



REFRAMING DIGITAL TWINS IN CONSTRUCTION: A SOCIO-TECHNICAL LIFECYCLE PERSPECTIVE

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Abstract

This paper proposes a socio-technical approach for the development and implementation of Construction Digital Twins (CDTs), extending beyond the dominant technocentric perspective. Grounded in insights from an industrial case study, this paper conceptualises CDTs as socio-technical systems, emphasising the interplay among people, process and technology across six proposed lifecycle stages of CDTs: Define, Design, Implement, Assess, Refine and Decommission. The paper also examines human-CDT interactions during the implementation phase, highlighting their mutual influence and the unique requirements posed by the dynamic, socially complex and unpredictable nature of construction projects.

Introduction

Construction Digital Twins (CDTs) have attracted growing interest for their potential to enhance various processes in construction projects, including safety management, progress monitoring, site logistics, quality control and construction robotics (Boje et al., 2020; Saif et al., 2024a). However, much of the existing research frames DTs primarily as purely technical systems (Miraj et al., 2025; Oti-Sarpong et al., 2022). This technocentric focus tends to overlook the complex social and organisational dynamics of construction environments, where multidisciplinary stakeholders, often with varying needs, responsibilities and goals, must collaborate effectively. Neglecting the social dimensions of CDT deployment can result in poor stakeholder engagement and may hinder their adoption in industrial practice. As the extensive research on digitalisation in construction has emphasised, the successful adoption of new technologies requires more than simply deploying digital tools; it also demands attention to the social aspects of their integrations (Miraj et al., 2025).

In response to the dominant technocentric perspective, this paper advocates for a socio-technical approach to CDT development and implementation, aiming to balance technological capabilities with stakeholder engagement. It conceptualises CDTs as socio-technical systems by examining the interdependence among people, process

and technology across proposed key stages of CDTs' lifecycle. The paper also analyses human-CDT interactions, highlighting how project stakeholders interact with and are affected by CDT systems during implementation.

Background

Socio-technical systems in Construction

The socio-technical systems (STS) theory was developed in the 1950s at the Tavistock Institute through studies in coal mining, highlighting the interaction between social and technical elements to optimise organisational performance (Trist and Bamforth, 1951). The theory argued for integrating technology to complement human operators, evolving to address the interdependencies between social and technical components in complex systems across various fields, including management, information systems, and engineering (Davis et al., 2014). The STS perspective has proven effective in the successful and sustainable implementation of new technologies. Münch et al. (2022) argue that technology adoption failures often arise from focusing solely on technological needs while neglecting social factors. Unlike traditional approaches that adapt people to technology, STS prioritises addressing both aspects concurrently (Appelbaum, 1997).

The ongoing digital transformation in the construction sector has driven increased adoption of STS to guide the integration of various technologies (Schweber and Harty, 2010). For instance, Sackey et al. (2015) applied an STS approach to Building Information Modelling (BIM) implementation by examining the interactions among people, process and technology. Similarly, Oesterreich and Teuteberg (2019) examined BIM adoption barriers through an STS lens. Li et al. (2019) proposed an STS-based framework for adopting distributed ledger technologies and smart contracts in construction. The integration of blockchain and BIM was also explored from a socio-technical perspective by Yu et al. (2024).

These studies among others have reported on the effectiveness and suitability of STS in supporting the integration of new technologies into construction

practices, particularly given the socially complex and fragmented nature of the construction sector.

DTs development: a dominant technical perspective

Developing a DT system requires following a systematic approach that considers its various components and their data interactions to ensure they all operate as a cohesive and goal-oriented whole (Broo et al., 2022, Aheleroff et al., 2021). To guide DT development, researchers propose reference architectures that outline the configuration and integrated technologies of DTs for various construction applications. A DT architecture typically refers to an enclosed arrangement of technological layers, each composed of interconnected software and hardware components with shared functionality, collectively providing the DT with the capabilities needed to fulfil its purpose (Saif et al., 2024a).

