

EDITORIAL: INTEGRATION OF DIGITAL TWIN TECHNOLOGY IN CONSTRUCTION PROJECT MANAGEMENT – OPPORTUNITIES, CHALLENGES, AND FUTURE DIRECTIONS

Wing Son Loh¹  and Yee Yong Lee^{2*} 

¹Department of Mathematical and Actuarial Sciences, Lee Kong Chian Faculty of Engineering and Science, Universiti Tunku Abdul Rahman, 43000 Kajang, Malaysia.

²Department of Civil Engineering, Faculty of Engineering, Universiti Malaysia Sarawak, 94300 Kota Samarahan, Sarawak, Malaysia

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*Corresponding author's email: yylee@unimas.my

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Abstract — Construction project management has traditionally relied on fragmented tools, linear workflows, and static documentation, often resulting in cost overruns, schedule delays, and suboptimal resource utilisation. The emergence of Digital Twin (DT) technology, coupled with advances in Building Information Modelling (BIM), the Internet of Things (IoT), and artificial intelligence (AI), presents a transformative opportunity to reimagine how civil engineering projects are planned, executed, monitored, and maintained throughout their lifecycle. This editorial scope examines the integration of DT technology into construction project management, highlighting its capacity to enable real-time visibility, predictive analytics, and data-driven decision-making. While the convergence of these technologies offers substantial benefits, including enhanced collaboration, risk mitigation, and lifecycle performance optimisation, significant challenges persist in areas such as interoperability, data security, workforce readiness, and implementation cost. This paper discusses the current state of adoption, identifies critical barriers, and proposes strategic pathways to accelerate the meaningful integration of DT-driven project management frameworks in the civil engineering sector.

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1.0 INTRODUCTION

The global construction industry is one of the largest economic sectors, yet it remains among the least digitised and most productivity-challenged industries worldwide. Chronic issues such as budget overruns, schedule slippage, safety incidents, and quality deficiencies continue to plague construction projects of all scales [1–3]. These challenges are fundamentally rooted in the fragmented nature of project delivery, where information silos, poor communication among stakeholders, and reliance on reactive rather than proactive management approaches undermine efficiency and outcomes.

In response, the concept of the Digital Twin (DT) has emerged as a paradigm-shifting technology with the potential to fundamentally transform construction project management. A digital twin is a dynamic, virtual representation of a physical asset, process, or system that is continuously updated with real-time data from sensors, monitoring devices, and other data sources [4, 5]. Unlike static BIM models, which primarily serve design and documentation purposes, digital twins enable bidirectional interaction between the physical and virtual environments, allowing project managers to simulate scenarios, predict outcomes, and optimise decisions throughout the project lifecycle.

The integration of DT technology into construction project management is further catalysed by the maturation of enabling technologies, including BIM, IoT sensor networks, cloud computing, AI and machine learning (ML), and advanced data analytics [6, 7]. Together, these technologies create a robust digital ecosystem capable of supporting real-time monitoring, predictive maintenance, automated progress tracking, and intelligent risk assessment.

Despite its promise, the widespread adoption of DT in construction project management remains in its early stages. Most implementations are confined to pilot projects or limited to specific phases such as operations and

maintenance. The transition from conceptual frameworks to scalable, industry-wide deployment requires addressing fundamental challenges related to technology integration, data governance, organisational culture, and economic feasibility.

This editorial scope explores the opportunities and challenges associated with integrating DT technology into construction project management. It examines the current landscape, discusses key enablers and barriers, and outlines strategic directions for researchers and practitioners seeking to harness the full potential of this transformative technology.

2.0 THE EVOLVING LANDSCAPE OF CONSTRUCTION PROJECT MANAGEMENT

The management of civil engineering projects has undergone significant transformation to address increasing complexity, tighter margins, and escalating stakeholder expectations. To understand the transformative potential of digital twins, it is essential to examine the historical progression of project management methodologies, from traditional reactive frameworks to the data-rich environments enabled by modern digital tools.

2.1. Limitations of Traditional Project Management Approaches

Traditional construction project management relies heavily on tools such as Gantt charts, critical path method (CPM) scheduling, earned value management (EVM), and periodic site inspections [8, 9]. While these methods have provided a foundational framework for decades, they are inherently reactive and limited in their capacity to handle the complexity and dynamism of modern construction projects. Information is often outdated by the time it reaches decision-makers, progress reporting is manual and prone to human error, and risk identification typically occurs after issues have already materialised.

