Application of digital twin technologies in construction: an overview of opportunities and challenges

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Abstract –

Digital twin technologies have been widely used among different industries, for which different conceptual models and system architectures have been proposed. However, the processes are required to establish a digital twin for intended use cases have not been fully studied. This study adopts a systematic literature review analysis focusing on case studies on digital twin models, highlighting the practical steps in developing a digital twin and the challenges faced by various researchers in this field. After a rigorous selection of relevant literature, a total of 23 scientific publications were systematically reviewed. The literature focused on recent publications (2016-2021) to convey updated information regarding the developments of digital twins in the construction domain. The findings synthesized the main processes of establishing and using digital twin technologies in the AEC industry, including the data acquisition processes, data transmission processes, data modeling processes, data integration processes, and the servicing processes. Although digital twin models could improve the stakeholders' decision-making processes, several challenges regarding data integration and data security still exist in the current applications. The digital twin models require people with the right skills to construct them, a large amount of funds, and the latest technologies with higher computational power to successfully develop them.

Keywords –

Digital twin technologies; Use cases; Information integration; Stakeholder collaboration; Sustainability

1 Introduction

The advancements of BIM applications have changed how the information could be generated, stored, and exchanged amongst the various stakeholders in the construction industry. However, digital technologies are evolving with the advent of the Internet of things (IoT) and Artificial Intelligence (AI) agents such as Machine Learning, Deep Learning, Data Analytics, etc. The evolution of BIM should be carefully considered in conjunction with these emerging technologies [1]. Artificial intelligence improves the sharing of information, helping to reduce the cost to the consumers and lesser impacts on the environment, adding 10% to the United Kingdom (UK) economy by 2030 [2]. According to Sacks et al. (2020) [3], the digital twin models, Automated Project Performance Control (APPC), Construction 4.0, automated data acquisition technologies have been emerging areas of research in the AEC industry.

National Aeronautics and Space Administration (NASA) has been using digital twin models from earth to control and run simulations of their spacecraft for accurate mapping [4]. The digital twin models in the aviation industry are used to twin models of aircraft and airport models, in the latter to facilitate the tracking and efficient control of luggage. The manufacturing industry creates digital twin models for small components and large factories. These digital twin models are also used for safety and logistics maintenance while maximizing the efficiency of the products [5]. For example, in the automotive industry, Tesla uses this technology to transmit the performance data from its vehicle to the 'mothership'. The automotive industry has already established synchronous data transmission between their cars and factory to improve the efficiency of products [6]. Digital twin models in the health and well-being industry have been used for planning and performing surgeries, detecting stress levels and emotional changes, tracking fitness, predicting the occurrence of illness, and customizing recommendations for an individual [7], [8].

The digital twin models also have been used for transportation management, energy usage optimization, asset anomaly detection, resource and logistics planning, safety monitoring, event prediction, and running simulations [9]. These emerging use cases generate a large amount of data from multiple sources, which needs to be stored and shared while ensuring safety and security [2]. The digital twin models could be used within a smart city, which facilitates connectivity using IoT devices. This helps to enhance the services, utilities, and infrastructure by testing various transportation scenarios [10], [11].

The current activities related to developing the digital twin models in the construction industry are at an early stage. There have been contributions from the academic community to exploit digital technologies and BIM in recent years. This has further led to the development of conceptual frameworks for the digital twin. The developments heavily rely on the performance of BIM and integrated IoT technologies. The application of digital twin models would help to address many of the construction-related problems.

Fuller et al. (2020) [10] reviewed the developments made across various industries on digital twin models using the emerging technologies and the challenges encountered by them. Boje et al. (2020) [12] summarized BIM applications and how they could pave the way for the concept of semantic digital twin models in the construction industry. Lu et al. (2020) [13] illustrated a clear road map for digital twin developments in the UK, which promoted the implementation of digital twin models at the city level. Compared to these studies, this paper adopts the systematic literature review analysis to summarize the practical steps to develop a digital twin and identify the challenges various researchers face in this field. This study highlights both the potential and the challenges of using digital twin technologies in the construction industry. The various digital models, data sources, and transmitting networks required to create a digital twin are demonstrated. The findings from this systematic review would provide insights into the future implementation of the National Digital Twin Program and Gemini Principles in the UK.

