FUTURE RESEARCH DIRECTIONS OF CONSTRUCTION DIGITAL TWINS

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Abstract

The Digital Twin (DT) concept has emerged as one of the main topics within automation in construction. However, compared with the applications in other industries, several challenges must be overcome when generating Construction DTs (CDTs). In order to capture the leading edge of CDTs and identify the challenges of their implementation, this paper conducts a review of the previous studies related to DTs in the construction industry. Based on the review, the future research directions for the generation and applications of CDTs are identified.

Introduction

The implementation of Digital Twins (DTs) is becoming prevalent and mature in many industries. As one of the most promising technologies for Industry 4.0, DTs can act as the platforms for real-time data storage and management as well as efficient tools for simulating, visualizing, and optimizing processes. However, compared with the applications in other fields, several challenges must be overcome when generating Construction DTs (CDTs). Construction projects have short-term stakeholders, while projects in the manufacturing industry have fixed stakeholders. Furthermore, the assembly lines in the manufacturing industry help with data collection using embedded sensors for generating the corresponding DT. However, the dynamic nature of construction projects poses major challenges for collecting detailed data. Planning the deployment of sensors while considering the optimized position, power supply and network environment, etc., is difficult and time consuming. In addition, because construction projects are unique, such deployment plans are not reusable. Even with optimized sensor configuration, data collection approaches in construction projects are usually error-prone due to uncertain factors, such as temporary occlusions that affect the performance of real-time location systems (RTLSs) and computer vision (CV) based methods. Moreover, construction projects generate a massive amount of data, which is difficult to process in near-real-time. Fortunately, with emerging technologies, DTs are becoming applicable in the construction industry (Boje et al., 2020; Jiang et al., 2021). In order to capture the leading edge of CDTs and identify the challenges of their implementation, this paper conducts a review of the previous studies related to CDTs. Based on the review, the future research directions for the generation and applications of CDTs are identified.

Concept of CDT

Previous studies have provided frameworks for applying DTs in construction sites. Boje et al. (2020) proposed a framework for the development of CDTs using the same DT paradigm proposed by (Grieves, 2014). On the other hand, Jiang et al. (2021) focused on the connection of the virtual space and the physical space by dividing the CDT into three parts: data, data connections, and services. The data connections are further divided into three parts: data collection, data transmission, and data storage. In addition, they emphasized that a CDT should provide some services to either the management/control in the physical space or to the DT system itself regarding the convenience of construction management and the enhancement of model reliability. Zhang et al. (2022) defined the CDT in another way, which is comprised of the physical environment, digital environment, communication mechanism, and feedback. In their concept map of a CDT, data processing is considered a subcomponent of the digital environment.

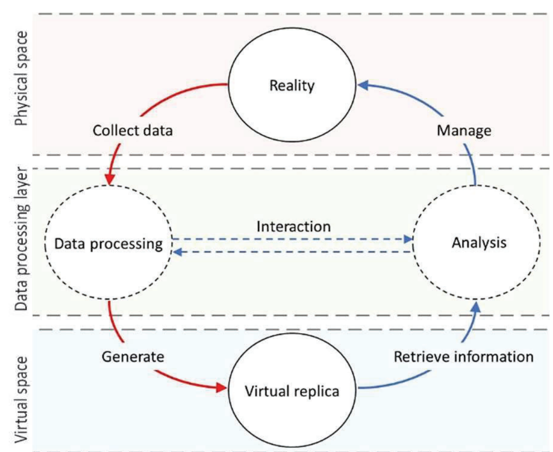

Figure 1 Structure of digital twin (adapted from (Boje et al., 2020))

Figure 1 shows the overall structure of DTs based on the framework proposed by Boje et al. (2020). In the physical space, raw data are captured from the real world. Through data processing, the raw data is processed to extract the useful information required for generating the virtual replica in the virtual space. Such data processing involves data smoothing, data filtering, semantic processing, and data fusion if necessary. Then, information is retrieved from the virtual space to conduct analysis for better decision making and project management improvement. The analysis can be performed through visualization, simulation, and machine learning. Finally, based on the analysis results, applications can be provided to support the management of the construction project.

