Conceptualizing Digital Twins in Construction Projects as Socio-Technical Systems

Mohammed Abdelmegid[1], Algan Tezel[2], Carlos Osorio-Sandoval[2], Zigeng Fang[2], and William Collinge[1]

[1]School of Civil Engineering, University of Leeds, UK
[2]Department of Civil Engineering, University of Nottingham, UK
m.abdelmegid@leeds.ac.uk, algan.tezel@nottingham.ac.uk, carlos.osorio@nottingham.ac.uk,
zigeng.fang@nottingham.ac.uk, w.h.collinge@leeds.ac.uk

Abstract –

Digital Twin (DT) has been proposed in the construction sector as the evolution of static Building Information Modeling (BIM) by enabling seamless data flow between physical and digital environments. This paper presents an integrated framework that conceptualizes DT in construction projects as a socio-technical system. This framework aims to address the social dynamics inherent in construction projects when implementing digital technologies. The proposed framework is developed as an amalgamation of components from existing DT and socio-technical systems to enable simultaneous focus on technical requirements and social readiness. It represents different DT maturity stages spanning from static digital models to fully functional DT with bi-directional data flow. These stages are mapped against the dimensions of a socio-technical system including goals, people, technology, processes, infrastructure, and culture. The findings of this study can serve as a research roadmap for creating a comprehensive approach for DT implementation in the construction industry. This approach can ultimately evolve into a DT execution plan (DTEP), which can be requested by clients and as an addendum to contracts in the future. Future work involves validating the framework and benchmarking it against established frameworks in other industries. Additionally, the framework can be extended to incorporate external factors such as policy, legal, and commercial factors.

Keywords –

Digital twins; Socio-technical systems; implementation frameworks

1 Introduction

Digital Twin (DT) is often described as a system of three components: a physical entity, a virtual replica, and information flow between both. Despite the multiple definitions of DTs in the literature, common characteristics can be identified such as the intelligence and agency of DTs, enabling them to sense and change the environment [1]. DTs find different applications in construction, spanning from health and safety (e.g. worker/plant interface, worker posture, crowd management etc), sustainability (e.g. near real time carbon estimates over site operations), logistics planning, and structural reliability monitoring of temporary and newly built elements. Several benefits have been reported to the use of DTs in construction. They can significantly boost productivity, reduce lifecycle costs, improve environmental performance, and advance safety standards [1, 2]. In decision-making processes, DTs provide valuable transparency into the impacts of decisions on both human factors and the natural environment, as stressed by Council [3].

DT technology has evolved significantly in recent years, emerging from its application in several industries such as aerospace and manufacturing [1]. However, there has been slow progress in embracing the technology in the construction industry with small pockets of adoption throughout a building's lifecycle [4]. Several studies highlighted the confusion of DT with Building Information Modeling (BIM) in the industry, highlighting that DT can be considered the natural progression from the more static and design-focus applications of BIM to a more dynamic and holistic approach, enabling real-time monitoring, analysis, and simulation of physical asset throughout their lifecycle [2, 4, 5].

One of the key misconceptions about the adoption of new technologies in the construction industry is that they will inherently improve current practices [6]. Such misconceptions can be observed in both academia and industry, assuming that organizations can organically embrace new technologies, neglecting the need for clearly defined implementation frameworks, execution plans, and the right skill sets [7]. With regard to DT, several studies emphasize the need for specialized research that addresses not only technological challenges but also the organizational, managerial, and behavioral aspects for successful implementation of DT in construction [6, 8]. Agrawal, et al. [1] stressed the need to investigate human-DT interactions in construction projects to ensure appropriate role allocation. Boje, et al. [2] highlighted the complex social systems around built environments, emphasizing the challenge of developing intelligent systems that can adapt to human dynamics and provide insights for decision-making. Council [3] underlined the need to extend DT research beyond technical solutions, calling attention to the necessity of addressing human and organizational factors, including ethics, management, and social considerations.

The aim of this study is to conceptualize a framework for the implementation of DT in construction projects, emphasizing the integration of social and technical aspects into construction projects through socio-technical systems. The following objectives are set to facilitate this aim:

- Investigate current frameworks for DT implementation in construction to identify key elements and common practices.
- Investigate methods of modelling digital technologies as socio-technical systems in the context of construction projects.
- Integrate the identified elements from DT frameworks with a socio-technical model, aiming to create a cohesive and adaptable framework that addresses the nature of construction projects.