As highlighted by Broo et al. (2022), many of these architectures and frameworks were originally developed within the manufacturing sector and later emerged into the more social construction sector. These architectures commonly integrate multiple key layers, including all or some of the following: the physical layer, data layer, communication layer (or IoT gateway), integration layer, analytics layer and application (or service) layer (Aheleroff et al., 2021, Harper et al., 2019). While these layered architectures offer a structured guide for DT development, they focus on technology integration, often overlooking the organisational context and involvement of stakeholders in defining and designing these architectures to their needs and expectations. Miraj et al. (2025) examined current DT research in the built environment and found it to be predominantly technocentric, lacking sufficient focus on organisational and managerial dimensions.

By neglecting the socio-organisational context in which DTs are implemented, technocentric frameworks may result in technically sound systems that are poorly aligned with user needs and organisational workflows. As Harty (2005) argues, neglecting the socio-technical dynamics can lead to user resistance and limited adoption. Hence, CDT needs to be approached as a socio-technical system to ensure its successful and sustainable adoption in construction projects.

DTs development: a social-technical perspective

A growing body of literature has acknowledged the limitations of a purely technical perspective in the development and implementation of DTs, calling instead for the integration of socio-organisational dimensions. For example, the Centre for Digital Built Britain, through the Gemini Principles, advocates for a socio-technical change programme as essential for the effective adoption of connected DTs (Council and Lamb, 2022). This approach emphasises the need to articulate not only technical value but also the social, environmental and economic benefits that DTs can enable. The call for integrating social and organisational factors has been

more pronounced in domains such as smart cities and urban planning. Several studies have promoted urban DTs that embed social considerations into their design and use (Yossef Ravid and Aharon-Gutman, 2023; Ruohomäki et al., 2024). Nochta et al. (2021) argued that city-scale DTs must be rooted in the specific socio-political context in which they are deployed, suggesting a fundamental shift from a technical to a socio-technical framing. Likewise, Oti-Sarpong et al. (2022) critiqued the technocentric bias in current literature and introduced a framework informed by the social construction of technology to reconceptualise DTs in urban contexts.

Despite this emerging discourse, most of these socio-technical considerations remain concentrated in the context of smart cities, with limited translation into construction projects. While Abdelmegid et al. (2024) contributed to mapping socio-technical dimensions such as people, goals, processes and technologies against DT maturity levels, their work remains largely conceptual and high-level. There remains a critical need for studies that examine how these socio-technical dimensions interact within real-world construction projects and how they can be systematically integrated into DT development and implementation stages. This paper aims to address that gap by extending socio-technical conceptualisations to the construction domain. Drawing on insights from an industrial case study, we explore how the People, Process and Technology (PPT) dimensions interplay within each stage of a proposed CDT lifecycle framework.

Methodology

This paper proposes a six-stage lifecycle of a CDT system (see Figure 1) and presents it through a socio-technical lens. The proposed lifecycle stages are informed by an eight-month industrial case study that documented the design, development and deployment of a CDT for monitoring workers' safety (see Saif et al., 2024b). The system integrates 4D BIM models with location-based wearable tracking sensors. The 4D BIM model identifies hazard zones and prepares their data (e.g., location, timeframes, resource assignments and access permissions) to be automatically sent to the tracking platform. This platform monitors worker-zone interactions, triggering real-time alerts in cases of unauthorised access and enabling proactive risk mitigation. Monitoring data can be visualised within the 4D BIM interface, allowing stakeholders to identify safety trends and evaluate the effectiveness of interventions. The case study involved a diverse range of stakeholders, including representatives from construction, IT and regulatory bodies (summarised in Table 1).

The research followed an action research methodology where one of the authors was an active participant in observing and contributing to the development of the case study, allowing for regular documentation. This participatory approach aligns with the selected interpretivism approach, emphasising that CDTs are shaped through dynamic interactions among social and

technical factors. The methodology is also underpinned by STS theory that guided the analysis of the case study findings by highlighting the interdependencies between technical components (e.g., 4D BIM model and wearable sensors) and social elements (e.g., monitored workers, supervisors and safety team). Data was collected through biweekly meetings and focus groups, where stakeholders defined system requirements and shaped its design. System testing sessions and workshops were also conducted for stakeholders and users to provide their feedback on system functionality and identify potential improvements.