Furthermore, it should be noted that DTs should be differentiated from similar concepts, such as BIM, simulation, and cyber-physical system, which were considered as DTs in different contexts. The detailed comparisons between DT and these concepts are discussed in (Huang et al., 2023).

Review Method

This section introduces the method used in this paper for the systematic review of the existing literature. The present study leveraged the content analysis structure from Chen et al. (Chen et al., 2022). There are three main processes of the review method: paper collection, initial review, and in-depth review and discussion.

First, an exhaustive search was carried out using two search engines: Web of Science and Scopus. The document type was limited to journals published during 2017-2022 (September). The search keywords included two categories: construction-related terms and technology-related terms. The construction-related terms included “Construction”, “Building engineering”, “AEC industry”, and “Civil engineering”. The technology-related terms included “Digital twin”, “Digital twining” and “Cyber-physical system”. 267 journal papers were collected from Scopus, and 186 papers were collected from Web of Science. After removing the papers that were not published in the mainstream journals (“Q1” and “Q2”) or had less than 50 citations, 103 initial papers were selected.

In the second step, a brief visual examination of the titles and abstracts was conducted to remove the less relevant papers. The papers related to CDTs were selected, resulting in a total of 34 journal papers, as shown in Table 1 and Table 2. Among these papers, seven are review papers, seven papers are conceptual and explain CDTs and digital models in construction projects. The remaining 20 papers are related to the DT applications in the construction phase, as shown in Table 2.

In the third step, an in-depth review of the papers selected in the previous step was carried out. The details of the literature review are available in (Huang et al., 2023). Based on the in-depth review, discussion regarding the future research directions was conducted.

Table 1. Selected review and conceptual papers

Topic	Reference
Review papers	Boje et al., 2020; Jiang et al., 2021; Mêda et al., 2021; Opoku et al., 2021, 2022; Ozturk, 2021; Zhang, et al., 2022
Conceptual papers	Alizadehsalehi and Yitmen, 2021; Sacks et al., 2020; Teisserenc and Sepasgozar, 2021b, 2021a; Tetik et al., 2019; Wei et al., 2022; Zhang, et al., 2022

Future Research Directions of CDTs

Previous studies regarding the technologies and implementations have proven that CDTs are promising. However, several limitations have reduced the applicability of CDTs in construction projects. Overall, the main challenges can be summarized into three aspects: (1) model generation; (2) applications; and (3) general issues. In this section, the future research directions are discussed regarding these aspects, as shown in Table 3.

The proposed research directions focus on novel research topics of CDTs based on current and emerging technologies. Towards generating near-real-time CDTs that have multiple functions and achieve high level of reliability (LOR), three phases are proposed: (1) Take-up phase: improving and leveraging the existing technologies; (2) Research and development (R&D) phase: developing new technologies that are clearly defined and under exploration; and (3) Emerging research phase: future work that needs innovative solutions. The following sections will discuss the future research directions from the take-up phase to the emerging research phase for each aspect.

Model Generation

Previous studies have proven that the parametric as-built 3D model can be generated by processing the point clouds using the as-designed BIM as a reference [3, 4]. Thereby, the construction progress can be also modeled according to the as-built 3D model. However, there are challenges that warrant further R&D:

1. **Near-real-time high-LOD modeling:** One of the current challenges is performing real-time high level of detail (LOD) modeling of the construction site. Near-real-time modeling will require addressing the current gaps regarding real-time data collection and efficient data processing.
2. **Construction resource modeling:** A high-LOD CDT should involve a high-LOD as-built model and high-LOD construction resource models. Even though previous CDT-related studies have generated virtual models for different construction resources, the LOD of these models is usually low. While many previous studies have contributed to modeling construction equipment, such as capturing the pose and activity of equipment (Chen et al., 2020, 2022; Vahdatikhaki et al., 2015), one of the current challenges is exploring efficient approaches to integrate the equipment model into near-real-time CDT generation. For workers, previous studies used only their position to generate the worker model in the virtual space. Information about the status of workers (e.g., their activity and pose) can be used to better monitor the workers’ productivity and safety (Li et al., 2021).
3. **Environment modeling:** The environment model of a construction site allows the implementation of environmental management; and it can help with the health and safety management by monitoring temperature, humidity, etc. (Yi et al., 2016).