This study is not limited to the concepts and terminologies on digital twin models but emphasizes the important processes required to develop digital twin models within the construction industry. This further helps in understanding the benefits and challenges faced by the various researcher.

Section 2 provides a comprehensive summary of the definitions of digital twin from various industries. Section 3 describes the methodology of the systematic review. The detailed findings from the review analysis are included in Section 4, followed by the conclusions and future research in Section 5.

2 Understanding digital twins

2.1 Definitions of digital twin

NASA provided the first definition of digital twin in 2012. Though the exact definition of a digital twin has not been unified in the current literature, researchers could still refer to the definitions from various domains and industries to find the commonalities. A list of the definitions is summarized as follows:

(1) Aerospace domain: A digital twin is a multiscale, multi-physics and probabilistic simulation of an asset integrated using the sensors and physical models to duplicate its corresponding flying twin [4].

(2) Infrastructure service domain: A digital twin is a dynamic representation of an asset or a process in a digital form representing all the features in the built environment [14].

(3) Manufacturing domain: A digital twin is a digital representation of a component or an asset that helps to optimize the manufacturing process by predicting the performance of the machine [15].

(4) Healthcare domain: A digital twin is a virtual replica helping to monitor and evaluate in real-time without being in close proximity to the physical object [16]

(5) Construction domain: A digital twin is a realistic digital representation of physical assets, distinguishing itself from other digital models due to its connection to the physical twin [3].

By summarizing these definitions, the main components for generating digital twin models include 1) the physical elements/assets, 2) the linked data, and 3) the virtual models. The digital twin models in various industries more or less have the same features and purposes of applications, providing dynamic and real-time information for the planning and control processes. Sensor devices such as RFID and laser scanner equipment are integrated with the digital model to act as a constant source of communication with the real world. By adding artificial intelligence or big analytics, the digital twin applications could further expand the potential to enable autonomous decision-making.

2.2 Resolving the misconceptions of digital twin and BIM

The digital twin technologies have been widely used among different industries, for which different conceptual models and system architectures have been proposed. However, this gradually led to some misconceptions and misunderstandings within a specific industry [10]. The very basic idea of using the digital twin technologies in the construction industry starts with using the BIM-based platforms and collaborative models to improve construction and design methods. The construction documents, specifications, and 3D design models are federated in BIMs instead of using spreadsheets and 2D CAD drawings [12]. To show the actual reflection of the physical assets at any given time as in line with the digital twin modeling concepts, the BIMs need to be continuously updated using the information collected from the sensors or ubiquitous IoT devices. However, there has been a lack of efforts to connect BIMs to digital twin models. The associated large amounts of BIMs and sensor data could be stored in the cloud or in relational databases to be further used for data analytics and machine learning applications to support decision-making, e.g., predictive maintenance of the HVAC systems [13]. The comparison between the use of BIM and digital twin modeling is illustrated in Table 1.

Table 1. The comparison of BIM and digital twin

	Building Information Modelling	**Digital Twin Modelling**
Purpose	Used to enhance efficiency during design, construction, and throughout building lifecycle [17][18].	Used to enhance operational efficiency by predictive maintenance and monitoring assets [19].
Feature	Real-time data flow not necessarily required [20]	Real-time data flow required for simulations [21].
Data exchange standard	IFC, COBie, etc., to support design information exchange [22].	Standards to support wireless sensor network transmission of information [23].
Main users	Architects, engineers, developers, and facility managers [24].	Facility managers and equipment engineers [25].