2 Background

2.1 Digital Twin Frameworks

Several frameworks have been developed to facilitate DT implementation in construction. Some were initiated to extend BIM applications to include the use of Internet of Things (IoT) and Data Mining algorithms to capture live data, incorporate it to a BIM model, and have a deeper understanding of how data can be translated to support decision making [9]. Other frameworks focused on data flow in construction DT. For example, Pregnolato, et al. [10] proposed a workflow consisting of five steps (data and need acquisition, digital modelling, dynamic data transmission, data/model integration, operation) interlinked with four components (real, link, virtual, experience). Zhao, et al. [11] introduced a bottom-up framework with six layers: preparation, data acquisition, data processing, data transmission, model logic, application. Similarly, Honghong, et al. [12] developed a framework for lifecycle digital transformation for bridge engineering consisting of 8 steps: data collection, data preprocessing, data transfer and storage, DT model building, model update, fusion, feedback, and human-computer interaction. Several other studies presented generic higher-level frameworks that link the physical, the digital, and the application layers of construction projects [2, 5, 8, 13, 14]. Among these studies, few indicated the social aspects of construction projects as key components of DT implementation. Xie, et al. [14] stressed the need to develop a framework that enables humans to become active elements of any DT environment. Agrawal, et al. [8] presented a digitalization framework to balance technology push (data/model and performance) with business pull (value and transformation). More specifically, Boje, et al. [2] developed a DT framework for conventional Life Cycle Sustainability Assessment. This framework evaluates social life cycle from six perspectives: working conditions, human rights, health and safety, cultural heritage, socio-economic, and governance. In a broader sense, Lu, et al. [13] introduced a road map for building and city level DT with three layers: trust, function, and purpose. In the trust layer, a sustainable plan is established, including society, economy, and environment. Although several frameworks have been presented in the literature, there are limitations in relation to providing a holistic view of DT implementation that addresses the key barriers in the construction industry from both technical and non-technical perspectives.

2.2 Socio-technical systems and Digital Twins

The socio-technical theory is based on the principle that understanding and enhancing the design and performance of organizational systems necessitate the simultaneous consideration of both 'social' and 'technical' aspects, treating them as interdependent components within a complex system [15]. This theory views an organization as a group of co-dependent subsystems engaged in dynamic interactions [16]. The historical development of socio-technical systems can be traced to Trist and Bamforth [17], which conceptualized the complex relationship between technological and social dimensions in heavy industries [18]. The application of socio-technical systems has evolved to encompass diverse industries [19]. Therefore, socio-technical systems form a holistic framework that has become fundamental to understand and improve the complex dynamics of organizational structures [20].

The adoption of a socio-technical perspective emerges as a critical imperative for the successful and sustainable implementation of new technologies. Münch, et al. [22] reported that the failure of new systems to meet user requirements often results from a biased focus on technological needs, neglecting the equally important social needs. In contrast to the traditional approach of developing technology first and then fitting people to it, socio-technical systems place the same importance on addressing technological and social needs concurrently [23]. In addition to the interdependent role humans play in system performance, a socio-technical system should also consider how humans are influenced by the system [16]. The emphasis of socio-technical systems on joint optimization, adaptability, and human-centric design establishes their key role in navigating the complexities of modern organizational challenges.

Socio-technical systems have been applied effectively within the construction context. Li [20] reported several studies on conceptualizing BIM implementation as a socio-technical system such as Sackey, et al. [24], which highlighted that success in BIM implementation necessitates prioritizing people and processes over technology and information. In addition to BIM, socio-technical approaches have been applied to Distributed Ledger Technologies (DLT) and Smart Contracts (SCs) by Li, et al. [18]. Ang, et al. [15] investigated the application of socio-technical systems to model an intelligent robot technology project. Their study examined stakeholder interactions, from ideation to successful prototyping, illustrating the efficacy of socio-technical systems in driving innovation.

A recent research theme emerges in DT literature related to the conceptualization of DTs as sociotechnical systems. According to Barn [26], DT encapsulates a socio-technical system, where social and technical elements are seamlessly integrated to achieve goal-directed behavior. The complexity of DT extends into a socio-technical dilemma as it [27]necessitates real-time adaptation to users and responding effectively to daily changes [27]. This dynamic interplay between technical functionalities and human interactions characterizes the intricate nature of DTs [2].

