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LEVERAGING DIGITAL TWINS FOR ENHANCED CONSTRUCTION PROJECT DELIVERY

Obinna C. Madubuike[1], Chimay J. Anumba[1], and Eleni Papadonikolaki[2]
[1]College of Design, Construction, and Planning, University of Florida, USA.
[2]Department of Materials, Mechanics, Management, and Design, Delft University of Technology, Delft, The Netherlands.

Abstract

The construction industry increasingly recognizes the potential benefits of cyber-physical systems, particularly Digital Twin (DT) technology, within the framework of Industry 4.0 and Construction 4.0. However, there remains a lack of clarity regarding the specific contributions of DT to the construction sector, often conflated with Building Information Modeling (BIM). This paper aims to address this ambiguity by conducting a historical review of DTs, delineating their key features, and elucidating the opportunities they offer throughout the stages of constructed facilities' life. Additionally, this paper outlines potential research trajectories and practical applications for leveraging DTs to enhance construction project delivery.

Introduction

We have experienced technological developments and applications in the construction industry in recent years. The construction industry is taking advantage of the wide range of technologies to facilitate digitalization and automation, enabling the integration of the construction processes at all value chain phases, resulting in the term ‘Construction 4.0’ (Oesterreich and Teuteberg, 2016). Construction 4.0 is attributed to Industry 4.0 which focuses on the seamless generation, analysis, and communication of data to enable smart manufacturing (Perrier et al, 2020). However, the construction industry’s adoption of digitalization is still low, particularly in the area of Digital Twin which played a huge role in realizing Industry 4.0 (Brilakis et al, 2019). However, the intent is to use a wide range of smart technologies to digitalize and automate construction processes and activities. This is done to ensure a reduction in construction costs, more accurately controlled construction activities, and time savings.

Several systems and technologies have been determined to contribute to the digitalization and automation of the construction industry. For Example, cyber-physical systems to plan and monitor mobile cranes on site (Kan et al, 2018), construction robots (Bock & Linner, 2016), and digital twin (DT) for healthcare facilities management (Madubuike & Anumba, 2022). Technological development is all attributed to enabling and ensuring that construction activities are carried out efficiently and easily. The construction industry has experienced significant project time and cost savings due to important technological developments that have improved construction operations (Son et al., 2010). Digitalizing the construction industry entails using smart technologies, systems, or data to convert physical models and tasks to virtual models and tasks, enabled by machines or robots. This paper investigates the extent to which Digital Twin is applicable for enhanced construction project delivery. It focuses on how DT can be applied in all phases of construction projects including design, construction, operation and maintenance, and decommissioning or demolition for enhanced project delivery. To achieve this, the paper covers the following: background to construction 4.0, DT in the construction project delivery process, key features of DT and its roles in the different project delivery stages, discussions centered on characteristics of construction problems amenable to DT, construction use cases, and the potential benefits of DT application in construction. It identifies salient points in the findings and highlights future research areas.

Construction 4.0

Background to Industry 4.0

The manufacturing industry is one of the oldest and has gone through several stages seeking improvement (Madubuike et al., 2022). It has moved from Industry 1.0 to Industry 4.0 in line with the phases of the industrial revolution. The breakdown of the various phases is as follows and shown in Figure 1:

- Industry 1.0 brought about the steam engine,
- Industry 2.0 saw the assembly line concept to reduce manufacturing lead time,
- Industry 3.0 embraced computer-integrated manufacturing which replaced labor, and
- Industry 4.0 employed digitalization and automation to ensure smart manufacturing (Roy et al., 2020).

Industry 4.0 has been made possible due to many great technological and scientific advances in the 21st century. The introduction and use of computers, the Internet of Things, and cyber-physical systems contributed to the emergence of Industry 4.0 (Forcael et al., 2020). The emergence of Industry 4.0 has also brought about progress in the construction industry resulting in the term ‘Construction 4.0’, which is primarily based on utilizing and integrating four key concepts: digital data, automation, connectivity, and digital access to enable the digitalization of the construction industry (Berger, 2016). The current trend in technological advancement supports the enablement of Construction 4.0 which, if properly considered, would meet the standards of Industry 4.0.