3 Methodology

This study takes a systematic literature review method to synthesize the potential and challenges of using digital twin technologies in construction projects. The literature for this research was acquired through the academic search engine database (i.e., Web of Science used in this study) and focused on the last 5 years (publication year ranging from 2016 to 2021). The database has the feature of customizing the search preferences. The search keywords were “digital twin in construction” or “semantic web” or “artificial intelligence” or “construction 4.0” or “BIM” or “building information modelling” to rectify the new advancements about the scope of research. It is also worth noting that this study considered the terms “cyber-physical model and system”, “virtual twin”, and “smart cities” as a digital twin application when used in a similar context. The initial search found that 6980 articles were published in the field of digital twin applications, out of which 4490 were published since 2019. Although many articles have been published on this topic, the authors further refined the search to journal and conference articles only in the “civil engineering domain” by the Web of Science search engine. Besides, with an in-depth review of the abstract of the articles from the refined search, 23 articles were left for the systematic review analysis. In addition, reports from government and non-government organizations were used as a reference to support the triangulation of the literature. This study also included recent publications on digital twin use cases from other industries as a reference to help the authors verify and validate the terminologies and concepts.

It is noted that the literature review did not intend to include all the work published on the digital twin applications in the construction industry as this is not an exhaustive review. Also, this review focused on articles published very recently (2016-2021.June) to convey the most up-to-date information concerning digital twins.

4 Findings

The systematic review identified and synthesized the main processes of establishing and using digital twin technologies in the AEC industry (Table 2), including the data acquisition processes (Section 4.1), data transmission processes (Section 4.2), data modeling processes (Section 4.3), data integration processes (Section 4.4) and the servicing processes (Section 4.5). The potential and challenges of implementing digital twin technologies were discussed in Section 4.6.

4.1 Data acquisition processes

The data acquisitions processes aim to collect the data from various sources in different types and available in distinctive formats. The data can be the geometric information, environmental conditions, scheduling parameters, and functional capabilities [26]. The data can be collected using radio-frequency identification (RFID), sensor systems, images and videos, quick response codes (QR), and related IoT devices [27]. The data collected from various sources need to be processed to ensure systematic data mapping. The data can be processed using data fusion, blockchain, and edge computing algorithms to be converted into a readable format such as Extensible Markup Language (XML) and My Structured Query Language (MySQL) [28]. For example, for the digital twin of the West Cambridge site, which has assets in quite a large number, the data regarding the environment and the physical elements were acquired from sensors deployed on the site. The other information was acquired using MySQL from the space management system (SMS), asset management system (AMS), and building management system (BMS) at the Cambridge University [13].

Table 2. Establishing and using digital technologies

Data acquisition	Data transmission	Digital modeling	Data/model integration	Service/objective	Reference
QR codes, RFID, IPC, sensors	WAN, LAN, Internet	3D geometric model, kinematic model	Virtual environment platform	Simulation and optimizing model	[21], [23], [29]–[32]
GIS, Sensing images, sensors, BMS data	Internet	BIMs, CIMs	Cloud computing	Monitoring and controlling of the physical city	[12], [13], [19], [25]
Real-time sensors, QR codes, Building management system, space management system, etc.	Internet, WLAN	BIMs	Machine learning, data analysis, and simulation engines	Anomaly detection for built asset monitoring in operation and maintenance	[11], [14], [24], [28], [33]
Geospatial datasets, demographic and climatic conditions	Internet	BIMs	Cloud computing, big data	Running Simulations for urban planners	[34]–[37]
Thermal imaging camera, data sets, IoT sensor devices, AI	Internet	CIMs, BIMs, thermography map	Machine learning algorithms	Energy planning renovations, simulation models	[38]–[41]

4.2 Data transmission processes

After data are systematically acquired, they need to be transmitted for modeling. The transmission of data from the real-world physical asset to the digital replica and vice-versa is the most critical part of developing a digital twin model. This phase provides insights into the physical element and helps to automate the system wherever applicable. A two-way mapping (i.e., a transmission) layer is required between the physical asset and the virtual model.

The transmission of the data could be done using short-range technologies such as Wireless Fidelity (Wi-Fi), Near Field Communication (NFC), Bluetooth, etc., and for wider ranges, the third-generation (3G), fourth-generation (4G), Wide Area Network (WAN), Long Term Evolution (LTE) wireless telecommunication technology could be used [20]. Wireless Local Area Network (WLAN) is the most widely used technology, but it has security issues. According to Silva et al. (2018) [42], Light Fidelity (Li-Fi) and Low Power Wide Area Network (LPWAN) are good alternatives due to their transmission efficiency. Moreover, the IoT devices help exchange data from the physical assets to the virtual models, and in turn, the virtual models are updated according to the data input from IoT devices [9].