According to Lei, et al. [28], DT should not only be technology-driven but should also encourage public participation and be understandable to a wider audience. Collaboration, both within and between organizations, is identified as a critical foundation for implementing DT, emphasizing the need to consider social, legal, and commercial/business perspectives for a more comprehensive understanding. Rebentisch, et al. [29] confirm that implementing DT within a socio-technical context not only enhances organizational goals, such as business performance and product lifecycle management, but also contributes to broader societal benefits, including social and environmental sustainability.

In the context of the built environment, DT represents a clear example of socio-technical systems. Jiang, et al. [30] emphasize the integration of various information and communication technologies in construction DTs for collaborative management and operation. This application reinforces the notion that effective DT in construction requires a harmonious relationship between technological advancements and social processes.

In summary, the incorporation of socio-technical systems in DT research extends the focus on technology to acknowledge the critical role played by social processes, collaboration, and comprehensive system reasoning in the implementation of DTs.

2.3 Relevant socio-technical frameworks

Several studies highlighted the importance of applying frameworks to guide the design of socio-technical systems to ensure that the whole ecosystem is considered when implementing new technologies [31]. Yu, et al. [21] presented a framework based on socio-technical systems theory to facilitate integrating BIM with Blockchain comprising three components: process, technic, and context. Similarly, Li, et al. [18] adopted a framework for DLT and SCs covering the technical, process, social, and policy dimensions. They demonstrated the role of socio-technical systems in addressing the barriers of technology implementation in the construction industry. The socio-technical hexagon by Davis, et al. [19] illustrates the interdependent components of dynamic socio-technical systems including goals, people, buildings/infrastructure, technology, culture, and processes/procedures. Ivanov [32] presented a DT framework based on socio-technical systems encapsulating key aspects of DT for supply-chain and operations management. This framework consists of seven elements: people, organization, modeling, task, scope, technology, and management. This study emphasizes that DTs are complex socio-technical phenomena incorporating human-artificial intelligence interactions.

3 A Conceptual Framework for Construction DT based on Socio-technical systems

As described in the previous section, several frameworks have been developed for construction DTs and socio-technical systems separately. We propose an integrated approach to conceptualize DT as a socio-technical system in construction projects by developing a matrix that illustrates how the key components of the socio-technical hexagon capture the requirements of DT at different implementation levels. We adopt the three levels of DT by Kritzinger, et al. [33], which differentiates between a static digital representation of the physical system (Digital Model), a partially integrated system with one-way data flow (Digital Shadow), and a fully integrated two-way data flow between the physical and digital system (Digital Twin). The Matrix in Table 1 outlines our proposed framework.

Table 1: A matrix illustrating the conceptual framework

Elements of the socio-technical system	Digital Model	Digital Shadow	Digital Twin
Goals and Metrics	• Utilize digital models for project visualization and planning. • Set objectives for accurate representation of physical objects in the digital space.	• Utilize the digital shadow for real-time monitoring and basic data exchange. • Set objectives for improved responsiveness and monitoring capabilities.	• Optimize project goals based on continuous two-way data exchange with the digital twin. • Set objectives for enhanced collaboration and decision-making through the digital twin.
People/Human Factors	• Train personnel on BIM tools for creating and updating digital models.	• Train personnel on utilizing real-time data from the digital shadow.	• Create work interfaces where construction teams can interact with digital twins. • Provide training on advanced tools and features of the digital twin.
Technology/Tools	• Implement BIM software for creating accurate digital representations. • Ensure compatibility with common industry tools for data exchange.	• Integrate sensors and automated data capture devices for real-time data. • Implement tools for monitoring and basic analysis of digital shadow data.	• Utilize advanced IoT devices and communication systems for seamless data exchange. • Implement AI algorithms for advanced real-time data analytics for decision support. • Integrate digital twin and its spin off technologies with legacy IT systems.
Processes/Practices	• Establish workflows for creating and updating digital models throughout the project life cycle. • Integrate digital models into planning and design processes. • Incorporate risks related to the digital model implementation (e.g., data accuracy, interoperability, etc) into the project risk management plan.	• Integrate digital shadow data into existing monitoring and reporting processes. • Establish protocols for responding to changes identified in the digital shadow. • Incorporate risks related to the digital shadow implementation (e.g., sensor malfunctions, data overload, etc) into the project risk management plan.	• Adapt construction processes for real-time collaboration and decision-making with the digital twin. • Establish workflows that leverage bi-directional data exchange for optimization. • Incorporate risks related to the digital twin implementation (e.g., data synchronization, ethical implications, etc) into the project risk management plan.
Physical Infrastructure	• Ensure hardware supports BIM and visualization. • Provide access to digital models across relevant project teams.	• Upgrade infrastructure to support real-time data flow for the digital shadow. • Ensure connectivity and	• Implement IoT infrastructure for bi-directional data exchange in the digital twin. • Ensure robust

