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TRAPPED IN TECHNOCENTRIC THINKING? REVISITING DIGITAL TWINS THROUGH A PRAGMATIC FRAMEWORK

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To conceptualise the requirements and shape of construction digital twins, literature often proposes ideal-types and frameworks involving sensorised, real-time, and highly automated systems. While concepts demand significant resource investments and changes to business processes, their benefits remain debatable. To refocus on the needs of construction practice, we propose an alternative characterisation of construction digital twin systems. This study explores the conceptual diversity of useful systems through a framework comprising latency, fidelity, physical-digital connectivity, and analytic capabilities. It uses an engaged scholarship approach to apply this framework to two cases: A construction control room and an underground utility digital twin. Results show that these cases deviate from techno-centric perceptions, exhibiting variations in latency (low to high), fidelity (low to high realism), physical-digital connectivity (loose to tight), and analytic capabilities (descriptive to predictive). We conclude that construction may defy techno-centric stereotypes. Instead of exploring how organisations must adapt to comprehensive technological twins, future research should prioritise contextual needs to develop useful systems that enhance decision-making practices in the field.

Keywords: digital twin; maturity; context; utilities; site control

INTRODUCTION

Digital Twin (DT) systems integrate a virtual entity in the digital domain with its counterpart in the physical world. Fundamentally, this involves the collection and transfer of sensory data from the physical system to a virtual model, which is then used to provide insights and control the physical system. Many of the presented DTs include fully automatic, real-time data flows between the physical construction assets and detailed virtual models to support autonomous decision-making. However, these "high-tech" ideas are often introduced to practice without critically considering why, and what types of construction-relevant applications these envisioned systems should support. This criticism on techno-centric solutions also exists in BIM literature, where comprehensive technological models, such as 5D and 6D, have emerged. This literature stated that while visions, propositions, and promises are necessary to

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encourage adoption, they should go hand in hand with realistic assessments of implementation scenarios. Also, sociology of technology studies argue that digital systems are highly intertwined with processes and practices, where the change of one aspect is likely to alter the other (Harty, 2005). Building upon this, we argue that the assumption of an all-inclusive, comprehensive Digital Twin may not add value in practice. Construction DTs are more likely to take varied forms; each tailored to specific use cases.

To support this use-case-centric re-characterisation of Construction DTs, we propose a framework that is informed by production systems literature. It incorporates the dimensions of latency, fidelity, physical-virtual connection, and analytic capabilities. To demonstrate its usefulness, we apply the framework to two of our DT-cases. In both cases, the systems support end-user decision-making by integrating data flows between physical and virtual environments; yet they differ significantly in form.

Following the explanation of our research method in the next section, we reflect on the current Digital Twin discourse and our proposed framework. Next, the results illustrate the existence of diverse, functional digital systems, with properties ranging from low to high fidelity and varying levels of automated integration. We finally discussed that our framework could help refocus Digital Twin efforts by addressing the critical “why” question behind their implementation.

METHOD

This study adopts a design-oriented engaged scholarship approach (Van de Ven, 2007), involving the abductive development of a framework through iterative engagement with case data and concepts from Digital Twin literature. Specifically, we reviewed the literature to identify the dominant definitions and evaluative dimensions in DT research and identify key assumptions underpinning current frameworks. Next, we critically reflected on these aspects through our experiences as researchers developing Digital Twin systems. This reflective practice helped us surface tensions between techno-centric DT-frameworks and our observations of real-world constraints and decision needs in construction. Based on the emerging understanding, we synthesized a four-dimensional framework that characterises DT artefacts. We then applied the framework to analyse two of our DT development cases. The first included a retrospective analysis of a completed DT implementation in a construction control setting; the second involved the conceptual co-design of a future DT system for infrastructure managers working on tree-underground infrastructure issues. Finally, our cross-case reflection validated the framework’s pragmatic utility.