Lu et al. (2020) [13] developed a Wireless Sensor Network (WSN), which was supported by IoT devices along with QR codes for managing the network of asset information for the transmission phase. The IoT devices used in this study were Monnit wireless sensors with a 1-min heartbeat. These sensors were used to capture data regarding the temperature, humidity, and motion at different locations. The data were uploaded to the gateway nodes using radio frequency, which were eventually sent to the Sensor Manager through the internet from the gateway nodes. QR codes were scanned by the maintenance personnel using the App Redbite Solutions [13] to update the information and transfer it to the asset management platform. The data from the asset manager and sensor manager were eventually collected and updated to the AWS DynamoDB for communicating with the digital models.

4.3 Data modeling processes

The data modeling processes consist of developing 3D or nD models in Building Information Models (BIMs) or higher-level city information models (CIMs) representing the physical elements in the real world. The digital replica of a physical asset for the digital twin needs a definition. The definitions for digital replica can be composed of data from BIMs, Geographic Information System (GIS), IoT sensors, asset management systems, weather data systems, cost/scheduling/safety management platforms. However, the data should be aligned to the intended use of the digital twin.

The digital models could be done using photogrammetry, drones, vehicle-based scanning devices, laser scanners, and digital cameras for generating highly detailed models. Besides, the digital design models of the proposed site, Mechanical, Electrical and Plumbing (MEP) components, and BIMs could be created using Autodesk Revit and other BIM authoring software.

4.4 Data integration processes

Once the modeling processes are completed, all the associated data are stored, analyzed, processed, and updated as changes occur. Since a large amount of heterogeneous data are generated and used, it is essential to have appropriate storage and integration. It is evident from various literature that researchers have used different platforms to ensure an effective and secured data management system. Cloud storage has been considered an effective option. The dynamic linking of different knowledge engines (KEs) to the physical elements helps gather the information continuously. The KEs are driven by the target domain knowledge, and the information is stored under them. The KEs are dependent upon the intended use of the digital twin.

The digital models created in BIM software could be exported to Industry Foundation Class (IFC) files. The IFC files could be integrated with the data stored in the DynamoDB, which translates data at a semantic level; a relationship between the data in DynamoDB using a set ID and the objects from the BIMs based on the globally unique identifier (GUID) was established to do so.

4.5 Providing services via the digital twin

When data are integrated and stored properly, the knowledge from the KEs is interpreted, enabling the exchange of information between the physical assets and the model. End-users and FM professionals play an important role in the decision-making processes. Moreover, regular feedback should be fed into the KEs from the people and professionals to enhance the FM functions.

In the following case study, the digital twin models were used for various servicing scenarios:

(1) Monitoring the ambient temperature and humidity of the working spaces.
(2) Maintenance planning optimization by using data from the building management systems and failure/maintenance logs.
(3) Allocating resources by prioritization of the maintenance tasks.
(4) Energy planning at an urban level for achieving low carbon output.

Similar applications on future projects having identical attributes could be done to contribute to the initiative of the National Digital Twin. These servicing use cases assisted the stakeholders' decision-making processes and enhanced the relationship between the end-users and buildings. After reviewing multiple case studies, it was found that the data acquisition, data transmission, modeling, data integration, and servicing processes compose the whole picture of digital twin modeling. However, the specific methods to conduct each process differ and depend upon the intended use of the digital twin models.

4.6 Evaluating digital twin applications

4.6.1 Potential of the applications

The data collected from digital twin models can be used for emergency and crisis planning and managing assets [26]. The data updates from the digital twin models help to portray the issues and constraints to various stakeholders, such as predicting the conditions of a physical asset, predicting energy consumption while maintaining the environmental codes, monitoring the structural health of the infrastructure assets, predicting structural life. When combining the data with AI algorithms and data analytics, these digital twin models are useful for forecasting or back-casting. In those cases, the future state of an asset can be determined and compared against a desirable planned state.