Towards Construction 4.0

The construction industry is characterized by complex and peculiar features such as the nature of projects, interest in technological investments, and the nature of sites which may make it difficult to implement digitalization or automation. Despite these complexities, the construction industry has experienced some increase in technology adoption, which is enabling the implementation of the concept of Construction 4.0. There is still no consensus on the definition of the concept of 'Construction 4.0'. Similar to DT, the definition of Construction 4.0 depends on researchers and its application. However, it centers around a decentralized connection between physical space and cyberspace using ubiquitous connectivity (Berger, 2016). However, Perrier et al. (2020) opined that Construction 4.0 is not limited to existing and new technologies but also implies using real-time data to transform project management processes for smart decision-making purposes. The manufacturing industry has implemented the concept of 'Industry 4.0' which has given guidance to the construction industry on the implementation of 'Construction 4.0'. Construction 4.0 is seen as an innovative construction management technique that allows for the creation of a smart construction site as driven by Industry 4.0 (Perrier et al., 2020). However, this definition focuses on a 'smart construction site' and does not integrate the project management process which is also a key part of the construction process.

Consequently, to integrate all aspects of construction, this study defines Construction 4.0 as a smart construction technique that integrates existing and new technologies including real-time data to transform and automate the project management and construction process thereby ensuring smart decision-making that leads to efficient project delivery. The emergence of technologies amenable to construction (Madubuike et al., 2022) is paving the way for the implementation of Construction 4.0. Although there is no single technology that can develop a Construction 4.0 environment, the combination of various technologies is considered vital. Perrier et al. (2020) identified different technologies categorized under 7 groups that could be combined to create Construction 4.0. The 7 technology groups include *Group 1* (BIM), *Group 2* (Monitoring – GIS, materials tracking technologies, just-in-time (RFID), and life cycle management), *Group 3* (artificial intelligence), *Group 4* (Data Science – cloud computing, data transfer, and data protection), *Group 5* (Modeling Systems), *Group 6* (Digital Fabrication – robots and autonomous machines), and *Group 7* (Prefabrication). Some of the listed technologies also combine to develop the Digital Twin technology which is still at its nascent stage and can provide a good basis for implementing construction 4.0.

Place of Digital Twins in Construction 4.0

Digital Twinning involves the use of smart enabling technologies to virtually represent a physical asset by obtaining real-time updates and effect bidirectional coordination such that the virtual model closely or accurately represents the physical asset (Madubuike & Anumba, 2023). There is no single definition for a Digital Twin, as each definition depends on the purpose for which the DT is designed. DT combines smart technologies and data sciences similar to Construction 4.0. While DT is centered on creating a digital replica that closely represents the physical assets including all its instances, Construction 4.0 focuses on automating the construction and project management processes, ensuring smart decisions and efficient construction project delivery. In much the same way as cyber-physical systems are a critical component of Industry 4.0; they are also very important in realizing the vision of Construction 4.0.

Digital Twin can be regarded as a key component of Construction 4.0, as all DT enabling technologies are required for Construction 4.0. This helps to delineate the relationship between DT and Construction 4.0 and demonstrate how DT will facilitate the implementation of Construction 4.0. For this study, DT has been defined as the virtual representation of a physical asset using DT-enabling technologies such as sensors, communication networks, and 3D models to obtain real-time updates and effect bi-directional coordination such that the virtual model represents a replica of the physical asset in all instances.