Elements of the socio-technical system	Digital Model	Digital Shadow	Digital Twin
		regular maintenance of remote sensing devices. • Provide database infrastructure for recorded data.	cybersecurity measures for protecting bi-directional data flow. • Ensure connectivity and regular maintenance of remote sensing and actuator devices. • Provide database infrastructure for bi-directional recorded data
Culture	• Foster a culture of using digital models for better understanding, project planning, and decision support. • Encourage knowledge sharing and avenues for learning from experience such as communities of practices and mentoring.	• Encourage teams to rely on the digital shadow for timely decision support. • Establish means to enable sharing knowledge through the digital shadow.	• Foster a collaborative environment through the digital twin by building trust in the knowledge created and shared through the digital twin. • Ensure alignment between organizational culture and digital twin practices.

We demonstrate the application of the framework in an example of production planning and control of piling operations in a construction site. For this example, we assume a large construction site with different soil and water profiles to create a reasonable level of complexity suitable for DT. There are different types of equipment required to perform this operation including piling rigs, cranes, water pumps, concrete trucks, haul trucks, and excavators. Also, there is a need to manage inventory and supply of materials at the site (e.g., concrete and reinforcement steel) and move excavated soil to a dumping site. The aim of using DT is to support production planning and control of the piling operations by minimizing idle time of machinery, optimizing inventory on site, and improving schedule reliability. Table 2 demonstrates the application of the framework to implement a DT for the piling operations.

Table 2: Illustrative example of piling operations

Elements of the socio-technical system	Digital Twin
Goals and Metrics	• Develop a dynamic model that automatically adjusts production plans and authorizes work orders to all production teams.
People/Human Factors	• Ensure clear role allocation is established between DT and decision-makers. • Ensure the facilitation of different stakeholders' communication with DT central hub.
Technology/Tools	• Embed AI tools (e.g., machine-learning, NLP, expert systems, etc) into the model to evaluate and predict project performance. • Utilize advanced IoT devices and communication systems for seamless data exchange between the model and construction equipment.
Processes/Practices	• Automatically update production plans to reflect optimum solutions. • Enable the digital twin to authorize work orders to production teams and suppliers.
Physical Infrastructure	• Deploy interconnected sensors and actuators to enable two-way information flow. • Utilize reliable cybersecurity tools and services to maintain project safety and security.
Culture	• Establish the digital twin as the central hub for knowledge sharing between academic, industry, and public organizations.

4 Discussion

The proposed conceptual framework offers an initial methodology to support DT implementation in construction projects by harmonizing components from DT and socio-technical systems. A key strength of the proposed framework is the emphasis on balancing social and technical factors across different DT implementation stages. By mapping these stages to socio-technical dimensions, construction teams can have a mutual understanding of the requirements to successfully implement DT. The matrix representation allows an incremental implementation of DT while ensuring appropriate social adaptation. Moreover, incorporating change management practices can mitigate organizational challenges of deploying new technologies [3]. In this section, we summarize the components of the framework in relation to the 'Digital Twin' stage in Table 1 to highlight the key requirements and challenges of DT implementation compared to the other lower levels.

4.1 Goals and Metrics

The framework establishes a goal to enable data-driven decision-making leveraging the ability of DTs to synchronize virtual and physical environments. Key performance indicators, such as model accuracy and optimization effectiveness, can be employed to ensure that the DT aligns with real-world situations. The DT should aim to generate insight for enhanced outcomes not only for the current project but for future ones. The framework provides a trajectory for DT to support cross-learning and continuous improvement throughout the project lifecycle.