Table 2. DT applications in construction

Application	Reference	Data sources	Tracked Resources				
			Finished products	Materials	Workers	Equipment	Terrain
Progress monitoring and quality control	(Pan and Zhang, 2021)	Laser scanner	X				
	(Rausch and Haas, 2021)	Laser scanner	X				
	(Tran et al., 2021)	Laser scanner	X				
Construction safety	(Jiang et al., 2021)	RTLS, ultrasonic ranging sensor, 3D gyroscope sensor, environment sensors, camera	X	X		X	
	(Kamari and Ham, 2022)	Camera		X			X
	(Wu et al., 2022)	Camera (images and videos)			X	X	
	(Jiang et al., 2022)	Rotation sensor, radius changing sensor, tilt angle sensor, vibration sensor, load and tilt sensor, stress sensor				X	
	(Li et al., 2021)	Load sensor, vibration sensors				X	
Construction equipment control	(Wang et al., 2021)	Videos from Microsoft Kinect depth cameras	X	X			
	(Zhao et al., 2022)	GPS, IMU, barometer, RFID		X		X	
Data management	(Jiang et al., 2021)	UWB, RFID		X	X	X	
	(Lee et al., 2021)	GPS	X				
Supply chain monitoring	(Greif et al., 2020)	Not mentioned		X		X	
Site measurement	(Shi and Wang, 2022)	Borehole measurements					X
Environmental management during construction	(Liu et al., 2020)	RFID, GPS, pressure sensors, proximity switch, acceleration sensor		X		X	
Multiple applications	(Niu et al., 2019)	Not mentioned		X		X	
	(You and Feng, 2020)	RFID, GPS, Laser scanner, UWB	X	X	X	X	
	(Wang et al., 2022)	RFID, strain sensors and position sensors for capturing the mechanical properties		X		X	
	(Jiang, et al., 2022a)	RFID, UWB		X	X	X	
	(Jiang, et al., 2022b)	RFID, UWB		X	X	X	

Table 3. Future research directions of CDTs

Aspects	Take-up phase	R&D phase	Emerging research phase
Model generation	• Parametric 3D model generation • Construction progress modeling	• Near-real-time high-LOD modeling • Construction resources modeling • Environment modeling • CDT specifications	• Lifecycle CDT • Reusable CDT • Simulation-based CDT • Federated CDT
Applications	• Progress monitoring and quality control • Construction equipment monitoring • Site layout adjustment	• Productivity analysis • Safety monitoring • Task navigation • Claim management • Supply-chain management	• Equipment and Robot control • Human-robot collaboration
General issues		• ROI study	• CDT execution plan guideline

Moreover, the construction progress and quality are affected by weather conditions. Therefore, these conditions should also be considered when generating a high-LOD CDT. However, there is limited research on the environment-integrated CDT, which fulfills the requirements of the abovementioned applications. Therefore, more research on this topic is needed in the future.

4. **CDT specifications:** The specifications of CDTs proposed in the previous studies can reflect the CDT LOD in some specific aspects. However, they are too generic to evaluate the reliability of the CDT, which is called the Level of Reliability (LOR) in this paper. For example, a high-LOD CDT cannot be considered reliable unless the CDT's real-timeness and correctness can be guaranteed. As such, the authors propose evaluating the LOR of CDTs based on four criteria: real-timeness, fidelity level, redundancy, and comprehensiveness. Real-timeness should be evaluated from two points of view: (i) the ability to perform real-time data synchronization and data processing for CDT modeling; and (ii) the ability to perform near-real-time data analytics and simulation to provide timely feedback to reality. The fidelity level refers to the LOD and the accuracy of the virtual model. The comprehensiveness refers to the diversity of data sources for model generation and decision-making, which can support multiple applications of CDTs. Redundancy refers to the inclusion of extra components in the twinning system in case of the failure of some components. This aspect mainly considers the situations when some of the sensors are not functional, or the sensing results are affected by inevitable factors on construction sites (e.g., occlusions).