Digital Twins in the Construction Project Delivery Process

Historical Perspective

While various literature has it that DT was developed in 2003, the origins of digital twin technology are traced back to the 1960s (Boschert et al, 2018; Madubuike et al, 2020). The NASA project in 1960 started with the twin concept where two physical space vehicles were created with one called 'the twin' which was placed on Earth to mirror the other vehicle in space (Boschert et al, 2018; Zhuang et al, 2018). However, in the NASA project, the 'digital' aspect was not included at that time. Subsequently, Micheal Grieves introduced the DT concept in his product lifecycle management course in 2003 (Grieves, 2014). Consequently, DT has been mentioned and applied in different fields and industries such as aerospace (Tao et al, 2017), automotive (Lahoti, 2021), energy (Sivalingam et al, 2018), healthcare (Laaki et al, 2019), telecommunications (He et al, 2017), and manufacturing (Roy et al, 2020). Additionally, the growth of the DT concept is beginning to be integrated into the different aspects of construction.

The flexibility in the DT application could be attributed to its features of real-time updates, bi-directional coordination, and the inclusion of digital models for its functionality. Keen (2019) identified that DT can take advantage of BIM and 3D models including other essential contractual information to create digital twin models of buildings using sensors and other smart technologies. Figure 1 provides the historical milestones with DT applications in various fields.

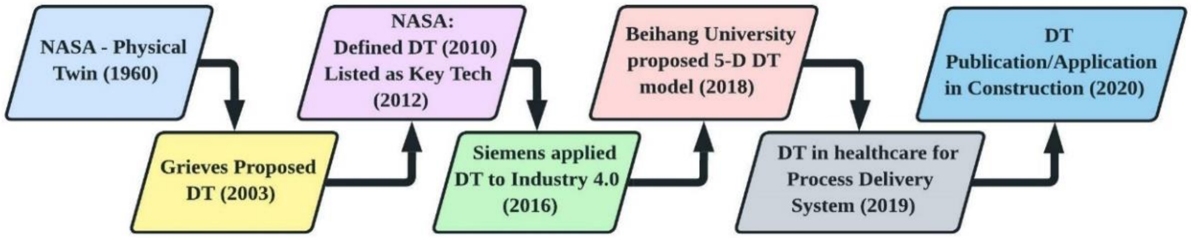

Figure 1: DT Historical Milestones (Adapted from Madubuike et al, 2020).

Key Features of DTs

DT has been identified as a promising state-of-the-art digital platform that enables the management and monitoring of physical assets (Martinez et al, 2018). It has key features that make it applicable to various fields and industrial sectors by representing the physical asset (including its operational changes) through appropriate sensors and communication platforms. Some key features of DT include a 3D digital model for visualization, real-time updates, predictive, and monitoring features, and bi-directional coordination (Madni et al, 2019).

Additionally, studies have developed DT system architectures that explain the relationship between the DT key features (He et al, 2018; Laaki et al, 2019; Madubuike & Anumba, 2022). One of the system architectures was used to develop a DT-based healthcare facilities management (Madubuike & Anumba, 2022; Madubuike et al, 2023). The system architecture was developed with six layers including the physical, sensing, application, communication, device, and virtual prototype layers. These different layers were integrated to prove the identified key features of DT.

Key Construction Applications of DT

The versatility of DT has made its application in various industries possible (Madubuike et al, 2022). Some DT applications in construction include the use of DT to monitor construction work progress (Braun et al, 2018), and using DT to monitor the state of bridges (Sacks et al, 2018). Another DT use case is Singapore's Frasers Tower constructed by Bentley Systems and Schneider Electric, providing a connected workplace for DT purposes (BIM News, 2020). DT for monitoring the state of a bridge (Sacks et al, 2018) and a DT-based system for healthcare facilities management (Madubuike & Anumba, 2021). The DT Hub to promote DT best practices for infrastructure and provide a testbed for the information management framework for the built environment that will enable future National Digital Twin (CDBB, 2020) is a huge step by Britain to provide a consensus view on the implementation of DT. Another DT implementation in construction includes DT for improved healthcare facilities management by monitoring indoor air quality (Madubuike & Anumba, 2023). Although publications on DT have focused more on the operations and maintenance phase, there are still opportunities in the construction phase.