To complement the case study insights and further support the conceptualisation of CDTs as socio-technical systems, a literature review was also conducted. To identify relevant literature, a combination of keywords such as ‘digital twin’ + ‘construction site’ or ‘construction projects’ was used. The results were then filtered to include only studies that presented real-world CDT implementations during the construction phase. The resulting studies were reviewed to highlight human interactions with CDTs during their implementation.

Table 1: Profile and roles of the key partners involved in the case study project

ID	Role/Expertise	Organisation	Main role in the project
1	HSE Inspector	Health and Safety Executive (HSE)	Oversight the development and ensure compliance with HSE regulations and expectations.
2	Construction Lead	Client organisation	Provided insights and coordinated access during testing and implementation at their site.
3	Construction Director		
4	Architectural Lead	Main contractor	Provided and assisted with the project’s 4D BIM model.
5	Site Manager		
6	Safety Consultant	Digital consulting firm	Ensured alignment with H&S standards and workflows
7	Digital Director		
8	Researcher		
9	Founder/CEO	Sensing systems supplier	Advised on technology selection and supported system development and deployment.
10	Operations Manager		
11	Chief Digital Officer	Software company (BIM services)	Guided the use of their BIM platforms and safety services for hazard identification and management.
12	Director of Digital Products		

The Proposed CDT Lifecycle

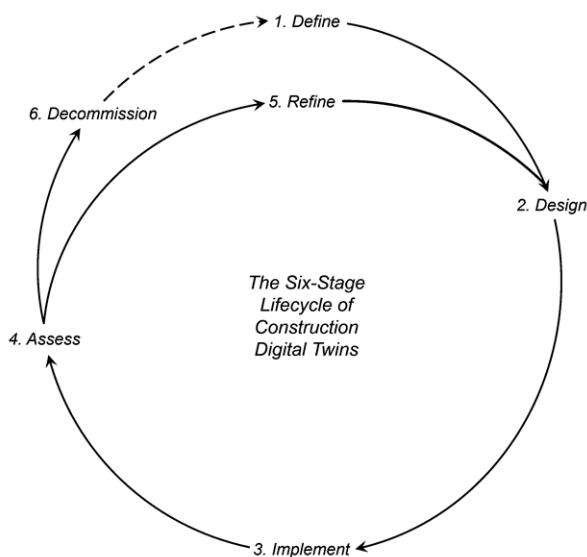


Figure 1: A proposed six-stage lifecycle of CDTs

The case study provided empirical insights into the development and implementation of a CDT system, from its initial conception by the Health and Safety Executive (HSE), through design, deployment, on-site validation, operation and eventual dismantling. By thematically analysing these system transitions, we identified six distinct yet generalisable stages that characterise the lifecycle of CDT systems. These stages are not merely technical phases but reflect the socio-technical dynamics and stakeholder engagements experienced during the case study. The stages are defined and explained with direct reference to the case study as follows:

1. Define: This is the first stage that involves clearly defining the system's purpose and its data and feedback requirements. The ‘purpose’ here refers to the system’s specific objective(s), often linked to a broader application or use case. The data and feedback requirements define key attributes of data acquisition and feedback provision including the frequency (how frequently data is being collected, and feedback is provided), latency (the time delay between data collection from the site and its corresponding update within the DT), required analytics and the degree of

automation in collecting data and providing feedback. The outputs of the define stage dictate the system design and the selection of its enabling technologies.

In the case study, the system's purpose was tracking workers to ensure their safe interaction with hazardous zones on construction sites. This purpose was initially defined by the HSE and further refined through consultations with safety managers and site supervisors. These discussions among stakeholders helped define functional specifications and data needs including a minimum one-minute sampling rate of workers' locations and a one-second response time in case of hazard detection.