Characterising the Emerging Digital Twin

Digital Twins utilise integrated sensor data and predictive models for proactive decision-making in building management (Riaz *et al.,* 2014). While sensory data integration is regarded as a foundation marking a paradigm shift from Building Information Modelling (BIM) to DTs (Tuhaise *et al.,* 2023), the "significant similarities in terminology and scope between the two concepts" raise ambiguity about what defines a DT (Chen *et al.,* 2024). Consequently, the literature has been developing optimal versions and technological definitions of the concept (Revolti *et al.,* 2024). These frameworks classify DTs based on the level of interaction between a physical asset and its virtual entity, ranging from static digital models with no interaction to digital shadows with one-way communication, two-way interactive

Digital Twins integrating physical and virtual entities (Tchana *et al.,* 2019), and more autonomous cognitive and federated DTs (Liu *et al.,* 2024).

On such taxonomic ladders, superior Digital Twins are said to offer "more functions and stronger capabilities" while increasing comprehensiveness, automation, and smartness (Calvetti *et al.,* 2025). This implies that the ideal-type DT includes all these functionalities and achieves the highest levels of autonomous decision-making. This techno-optimal view, however, neglects that systems must also be able to support diverse decision-making needs that vary in context, timeliness, urgency, and abstraction. Construction DTs' shapes, therefore, "must be evaluated for each case", so a "one size fits all" blueprint for DTs does not exist (Agrawal *et al.,* 2023). The techno-idealistic fits into what Boyd (2021) describes as a hyperreality. Hyperreality promotes digitalisation "with only a limited amount of critical analysis," based on the belief that computers can emulate complex human thinking processes. It leads to abstract technologies that are presented as straightforward solutions for wicked yet concrete sociotechnical problems.

Framework to Characterise the Construction DT

If the scope and capabilities of DTs are not carefully considered, this may result in overly optimistic yet dysfunctional solutions, which fail to meet stakeholders' needs (Agrawal and Fischer, 2024). We argue that four dimensions from production systems literature on Digital Twins can guide designers in considering these aspects. These are: latency, fidelity, physical-digital connection, and analytic capability.

First, latency specifies the time lag between information that is passed between a physical and virtual entity of the DT. What the right lag time is, is dictated by specific application scenarios for the digital system (Sado *et al.,* 2024). In manufacturing processes or critical infrastructure management, real-time data may be needed for adequate decision-making (c.f., Lu *et al.,* 2020). Conversely, decisions regarding predictive maintenance and long-term planning data may not need to be exchanged instantaneously. Designers, hence, should strike a balance between desired decision outcomes and investment in data management resources (Boschert and Rosen, 2016).

Second, fidelity is the degree of correspondence between the virtual and physical entity. The term stems from computer vision and can also be understood as the level of complexity, level of detail or granularity that is required to represent the physical reality adequately. As such, high-fidelity models are computationally intensive and capture intricate details of the real-world to support precise simulations, such as in vehicle lifecycle prediction and structural health monitoring. Other models, alternatively, are less demanding and may use fewer complex visualisations to support quicker decisions (Kontaxoglou *et al.,* 2021). The appropriateness of model fidelity should ultimately match the speed and type of decision-making of each use case (Bazmohammadi *et al.,* 2022).

Third, physical-digital connection encompasses the connectivity between the physical and virtual realms. Taxonomies progressively model levels of automation of the data integration between physical and virtual systems. Digital models are updated manually by experts; digital shadows automatically capture real-time sensor data; and digital twins even offer bidirectional control loops with the physical system (Revolti *et al.,* 2024). This evolution enables capabilities such as real-time monitoring, predictive maintenance, and autonomous decision-making. However, it depends on the context of use how this integration is shaped. Typically, the built environment remains at the digital shadow stage, with human oversight ensuring that data integration is both necessary and resource efficient.

Fourth, analytic capability refers to the type of analysis that is desired by users. Descriptive analytics integrates historical data to visualise or analyse patterns within systems (e.g., Gürdür Broo *et al.,* 2022). Diagnostic analytics extends this by utilising data to identify reasons behind past outcomes and identify existing issues with the physical system. Further, in predictive analytics, current data is used within machine learning algorithms to forecast future states or events (Kang and Mo, 2024). Finally, prescriptive analytics also recommend actions to decision-makers (Jeon *et al.,* 2024).

Essentially, Table 1 characterises the techno-centric ideal-type DT along the four dimensions. It also describes design choices besides this ideal type.