In addition, there are emerging aspects to be discussed for the generation of CDT:

1. **Lifecycle CDTs:** Lifecycle continuity is another important aspect that needs to be considered for the future development of CDTs (Sacks et al., 2020). To this aim, it is highly recommended to have a guideline to help companies define the scope and deliverables of a CDT at different phases of the project. Moreover, in the future, there should be a standard format of CDT (acting like Industry Foundation Classes (IFC) in BIM) that ensures the interoperability of CDTs, so that a CDT can integrate different entities (e.g., HVAC system components and their operational characteristics) for different applications in different project phases.
2. **Reusable CDTs:** In order to save time in the generation of CDTs, reusable CDT should be considered. Previous studies in the manufacturing domain have proposed a platform, called *DIGITbrain* (Zambrano et al., 2022), to support the "modular construction" of DTs by reusing the fundamental parts of previous DTs. The previous DT of a system is decomposed into multiple constituting parts, i.e., data, model, and algorithms. The platform will then identify the reusable parts as fundamental building blocks and save them for later users when they try to generate a DT of a similar system.
3. **Simulation-based CDTs:** Previous studies have mentioned simulation as one of the main benefits of CDT. In general, simulation has two types: (a) simulation based on the footprint of the previous projects to simulate the construction process and improve the design and project plan of future projects; and (b) simulations based on captured data during the execution of the current project to predict risks in the near future. The second type of simulation has not been fully studied in previous works. Overall, all previous CDTs are data-driven, which only tell the current or previous situations of the construction project. In order to provide efficient prediction, it is necessary to apply simulation based on the collected information in the CDT. Researchers in chemical engineering [26] developed a framework of simulation-based DT using the first-principal model for a heat production plant. Yeung et al. [180] emphasized the role of simulation in CDT as the enabler of predictive situational awareness during decision-making. In addition, they mentioned that simulation in CDT can be used for continuous optimization and automation in construction.
4. **Federated CDTs:** Essentially, a construction site can be considered a system consisting of different assets involving the structures, terrain, materials, components, equipment, workers, etc. Therefore, the CDT can be understood as a system twin, which consists of asset twins (*IBM*, accessed Sep. 2022). Similarly, according to Sacks et al. (Sacks et al., 2020), the CDT relies on a network of different DTs. As such, CDT can be generated by federating the DTs of different assets (e.g., equipment twin, worker twin, component twin, etc.). In addition, the CDT can be federated with other DTs outside the construction domain; for example, federating with the city twin to use the traffic information to better represent hauling operations. Unlike the previous implementation that integrated multiple data sources to generate CDTs with multiple applications, a federated CDT has a decentralized architecture that distributes model generation tasks to different computation resources.

Applications

The previous CDTs were applied for progress monitoring, construction equipment monitoring, and site layout adjustment. However, the applications provided by such CDTs are usually limited. In some cases, these applications can be provided by the current practices of simulation, data analysis, or BIM uses without generating DTs. Thus, R&D is needed to realize several compelling CDT applications as explained in the following:

1. **Productivity analysis:** Productivity analysis in the previous CDT studies is mainly conducted by comparing the as-built model versus the as-planned model. Productivity analysis is expected to be more detailed and comprehensive by considering the status of construction resources to identify the factors affecting productivity (Chen et al., 2022). This will

also allow evaluating the productivity of workers and equipment.