DT Role at Construction Project Delivery Stages

The versatility of DT is seen in its applicability to different fields and industries including the construction industry. However, DT application in the construction industry is still in its nascent stage. Although publications on cyber-physical systems in construction date back to 2009, DT publications in the construction industry started in 2019 with just 2 publications which later grew to 17 in 2021 according to the Web of Science (Madubuike et al, 2022). There is an increasing volume of literature on DT applications in the construction industry. However, much of the literature on DT in construction focuses on concept proposal and prototype development with fewer cases of industry implementation. This shows that the construction industry is still exploring the best application areas for DT. The applicability of DT to the 4 high-level stages of the construction project delivery process is discussed below:

Design

The design stage is one of the earlier stages of any construction project where the planning and design of the project to be constructed are conducted. The design stage is very important as it defines the product and the associated processes needed to bring it to fruition. In Latin American countries, it was determined that 20-25% of the construction period is lost due to design deficiencies (Undurraga, 1996). Additionally, design changes during construction are responsible for the increase in project costs, delays, and in some cases, poor quality of work (Hindmarch, 2010). Several design management tools and techniques such as the Analytical Design Planning Technique (ADePT), Last Planner methodology, and Construction Design Change Management (CDCM) model have been identified (Hindmarch, 2010). However, these tools and techniques lack the essential feedback experience that would help avert any future change when construction begins. Consequently, DT can be used at the design stage to run 'what-if' simulations of real-life scenarios to ensure that most or all possible changes are fully considered at the design stage.

DT implementation at the design stage is currently being considered by construction sector companies embracing the growing trend in technology. This would entail ensuring that all requirements and conditions essential for DT implementation are considered at the design stage. It will ensure an effective and seamless integration of the digital model with the physical facility being constructed. Additionally, the use of VR and AR can be considered good tools while implementing DT in the design phase where project stakeholders can experience the 3D model and make all necessary observations and changes before construction. Negendahl (2015) proposed using 3D geometrical models to run building performance simulations (BPS) at the design stage to ensure buildability and effective building performance. Sacks et al (2018) and Brilakis et al (2019) proposed a geometrical digital twin in developing a design model. However, this was to develop digital models for already existing structures. A geometric digital model can be augmented with semantic information and is the first step to creating a digital twin (Brilakis et al, 2019). This model is then continuously updated with construction and operational data/information that enable it to adequately represent the physical facility and facilitate bi-directional coordination between the two.

Construction

The construction stage is an important phase of construction where all design ideas and plans are implemented. The construction phase is laden with complexities that may affect the adoption of modern technology. Some of the complexities include difficulty understanding the construction phase requirements and adopting modern technologies due to insufficient information (Shahrabi & Mohammadi, 2013; Anumba, 2000). However, DT has proven to be versatile and can be implemented at certain phases of the construction stage to ensure that projects are well constructed to meet the client's needs.

DT can be used to monitor construction work progress (Braun et al, 2018), and workers' productivity, and compare as-builts to the initial designs. DT can provide the opportunity for stakeholders to get involved in a project for site inspection even without being physically present. This can be possible using third-party applications that enable 3D/360-degree remote viewing. The creation and implementation of DT in the construction phase also depend on the available digital model or the Building Information Model (BIM), which contains the 3D geometric information necessary for DT creation.

One of the major purposes of every DT implementation is to create a digital model that truly represents the physical facility and enables real-time performance monitoring. Consequently, the digital model created at the design stage is developed further during construction to capture the actual as-built information, which is vital for the operations and maintenance stage.

Operation and Maintenance

The effective implementation of the design and construction stages would determine the outcome of the operation and maintenance phase. The operation and maintenance phase defines the building's performance and its lifecycle management. It is imperative that buildings or any other infrastructure should be designed and constructed with lifecycle management in mind. DT offers effective opportunities to monitor and manage facilities and ensure improved facilities' performance. The implementation of DT for the operations and maintenance stage should be considered at the inception stage (Grieves & Vickers, 2017).