Table 1: A characterisation of the techno-centric ideal-type DT along the four dimensions

Dimension	Definition	Technocentric ideal type	Design Choices for Construction DTs
Latency	Data collection and exchange rate between physical and virtual system	Realtime and continuous	From instantaneous data exchange to - aggregated data collected at intervals
Fidelity	Complexity, detail and accuracy desired for adequate decision-making	High-resolution 3D models	From high-resolution graphics to simplified dashboards
Physical-Digital Coupling	Directionality of information communication between system components	Bidirectional	From static model to one-directional connectivity and bidirectional interaction
Analytic Capability	Level of intervention in the human analysis and decision-making processes	Prescriptive	From descriptive to diagnostic, predictive and prescriptive

Framework Application

We apply the framework to an implemented (retrospective) and conceptually designed (future) DT case below.

Retrospective Case: AEC Production Control

This DT system was designed to control construction production by integrating near-real-time data. It enhanced situational awareness and supported look-ahead planning (Soman *et al.,* 2025). Based on the analysis of decision routines, a system was developed that abstracted the physical construction site in digital counterparts, which were presented in a control room (such as 4D progress, weather, workforce presence, delivery schedules, and workplace congestion). Data exchange ensured the DT was updated at relevant frequencies to support real-time planning and decision-making. To achieve this, data flows were standardised, and integration issues were resolved by developing APIs. The resulting DT supported consistent, automated reporting and improved communication of productivity data via real-time dashboards. Based on this, the system could make automatic routine decisions while also flagging non-routine construction events that required human oversight. The streamlined information flow to the control room eventually reduced update meeting times from 45 to 10 minutes per week. This saved the information manager five hours weekly and reduced the monitoring workload from eight hours of workshop time to a single 45-minute session.

The Production Control DT achieves a moderate level of *fidelity* that captures essential construction details without overcomplicating the model. It aggregates data from multiple sources, including continuous sensor inputs for weather conditions and workforce occupancy, to create a dynamic digital shadow of the construction site. This process leverages data from common data environments and 3D/4D representations.

The physical-digital coupling in this DT is primarily unidirectional, with sensor data flowing from the construction site to the digital model. While this enables real-time monitoring and basic analytics, control remains with human operators, ensuring informed decision-making without automated intervention.

This system is characterised by a differentiated latency strategy. Continuous sensor inputs provide near real-time monitoring of critical parameters such as weather fluctuations and site activity. Further, this "right-time" data is also aggregated to support planning phases. The DT thus supports immediate intervention on issues but also supports longer-term programming. As a result, the DT serves as a live repository that supports routine and non-routine decision-making.

Analytically, the system includes descriptive analytics by displaying the current physical state of the construction site, but also diagnostic analytics by identifying compliance issues—such as verifying if the number of workers adheres to safety regulations and detecting planning constraint violations. Also, basic predictive insights that estimated task confidence levels were provided to assist in foreseeing potential scheduling conflicts and resource bottlenecks. In this case, most critical decisions regarding scheduling and resource allocation were made by human operators. This interplay ensures that the DT functioned as a supportive tool rather than a fully autonomous system.

Future Case: Tree-Underground Utilities Digital Twin

In our latest DT research project, we have been working with eight municipal infrastructure managers to co-define the conceptual requirements for a DT system that they may be developing in future. The purpose of their DT is to support decision-making about relocating cables, pipes, and trees, which are often closely co-located in the same urban underground space. The managers stated the need to track the evolving shapes and sizes of tree root zones to assess potential risks of interference with underground cables. Over time, persistently high groundwater levels could, for example, lead to root zones expanding laterally and becoming shallower, encroaching upon cable beds. Consequently, trees become unstable and fall in strong winds, also damaging cables, pipes, and road infrastructures.

The conceptualised DT system facilitates the diagnosis of vulnerabilities and the simulation of risks by integrating infrastructure data (i.e., road and utility locations) with historical records of groundwater levels and wind conditions. Since the physical phenomenon of root zone growth and cable intrusion occurs gradually, the DT uses monthly intervals to simulate and predict tree growth as a function of groundwater levels and wind conditions. The system alerts engineers when there is a probability that root zones will intercept utilities within the next predicted maintenance period. The professionals then use this information to determine intervention strategies.