2. **Safety monitoring:** Safety monitoring in previous CDT studies mainly considered the position relationships between objects on construction sites (e.g., proximity between workers and equipment). However, a high-LOD CDT, which integrates multiple data sources, allows considering more aspects in safety monitoring, such as workers' awareness (Chan et al., 2020; Hasanzadeh et al., 2016).
3. **Task navigation:** Task navigation can be a function that provides support to workers on construction sites (Jiang, et al., 2022). By synchronizing the up-to-date construction progress with the workers' tasks, they can better understand the construction site and their tasks. As such, it is possible to improve their productivity.
4. **Claim management:** By comparing the as-planned and the as-built models, or by forensic analysis of accident scenes using the CDT, claim management can be performed (Guévremont, 2021). In addition, with the integration of blockchain technology, transparent data sharing based on CDT between different stakeholders can be achieved, which mitigates the disagreement on the non-contractual BIM and 4D simulation. Furthermore, a CDT can be used as evidence to help with claim avoidance or settlement. Depending on the type of the contract (e.g., integrated project delivery vs. design-bid-build), the CDT can be more or less useful in the context of claim management. Further research is needed regarding the applications of CDTs in claim management.
5. **Supply chain management:** By federating the CDT with the supply chain DT, the supply chain of the construction project can be monitored. Previous research has discussed the generation and applications of supply chain DTs in the manufacturing industry (Abideen et al., 2021) and in modular construction (Greif et al., 2020; Lee and Lee, 2021). Further research is needed to learn from the previous studies and to integrate the supply chain DTs with CDTs.

The emerging research regarding CDT applications include two aspects:

1. **Equipment and robot control:** The CDT can be used to control construction equipment and robots to perform construction-related activities. Previous studies have tried using robots to collect data from construction sites (Asadi et al., 2018; Kim et al., 2018, 2019) and to perform some construction tasks (e.g., off-site automated prefabrication (Bock and Linner, 2015) and bricklaying (Ding et al., 2020; Dörfler et al., 2016; Zandavali and Jimenez Garcia, 2019)). However, these methods are not mature enough to be applied on construction sites. Further research is required to explore how CDTs can be used to leverage robotics in construction.
2. **Human-robot collaboration:** Collaboration between robots and between humans and robots is critical regarding construction safety and productivity (Xiao et al., 2022). Coordinating workers and robots on construction sites will need a high LOR CDT which can provide accurate information about the site condition, worker status and robot status in real-time. Therefore, realizing this goal will require the fulfillment of all of the abovementioned gaps.

General Issues

In addition to the abovementioned challenges, the following general issues may also impede the implementation of CDTs.

The return on investment (ROI) is always a critical factor when implementing new technologies. For CDTs, the ROI can be affected by many aspects: (i) the cost of sensors and tools, (ii) the cost of installation, (iii) the cost of development, (iv) the cost of maintenance, and (v) the return from CDT applications. For the time being, it is difficult to provide a precise evaluation of the ROI of implementing CDT due to the lack of case studies. It is necessary to have ROI studies in the near future which justify the value of CDTs in construction projects.

As for the emerging research directions, developing a CDT execution plan guideline will be the next step. For the time being, there is no general guideline for implementing CDT. This guideline, which can help construction companies develop a CDT execution plan, is similar to the *BIM Project Execution Planning Guide* (Messner et al., 2019); and it aims to define the project goals and the corresponding DT applications, develop implementation plans, and define the CDT milestones and deliverables to achieve the smooth shift between different project phases. Such a guideline will also provide suggestions and examples about how to manage the contract and legal issues related to CDT implementation.

Summary and Contributions

This paper provided a review of the recent development related to CDTs. By reviewing the selected papers, the current research gaps of CDT research and applications were identified. CDTs are yet to be comprehensive, efficient, and functional enough to fully support construction management. The promising benefits of providing prediction, as well as providing control and enabling human-robot collaboration on construction sites are still to be developed. Based on the discussion about the current CDT status, future research directions for generating high LOR CDTs and their applications were discussed.

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