2. Design: This stage involves designing the system architecture and selecting suitable technologies. A collaborative approach among construction professionals, technology providers and end-users is crucial to ensure the system functionalities align with the system purpose and requirements defined in the previous stage. In the case study, the architecture was co-developed with stakeholders to ensure reliable hazard zone tracking. The selection of enabling technologies (e.g., sensors, networks and platforms) was conducted in consultation with IT providers (see Table 1) and driven by key data and feedback requirements, including accuracy, responsiveness and an effective alerting mechanism.

3. Implement: System implementation involves deploying the CDT on-site, integrating both hardware (e.g., sensors, networks and display screens) and software components (e.g., cloud storage, analytics platforms and visualisation platforms). Validation through real-world testing is essential before full operation in the actual construction site to ensure the system functions as intended in alignment with the defined requirements.

In the case study, the system was introduced in phases, starting with small-scale trials followed by a full implementation over one week on the construction site. A key socio-technical consideration during the implementation stage was providing training and support for site personnel to familiarise them with system functionalities. Another socio-technical aspect involved addressing workers' concerns regarding tracking their locations by explaining the purpose of tracking and clarifying its limitation to certain zones and shift times.

4. Assess: Performance assessment is an integral part of the implementation stage, ensuring the CDT remains effective and adaptable to evolving needs as construction progresses. The assessment methodology should align with the adopted socio-technical perspective, recognising that the CDT's performance should not be evaluated solely based on its technical capabilities, but also through the feedback of project stakeholders who interact with and are impacted by the system. In the case study, stakeholder feedback

was collected through onsite meetings and was critical in evaluating aspects such as interface intuitiveness, alerting mechanisms, system compatibility and reporting capabilities.

5. Refine: This stage connects system implementation with iterative design updates by identifying areas of improvement based on the findings of the performance assessment. Improvements may involve adjusting technical parameters such as data acquisition accuracy, frequency or latency, as well as enhancing user interface, connectivity and interactivity, improving stakeholder engagement and satisfaction if needed. The refine stage enables a dynamic and feedback-driven system design rather than a static design. This is particularly critical in dynamic construction environments where site conditions and stakeholders' needs can change, requiring system adjustments.

6. Decommission: Given the transient nature of construction sites, CDTs accordingly have a short life span, serving their intended purpose during the project phase. The Decommission stage is proposed as a strategy to manage the system end of life once its intended purpose has been fulfilled, or the construction project concludes. Options include relocating or repurposing the system for a new construction project or dismantling and responsibly recycling its non-functional components (e.g., sensors, batteries and other hardware) to minimise its environmental impact. As the case study was a trial based on industrial collaboration, the CDT system was simply dismantled after the successful implementation and the IT providers maintained their system components.

Conceptualising Construction Digital Twins as Socio-Technical Systems

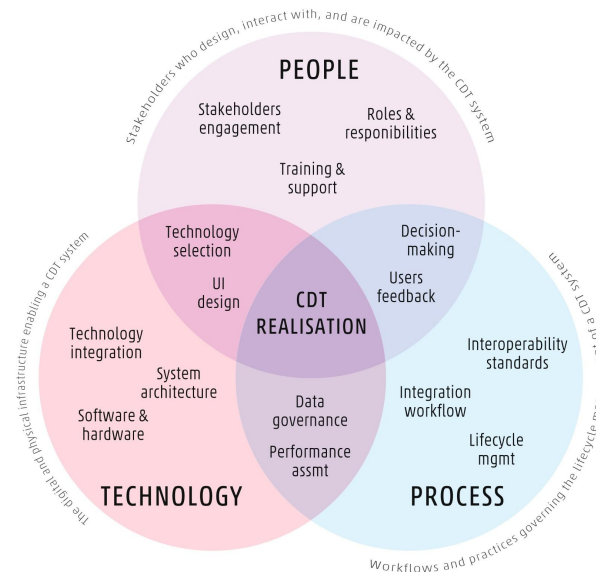


Figure 2: The interrelationships among people, process and technology in CDT implementation

Adopting a socio-technical perspective for the development and implementation of CDTs was mainly motivated by the industrial case study. The engagement of diverse stakeholders across all stages significantly shaped the design and deployment of the safety system to ensure a user-centric system that integrates well with construction workflows. To frame this socio-technical perspective, the People, Process and Technology (PPT) model was adopted as a conceptual foundation that was originally introduced in organisational change and IT management (Morgan and Liker, 2020). The PPT model has been widely applied to a construction context such as by Zahin (2025) to create a roadmap for digital innovation in construction, to evaluate BIM and blockchain integration in construction by Yu et al. (2024) and in the proposition of a framework for development of DT in road

and rail infrastructure asset management by Douglas (2024).