DT implementation in the operation and maintenance phase has been considered by various studies. Some examples include the use of DT for bridge inspection (Sacks et al, 2018), DT for a connected workplace in one of the office towers in Singapore, and a DT-based system for healthcare facilities management (Madubuike & Anumba, 2021). These examples show that the implementation of DT in construction, particularly in the operation and maintenance phase, is beginning to grow. There are more prospects for DT implementation in the operation and maintenance phase, especially in monitoring the performance of key equipment and building components (Madubuike & Anumba, 2021; Madubuike, 2022; Asare, 2023; Kang & Mo, 2024).

Decommissioning/Demolition

Decommissioning/demolition is the last stage in the lifecycle of any constructed facility. It comes up when a facility has reached the end of its useful and economic life. Some important considerations before decommissioning and demolition include relevant components of the facility that could be salvaged given their current use/reuse value, ensuring that the demolition would not be harmful to the environment or surroundings, and the selection of the most appropriate techniques for the demolition (Anumba et al, 2008; Stevens, 2019). Currently, no study has addressed DT applicability with decommissioning or demolition. However, DT can be used to run demolition simulations of real-life scenarios to understand what better techniques to adopt and the possible effects of the techniques adopted. DT offers a range of benefits depending on what purpose it was created for.

Discussion

Bi-directional Coordination

Bi-directional coordination is the final of the DT features which enable information flow between the physical to digital model and vice versa. Figure 2 provides a proposed simple schematic representation for DT bi-directional coordination. The sensors obtain information from the physical asset which updates the DT platform and the controller. The controller detecting any anomaly in the data received, sends a control effort to the actuator. The actuator inputs a control signal that updates the physical asset. An example where this bi-directional coordination model can be applied would be in controlling systems within buildings such as the HVAC system and others.

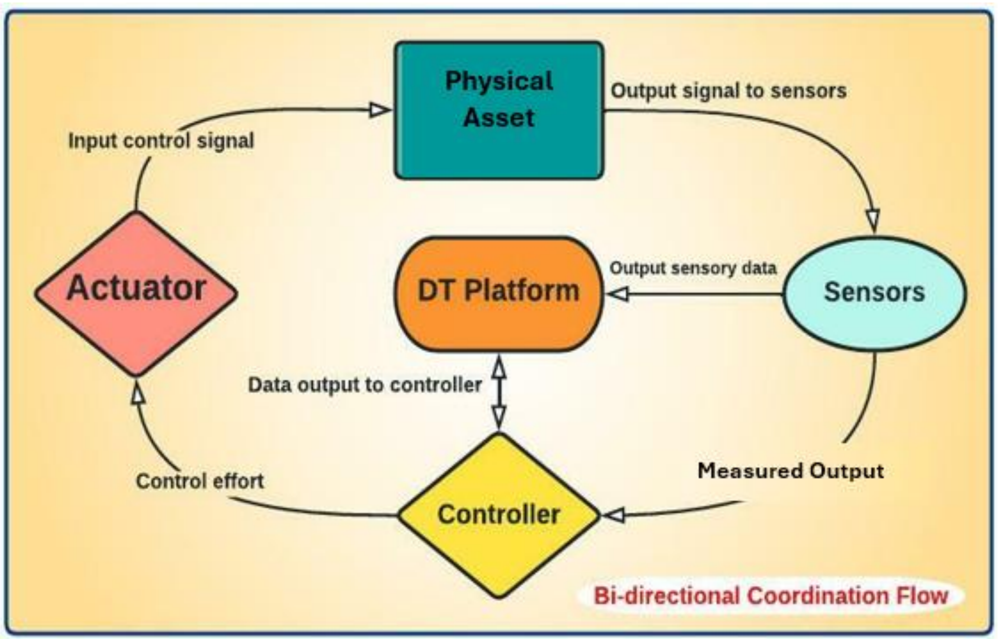

Figure 2: Schematic representation of DT Bi-directional Coordination.

