	0.2	0.1
F32	Design flexibility	0.6	0.5	0.1
F42	Increased competitive advantage	0.3	0.2	0.1
F6	Shared knowledge and training schemes in the industry	0.275	0.2	0.075
F25	Consulting	0.075	0	0.075
F49	Reduced claims or litigation (risks)	0.075	0	0.075
F50	Optimum performance of manufacturing	0.075	0	0.075
F16	Lack of commitment from clients	0.15	0.1	0.05
F44	Reduced Labor	0.15	0.1	0.05
F29	Time-saving	0.85	0.8	0.05

(*continued*)

Table 2. (*continued*)

Code	Factors	Matrix X	Matrix Y	X – Y
F52	Immaturity of the technologies	0.85	0.8	0.05
F51	Supporting education and training	0.025	0	0.025
F60	Difficulty in explaining the output of the new technology to the client	0.025	0	0.025
F45	Shared value or value chain	0.225	0.2	0.025
F5	Appropriate legislation	0.4	0.4	0
F9	Advanced technology development in the industry	0.2	0.2	0
F41	Improved information retrieval process	0.3	0.3	0
F10	Pressure to innovate	0.075	0.1	–0.025
F20	Awareness and willingness within organizations	0.775	0.8	–0.025
F57	Lack of practical validation	0.05	0.1	–0.05
F58	Energy consumption	0.05	0.1	–0.05
F59	Lack of better performing devices	0.05	0.1	–0.05
F3	Market demand	0.525	0.6	–0.075
F17	Health and safety risks in the workplace	0.025	0.1	–0.075
F23	Organizational business modal adaptation	0.425	0.5	–0.075
F24	Unclear benefits, gains, and business value	0.125	0.2	–0.075
F13	Effective communication among project stakeholders	0.4	0.5	–0.1
F21	Organizational culture	0.6	0.7	–0.1
F28	Cost-saving	0.9	1	–0.1
F31	Simulation and visualization for better decision-making	0.6	0.7	–0.1
F48	Ease to use	0.075	0.2	–0.125
F14	Clear contractual provisions	0.15	0.3	–0.15
F4	Fragmentation of the construction industry	0.425	0.6	–0.175
F38	Mass customization	0.125	0.3	–0.175
F34	Improved automation and information sharing level	0.625	0.8	–0.175
F40	Project planning optimization	0.3	0.5	–0.2
F33	Resource and waste optimization	0.6	0.8	–0.2
F8	Persuasion and inspiration	0.275	0.5	–0.225
F36	Increased accuracy and reduced errors	0.35	0.6	–0.25

5 Conclusion

This study reviewed the existing literate in terms of C4.0 technology implementation from a due sustainability and digitalization transition perspective and proposed future research directions in addressing research needs and literature gaps. A list of 60 factors is found that may influence C4.0 C4.0TechIm in construction firms. Although previous studies provided theoretical discussions on these factors, there is still a need to incorporate such factors in the developed models, frameworks, and tools and study their collective impact on C4.0TechIm. As a result, research endeavors should focus on developing models, frameworks, or decision-making tools that cover all the identified 60 factors regarding C4.0TechIm, thereby holistically managing complex digital and sustainable construction businesses and gaining competitiveness. The outcomes of this study could inform scholars and practitioners about C4.0TechIm in the construction industry and the factors that influencing it. It also provides a robust foundation for comprehensive decision-making processes and integration management of C4.0TechIm for construction firms.

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