When trees or utilities are relocated, updated physical system data is fed into the virtual model.

The *latency* of the DT system for trees and utility management is significantly higher than in techno-centric twins, as data collection occurs at intervals of months. While the system can use real-time data from groundwater and weather databases, these data can be aggregated without compromising on quality for the decision-maker. In other words, since tree relocation and utility reinforcement are planned over months, real-time sensors or high-frequency inspections would only add computation and data management costs to the system, while not improving intervention decisions.

The DT's physical-digital coupling is also less tight and automated than the techno-centric ideal-type. Data on tree root sizes is manually collected using ground radar images and complex seismic interpretation software. Also, intervention decisions are made by managers rather than by the system itself. On the dimension of *fidelity*, the DT employs a detailed and complex physics model for simulating wind loads, root zone movement, and soil stability. This is combined with the seismic data to predict the sizes of root zones and locations of buried utilities. While models are complex, the user interface has a low-detail geospatial resolution only to represent potentially conflicting underground space volumes occupied by both utilities and tree roots. This multi-fidelity approach balances detailed data with users' decision needs.

Finally, the analytic capabilities of the conceptualised system are diagnostic and predictive. On one hand, the simple visual 3D interface presents the current underground conditions to support the diagnosis of the existing clearance space between root zones, cables, and the surface level. On the other hand, the system has the predictive ability to develop scenarios and identify the locations in the municipality where tree growth and water levels become critical. As with the previous case, this DT system uses 'right time' data instead of real-time data. Again, the capabilities of this DT would not benefit from becoming autonomous, as intervention decisions and actual execution of maintenance and reconstruction of underground spaces require more complex human judgment that cannot be emulated by a DT system.

DISCUSSION

The construction production control and underground DT cases perform data integration between physical and virtual systems to enhance the asset's life cycle management. While this is one of the foundational features of DTs (Fang *et al.,* 2025), the functionalities and shape of the DT solutions differed, deviating from the comprehensive and techno-centric DT ideal-type defined in Table 1.

The application of our alternative framework supports the argument that the deployment of construction DTs benefits from the consideration of data latency. This may be real-time, as in the AEC production control case. In this and similar cases, such as occupancy management systems and environmental monitoring, data transfer delays might lead to inefficiencies or safety concerns (Rajan and Li, 2024). Higher latency, where data is collected and analysed at intervals, was evident in the tree-utility case, which, like predictive maintenance, requires less than instantaneous data exchange (Wong *et al.,* 2022). Therefore, it is not real-time but 'right-time' data collection that matters for users' specific project goals.

In terms of fidelity, the cases show the need for application-specific fidelity levels. Both multi-fidelity systems make pragmatic use of computational resources, which may include high-fidelity physics and coarser representation models in a single use case. Alignment between fidelity and the operational context is key—straightforward tasks may not require the sophistication afforded by high-fidelity models (Sacks *et al.,* 2020, p. 2). This adaptability presents an opportunity for the built environment sector to leverage DT technology in a manner that is both resource-efficient and highly functional (Perno and Hvam, 2020). Both cases remain at the digital shadow stage, where physical and cyber connectivity is limited to one-way data exchange. Direct digital intervention—where the virtual system actively drives changes in the physical world—is still rare, as human oversight remains essential in construction cases reported in the literature.

Essentially, our two cases involve the design of DTs that aim to reduce the cognitive load on engineers rather than replace their expertise. This aligns with the literature. Current applications focus on enhancing situational awareness and predictive capabilities (Deng *et al.,* 2021; Dodt; Pronost *et al.,* 2023). Similarly, a health monitoring DT case in the literature provides insights into infrastructure behaviour and maintenance strategy development but still relies on human judgment to implement these strategies (Parida and Moharana, 2024). As human-computer role divisions in DTs can vary, from analyst, observer, decision-maker, to action-executor, depending on the analytical capabilities required (Agrawal *et al.,* 2023), this underscores the fact that the promise of a fully-fledged automated DT, which prescribes scenarios and makes changes autonomously, remains aspirational.