For CDT development and implementation, the PPT model highlights the interdependence of three key socio-technical elements: *People* (stakeholders who design, interact with and are impacted by the CDT system), *Process* (workflows and practices governing the lifecycle management of a CDT system) and *Technology* (the digital and physical infrastructure enabling a CDT system to serve its purpose). Figure 2 summarises these key interrelations based on the case study insights, which are further detailed and mapped across the six proposed stages of CDT's lifecycle in Table 2 to guide ensuring a balance among these three key elements.

Table 2: Guidance for balancing People, Process and Technology across CDT lifecycle stages

CDT Lifecycle Stage	People	Process	Technology
Define	Define stakeholders' roles and responsibilities and identify their needs and expectations.	Define CDT's purpose and its data and feedback requirements in alignment with project goals and industry regulations.	Identify required data types, integration needs and feedback mechanisms to guide technology selection.
Design	Facilitate collaboration among project stakeholders, end-users and IT providers to ensure a user-centric design.	Design the system's layered architecture and its data management strategy that ensures interoperability within project workflows.	Select the enabling hardware and software technologies that align with the defined requirements and system architecture.
Implement	Provide on-site training and onboarding, ensuring site stakeholder involvement in the deployment and validation.	Deploy CDT's components while ensuring its integration with construction workflows and establish validation procedure before full operation.	Connect onsite system hardware (i.e., sensors and networks) with its software and visualisation tools.
Assess	Collect users' feedback and evaluate stakeholder satisfaction with CDT functionality (e.g., user interface, compatibility, accessibility and reporting).	Define and evaluate key performance indicators of CDT's impact (pre and post-deployment) on the construction process. It could be related to specific aspects (e.g., safety, productivity, sustainability, etc.) depending on CDT's area of application.	Assess performance metrics of the used technologies (e.g., sensing accuracy, network latency, data processing speed).
Refine	Engage users to identify areas of improvement to enhance system usability and user satisfaction.	Conduct iterative design updates based on assessment findings and refine workflows if needed.	Optimise or upgrade technical components if needed such as replacing sensors for higher accuracy, enhancing the network for improved latency, or upgrading user interface for better interactivity.
Decommission	Manage stakeholder transition, knowledge transfer and data archiving.	Plan for system reallocation, repurposing, or workflow adaptation while minimising disruptions.	Dismantle technical components for reassembly at another site, or retire and responsibly recycle hardware components when needed.

Human-CDT interaction

A key aspect of the proposed socio-technical perspective is examining how humans (i.e., project stakeholders) interact with CDT systems during the implementation phase. Unlike DTs in highly automated sectors like manufacturing and automotive, where data acquisition, analysis and decision-making processes are characterised and may be required to be automated, DTs in construction projects often require human involvement at multiple stages (Saif et al., 2024a). These interactions can be categorised into four key areas: data acquisition, data interpretation, decision-making and ethical considerations of data security and privacy.

Human-assisted data acquisition

While DT conceptualisation in manufacturing typically requires a fully automated mechanism of data acquisition for a system to be considered as a DT (Kritzinger et al., 2018), construction sites present a more complex and dynamic environment, often requiring manual or human-assisted data collection. For example, laser scanners and photogrammetry techniques are commonly used to generate 3D models for progress tracking and quality control, but their operation requires human intervention, whether in positioning scanners, adjusting settings or validating scan results (Tran et al., 2021, Pan and Zhang, 2021). Similarly, drones used for site monitoring need human pilots for navigation and data collection in areas where automated flights may not be feasible due to site constraints or safety concerns. In such cases, humans play a role in assisting CDT systems in gathering reliable data.