Characteristics of Construction Problems Amenable to DT

The application of DT to the realization of construction 4.0 is still at the nascent stage due to the construction industry's slow adoption of emerging technologies. The construction industry (CI) is one of the major industries with unique and complex processes, interrelated activities, and high uncertainty levels. Consequently, no two similar construction projects are directly similar. This can be attributed to the volatile nature of the construction industry (Brilakis et al, 2019) which makes it difficult for the adoption of smart technology. Some of the characteristics of the CI include methods of procurement, a large number of small and informal contractors, fragmentation with too many stakeholders, no single regulatory authority, reliance on temporary skills, and cultural influence (Boadu et al, 2020). However, given the growing technological trend in the construction industry, some of the problems associated with these CI characteristics can be addressed through DT adoption t. The real-time monitoring feature of DT can be used to monitor construction work progress and construction workers, generating DT models of physical structures and enabling real-time updates and bi-directional coordination for the lifecycle performance of a facility (Braun et al., 2018; Brilakis et al., 2019).

DT Best Practices

DT has proven to be a fast-growing and versatile technology applicable in various fields. Given the versatility of DT, calls have been made to create DT best practices. Brilakis et al (2019) explored DT and its market while requesting its standardization for market demands. Other researchers have argued that its different protocols and standards affect the potential for DT standardization (Qi et al, 2019; Madubuike & Anumba, 2021). However, there has been some progress made in providing interoperability in DTs. Some of the DT best practices include the 3rd Generation Partnership Project (3GPP) for 5G communications for DT, oneM2M to standardize a service layer IoT platform, ISO/TC 184 for industrial data standards, ISO/IEEE for digital health data, and IEC TC65 for interoperability in the smart factory (Song & Le Gall, 2023). The creation of these best practices and standards may help improve DT adoption in construction which is characterized by complex and unique projects.

Potential Benefits of DT in Construction Project Delivery

DT offers several potential benefits that may be integrated into the various phases of a construction project. The potential benefits that DT has to offer in construction product delivery if properly implemented can be drawn from other fields and areas where DT has been successfully implemented. Understandably, construction project delivery (CPD) is guided by three major baselines – quality, cost, and schedule. The potential benefits of DT for construction project delivery can be weighed against these baselines. The following are DT potential benefits that can be attributed to CPD including automated progress monitoring, updated as-built drawings, safety monitoring, resource planning and logistics, optimization of equipment usage, quality assessment, monitoring and tracking of workers, monitoring of a facility, facilities management and operations, decision making and sustainable development (Madubuike & Anumba, 2022).

Conclusions

Digital Twin technology has shown flexibility and applicability in various industries particularly in the manufacturing industry leading to the emergence of Industry 4.0. Consequently, the construction industry has taken a cue from the emergence of Industry 4.0 to initiate the emergence of Construction 4.0. Similarly, Construction 4.0 adopts smart technology, digitalization, and automation to make smart decisions during the construction and operations of buildings and facilities. Although Construction 4.0 is yet to be actualized like Industry 4.0, studies show that DT application in construction is growing. This paper made efforts to discuss DT application in construction with a focus on the various stages of construction. DT applications in the design, construction, operations and maintenance, and decommissioning/demolition stages were discussed.

DT provides potential benefits to the various phases of construction which would ensure enhanced construction project delivery. In the design phase, DT can help in capturing as-built information that will fully represent the finished project. For the construction phase, it can be used to monitor project progress. During the operations and maintenance phase, DT can provide real-time updates to monitor facility performance. The use of DT to run simulations to salvage valuable building components and determine effects on the environment before demolition is another considerable benefit. In summary, DT helps in smart decision-making for improved construction project delivery.

The growing trend in smart technologies and DT studies in construction will help enhance construction project delivery through the DT approach. Understanding the concept, characteristics, and applicability of DT together with the characteristics of the construction industry amenable to DT are essential in improving construction project delivery through the DT approach. DT offers potential benefits in enhancing construction project delivery by ensuring cost reduction, avoiding design errors, minimizing delays during construction, monitoring construction progress, and real-time reporting on a facility's performance. These potential benefits of DT cut across the various stages of construction delivery. Future DT research can investigate in detail the implementation of DT at the various stages of the construction process highlighted in this paper.

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