4.2 People/Human Factors

The framework highlights DT alignment with organizational structure as a key factor for integrating construction teams with DT workflow. This includes clear allocation of roles and responsibilities for staff interacting with the DT to alleviate the adverse consequences of incorrect role allocation such as cost increases, unrealistic expectations, and strategic misalignment [1]. Training programs should aim at capability building and establishing trust in DT outcomes, thus, enhancing organizational readiness for widespread adoption of DT for optimized project performance.

4.3 Technology/Tools

This component of the framework emphasizes the need for robust bi-directional data flow through advanced integration of interconnected sensors and automation technologies. However, one major concern is the integration of DTs and their spin-off technologies with legacy IT systems through appropriate Application Programming Interfaces (APIs) while ensuring cybersecurity and data protection in organizations across the supply chain. For example, large-scale infrastructure projects (e.g., highways, pipelines, water channels, railways, etc) rely heavily on Geographic Information Systems (GIS) for spatial coordination. In such projects, geospatial data should be connected with DTs in a similar way to current integrated GIS/BIM approaches.

4.4 Processes/Practices

The framework advocates for a paradigm shift necessitating the need for process engineering to accommodate the multi-disciplinary effort for DT implementation. As DT technology is rapidly evolving and increasing in complexity, overwhelming the internal capabilities of construction organizations, a new business sector might emerge to provide specialized consultancies and non-profit organizations to guide construction companies in establishing processes and practices for DT implementation.

4.5 Physical Infrastructure

The framework points out to the need for interconnected sensor and actuator systems to enable bi-directional data flow. However, decisions related to infrastructure requirements should carefully consider cost-benefit analysis. The cost of investment in DT infrastructure and maintenance can be necessary in large complex infrastructure projects but difficult to justify in small construction projects that run on tight profit margins, which might lead to 'pseudo-DT' applications much like some examples in the BIM domain. Reusability of DT infrastructure across different projects can be one of the key factors for cost-benefit analysis. Leasing such equipment from specialized subcontractors can be another business decision in future construction projects. In addition to economic challenges, practical and legal challenges require attention when deploying DT infrastructure such as licensing for drones and security of site equipment.

4.6 Culture

DT implementation requires strong commitment across all industry levels to foster buy-in at individual, team, department, organization, supply chain, and the overall sector. This buy-in should ideally be intrinsic and not merely forced through government mandates, contractual requirements, or secondary reasons, e.g., to create an innovative company persona or image. Achieving such level of intrinsically motivated adoption is a key challenge for construction projects as can be observed even with less advanced technologies such as BIM. Hence, building trust in DT capabilities should be in the core of any implementation plans. Pilot demonstrations, participatory decision-making, contractual incentives, and awareness programs can be among the promoting techniques for DT cultural transition. However, it is crucial to address ethical risks and underlying biases in a transparent manner in any effort to influence cultural transition.

5 Conclusion

This paper introduces an integrated framework to conceptualize construction DT as a socio-technical system. It aimed at bridging a recognized gap in construction DT research regarding the lack of managerial, human, and social considerations in existing construction DT approaches, which primarily focus on the technical aspects of DT such as data integration and analytics. The framework addresses this gap by balancing the focus between technical and social requirements in DT implementation in construction projects. Therefore, this study suggests a more holistic view of DT across critical areas such as performance metrics, training, process re-engineering, and cultural readiness.

The outcomes of this study can form a research roadmap to develop a holistic approach for systematic DT implementation in the construction industry. This approach will eventually evolve into a DT execution plan (DTEP) that can be used for contractual and governance requirements by construction companies to successfully deploy DT technologies and realize their value to business performance as well as social outcomes. Due to significant investment requirement and data richness of DT systems, such DTEP document will be more critical than current BIM execution plans. Future research involves testing and enhancing the framework in industry settings and benchmarking against frameworks in other sectors. Such testing should incorporate expert validation to gain better insight into the enablers, challenges, and practical implications of implementing the proposed framework. In addition, examining the dynamic interrelations within the socio-technical system when implementing DT is vital to ensure alignment between all components of the framework. Modeling the framework development in a simulation environment that can capture long-term business and social outcomes (e.g., Systems Dynamics) is a possible approach for testing and validation. Finally, we recognize the need to incorporate other external aspects to the framework such as policy, legal, and commercial factors that influence the diffusion of digital technologies in the industry.

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