Human expertise in data interpretation

While CDTs can employ different computational techniques for analysing construction data, human expertise remains essential in interpreting and analysing certain types of data where such techniques might fall short (Agrawal et al., 2023). For instance, quality control often requires comparing as-built models with as-planned models to identify deviations and potential defects (Tran et al., 2021). Although automated deviation detection algorithms offer certain capabilities (To et al., 2021), human judgment remains essential in determining whether detected discrepancies are critical, acceptable or require corrective action (Meyer et al., 2023). This demonstrates how CDTs support, rather than replace, human expertise, as human intervention ensures that data-driven insights are contextualised for decision-making.

Insights extraction and decision-making

Another defining characteristic of DTs is their ability to generate actionable insights, ideally through automated feedback and decision-making mechanisms. However, in construction, the complex and interconnected involvement of multiple stakeholders often limits the feasibility of fully automated decision-making (Saif et al., 2024a). Instead, site stakeholders play a key role in extracting insights from CDT visualisations and making informed decisions. For example, in the safety case study,

a CDT system tracks worker locations and detects unauthorised entries into hazardous zones, triggering alerts. While this automated warning system enhances safety, decisions on corrective actions such as adjusting site layouts or implementing additional safety measures are ultimately made by safety planners. Similarly, when progress tracking dashboards indicate schedule delays, site managers should highlight potential causes (e.g., material shortages, and labour availability) and take appropriate corrective actions. Thus, human decision-making remains integral to translating CDT-generated insights into effective interventions in construction sites.

Socio-ethical considerations in human data security and privacy

The adoption of DTs in construction projects introduces concerns regarding data security and privacy, especially when collecting personal data (Saeed et al., 2024). This was evident in the safety case study, where workers' locations were tracked using sensors attached to their helmets. To understand the workers' perspectives on such concerns, a survey was distributed among them. Given the trial nature of the case study and the workers' prior consent to be monitored, there were discussions about ethical issues regarding constant monitoring and discomfort associated with workplace surveillance. Unauthorised access to personal data may also present risks of misuse or broader socio-ethical dilemmas, as reported by Indiparambil (2019). CDT implementation should integrate data governance policies and ensure compliance with privacy regulations that offer transparency in data usage. Setting tracking boundaries such as limiting monitoring to specific zones or work hours, can also help balance monitoring objectives with privacy rights.

Discussion and Conclusion

This paper contributes to ongoing research by proposing a socio-technical perspective for the development and implementation of Construction Digital Twins (CDTs). This proposition was inspired and informed by an industrial case study, where collaboration among stakeholders from construction, IT and regulation backgrounds played a critical role in shaping a user-centric DT system that aligns well with construction workflows. By mapping the interactions of key socio-technical elements (i.e., people, processes, and technology) across six proposed stages covering the CDT lifecycle, the paper offers structured guidance for maintaining a balance among these elements at each stage. The paper also examines human-DT interactions during the implementation stage to understand their mutual influence, which is crucial for effective DT adoption as emphasised by Agrawal et al. (2023). This contribution moves beyond the predominantly technology-focused narratives in the existing literature by highlighting the importance of stakeholder engagement and workflow integration in DT design and implementation. As such, the findings offer initial

guidance for practitioners aiming to design and deploy DTs in construction projects in a way that balances socio-technical considerations.

Despite its contribution, this study has limitations, including its reliance on a single case study focused on a specific use case, which may limit the generalisability of the findings to other CDT applications or project types. Furthermore, while the case study was rich in engagement and observational depth, it was conducted as a trial, with all parties having agreed in advance on their roles and responsibilities. This arrangement contributed to a relatively smooth development and implementation process. In real-world construction projects, however, additional challenges and socio-technical dynamics may emerge that were not reported or addressed in this study. Therefore, future research is recommended to validate and further refine the proposed approach across diverse project contexts and CDT use cases.

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