Besides the predictions, the digital twin models help stakeholders choose the right design solutions for a structure with low carbon emission and clean energy. Specifically, the iterated possible design solutions could be quickly produced to facilitate the generative design when simultaneously considering the environmental, cost, and schedule benefits.

The data updates are also helpful in monitoring the construction workforce in real-time, which continuously provide feedback about the construction workforce when exposed to risks related to the body segments.

Particularly in dangerous sites such as nuclear power plants, a constant real-time update about the installation work is necessary to protect workers from hazards and minimize human interventions.

The digital twin models allow the involvement of the wider audience in assisting urban planning and designing practices by utilizing the data such as the preference of citizens and material usage prioritizes. Since the data are collected from the citizens or the end-users, the digital twin models could efficiently bridge the gap between the people and buildings/cities. This would provide the required agility and customization whenever needed. At the city and urban level in general, digital twin models link the various buildings and citizens together to generate a unified federated model to ease the convenience of managing the city developments.

4.6.2 Challenges of the applications

Across the literature, it is noted that the basis for developing digital twin models for specific use cases is the data, and data integration is critical for a successful implementation of the digital twin while being linked to the physical assets. However, the major challenge remains the integration of data from multiple technology sources in different formats.

The data required for the digital twin models are stored in disparate systems, and at times, it is challenging to determine whether the data from one machine is the same as on the other. The data sources are usually heterogeneous. Furthermore, there could be a difference in the nomenclature of the database from system to system. The synchronization of data to ensure continuous feedback loops is also a challenging task. Since the digital twin models monitor the assets in real-time, it is necessary to have a continuous stream of information without any breakdowns. The quality of data collected should meet the requirements of the intended use. The quality of data can deteriorate while extracting it from the source or while transforming it.

The digital twin requires data to be transmitted from the physical asset to the digital replica in real-time, which involves a significant amount of cost and time. These economic aspects have not been justified. Many studies have linked the IoT with the digital twin as the devices are getting cheaper and their applications more user-friendly. Nevertheless, the problems of linking the IoT data with the digital models persist. The formats of BIMs and the semantic web data of the IoT devices still need to be further standardized and developed to integrate the data. However, in terms of data standards, the manufacturing, aerospace, and healthcare industries have made more significant progress in this field.

Digital twin models are exposed to cyber threats; thus, data protection and privacy are key priorities [43]. Since the data is sensitive, it needs to be protected; otherwise, it could lead to trust issues. The digital twin models should be used following a common data transmission and exchange standard.

Installation and maintenance of the sensors on a construction site is a concern to a few. There are always chances of sensors getting damaged or stolen from construction sites. Moreover, these devices generate a large amount of data that needs to be stored, filtered, and matched with the BIM models. Besides, the physical assets in the construction industry need to last for decades, making the lifecycle maintenance a critical task.

The construction industry is complex and involves multiple stakeholders; therefore, all the project members must work collaboratively. Furthermore, the involvement of multiple stakeholders might lead to a longer time to construct the physical asset and digital twin models. The digital twin models require people with the right skills to construct them, a large amount of funds, and the latest technologies with higher computational power to successfully develop them.

5 Conclusions and future work

Digital twin-related topics have recently gained great attention in the AEC industry to improve data processing productivity. This study conducted a systematic literature review to understand the practical steps to develop a digital twin application to enhance construction integration and the challenges faced by various researchers in this field. Firstly, a comprehensive summary of the definition of digital twin from various industries was provided. Secondly, the method for systematic review was presented, and 23 articles were narrowed down for detailed analysis. The results presented the main processes of establishing and using digital twin technologies in the AEC industry, including the data acquisition processes, data transmission processes, data modeling processes, data integration processes, and the servicing processes. In the end, the digital twin application potentials and challenges were summarized. In the future, the digital twin applications should consider the collaborations among different stakeholders to ensure the proper time for model development. The ACE industry should focus on the training and development of skilled professionals specifically for digital twin applications. The related parties should also pay enough attention to the budget planning during decision makings.

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