The findings contribute to the literature by emphasising the earlier claims of Agrawal *et al. (*2023) that DTs do not fit a one-size-fits-all stereotype. Techno-centric frameworks (c.f., Liu *et al.,* 2024; Tchana *et al.,* 2019) currently lean towards such stereotypes, which include real-time, fully integrated, and automated, high-fidelity DTs. Yet, such hyped and optimistic conceptualisations risk rejection (Wright and Davidson, 2020). The characteristics of a much less centralised and controlled industry, with varying site conditions, complicate achieving ambitions that are more commonplace in manufacturing and production environments where the DT concept emerged. The dynamic and iterative relationship between digital capabilities and the scope of the twinned entities in construction, consequently, requires construction managers to invest in DTs to make various trade-offs between the investment in technological capabilities and pragmatic needs from stakeholders (Agrawal and Fischer, 2024).

Agrawal *et al. (*2024) conceptualised the nature of DTs by eliciting their dynamic twinning properties. This study further translates this by focusing on measurable design parameters—fidelity, data frequency, latency, and physical-virtual coupling—to guide the development of digital twin systems in construction. This offers concrete, operational dimensions that directly inform system design and performance in practice, supporting better alignment between construction processes and DT systems during the implementation stage.

Ultimately, we advocate that both technological and managerial studies in CM should steer away from focusing on the ideal-type techno-centric Digital Twin towards a more ambivalent conceptualisation that better fits the context of our industry. This supports the point that a hyperreality may emerge when the construction industry uncritically promotes DTs, resulting in a too great a loss of meaning of reality through abstract digital models, and a loss of control where systems enforce structures that favour only specific stakeholders (Çıdık *et al.,* 2017), and a loss of perspective in settings where DTs are designed as transferable black boxes but only tested successfully in settings with heavily fixed boundaries (Boyd, 2021). To avoid hyper-real discussions, the technological knowledge domain needs to align better with the practice domain, as design scholars advocate (Hevner, 2007).

Acknowledging context in technology design further means that adoption studies of DTs should focus less on how organisations should change themselves to facilitate the uptake of ideal-type DTs, as happens with established maturity models (Haraguchi *et al.,* 2024; Liu *et al.,* 2024) or the elicitation of DT-adoption factors (Arowoiya *et al.,* 2024). Instead, a more fruitful endeavour would be to explore the rich context and design principles of impactful technologies.

Notably, this research has limitations. By using a pragmatic utilitarian perspective, rather than a techno-centric one, this study proposes four useful labels as dimensions. These dimensions were demonstrated in two cases. It is likely, though, that unexplored dimensions may emerge during extended analyses. By no means do we aim to be exhaustive, and so we encourage the further exploration of dimensions that help guide and describe DTs based on their usefulness. Based on a wider comparison of cases and dimensions, aspects like modularity may also be included. Such a term may describe well how a designed DT may be able to support decision-making in complex use cases, where it becomes part of a larger system of connected DTs. The feasibility and validity of such a dimension would need to be explored in future work through a variation of empirical DT design cases.

CONCLUSION

This study presents a pragmatic and user-centric framework that conceptualises the nature of Construction DTs through dimensions of latency, fidelity, physical-digital connectivity, and analytic capabilities. Using an engaged scholarship approach that iterated between our own fieldwork design experiences and concepts in the literature, we synthesized this framework and illustratively applied it to the DT-cases for AEC production control and tree-underground utility management. The results highlight the diversity of the DT concept and support our claim that debates should move away from techno-centric models, which fail to reflect the realities of construction practice where variability, uncertainty, and human judgment play critical roles. We aim to provide actionable guidance for developing context-sensitive digital systems that are better suited to the dynamic and human-centric nature of construction.

This research holds relevance for the construction management research community as it challenges the prevailing techno-centric paradigm dominating DT discourse. We advocate for a rethinking of digital innovation, not as a linear technological progression but as an iterative, situational design process focused on supporting context-aware decision-making. We encourage CM researchers to prioritise usefulness over technological maturity and move beyond the binary "Is this a digital twin, or not?" debates. This approach could open pathways for theory development around digital technology adoption anchored in construction-specific practices, challenges, and needs. In practice, we hope the proposed framework contributes to digital twin systems that effectively support decision-making, which is a vital step towards bridging gaps between digitalisation studies and practical implementation.

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