2.2. The Rise of BIM as a Foundational Enabler

Building Information Modelling (BIM) has significantly advanced the industry's digital maturity by enabling three-dimensional, data-rich representations of built assets [10, 11]. BIM facilitates clash detection, design coordination, quantity take-offs, and visualisation, thereby improving communication and reducing rework during the design and pre-construction phases. However, conventional BIM implementations are predominantly static and design-centric, with limited capacity for real-time data integration and operational feedback. The extension of BIM into higher dimensions (4D scheduling, 5D cost estimation, 6D sustainability, and 7D facility management) has broadened its applicability, yet the full potential of BIM as a living, responsive model remains underexploited without the integration of real-time data streams.

2.3. The Digital Twin Paradigm: Beyond BIM

The digital twin concept transcends the capabilities of traditional BIM by creating a continuously evolving virtual replica that mirrors the physical state of a construction project in real time [12, 13]. Enabled by IoT sensors, drones, LiDAR scanning, and AI-driven analytics, digital twins ingest live data from the construction site, including equipment performance, environmental conditions, worker movements, material usage, and structural health, and synchronise this information with the virtual model. This real-time synchronisation enables project managers to move from reactive monitoring to predictive and prescriptive management, fundamentally altering the decision-making landscape.

3.0 OPPORTUNITIES OF DIGITAL TWIN INTEGRATION IN PROJECT MANAGEMENT

The transition from static documentation to dynamic, data-driven environments unlocks unprecedented capabilities across the project lifecycle. By bridging the physical and virtual realms, digital twin technology offers a multitude of strategic advantages that fundamentally enhance how construction projects are executed, monitored, and optimised, delivering measurable value to all stakeholders.

3.1. Real-Time Progress Monitoring and Automated Reporting

One of the most immediate benefits of DT integration is the ability to monitor construction progress in real time with a high degree of accuracy. By combining point cloud data from laser scanners or photogrammetry with the BIM model, digital twins can automatically detect deviations between the as-planned and as-built states [14, 15]. This enables automated progress reporting, early identification of delays, and data-driven schedule recovery strategies, significantly reducing the reliance on manual inspections and subjective assessments.

3.2. Predictive Risk Management and Safety Enhancement

Digital twins, when coupled with AI and ML algorithms, can analyse historical and real-time data to predict potential risks before they materialise. For example, by monitoring structural loads, environmental conditions, and equipment performance, DT-enabled systems can forecast safety hazards such as scaffold instability, crane overload, or hazardous gas accumulation [16, 17]. Predictive risk models can also assess the likelihood of schedule delays or cost overruns based on current performance trends, enabling proactive mitigation strategies.

3.3. Resource Optimisation and Supply Chain Integration

Effective resource management is critical to project success. Digital twins can integrate data from enterprise resource planning (ERP) systems, supply chain platforms, and on-site sensors to provide a holistic view of material availability, labour allocation, and equipment utilisation [18]. This integration enables just-in-time material delivery, optimised workforce scheduling, and reduced idle time for heavy machinery, leading to significant cost savings and improved productivity.

3.4. Enhanced Stakeholder Collaboration and Communication

The shared, immersive environment provided by digital twins fosters improved collaboration among diverse stakeholders, including owners, designers, contractors, subcontractors, and facility managers. Cloud-based DT platforms enable real-time access to project data from any location, supporting remote inspections, virtual walkthroughs, and collaborative decision-making [19]. This level of transparency and accessibility reduces misunderstandings, accelerates issue resolution, and promotes a culture of accountability.

3.5. Lifecycle Performance and Whole-Life Asset Management

Perhaps the most profound impact of digital twin technology lies in its ability to bridge the gap between construction and operations. A DT created during the design and construction phases can be seamlessly transitioned to the facility management stage, where it serves as a living repository of asset information [20, 21]. This continuity supports predictive maintenance, energy optimisation, renovation planning, and end-of-life decision-making, thereby maximising the return on investment across the asset's entire lifecycle.

4.0 CHALLENGES AND BARRIERS TO ADOPTION

Despite the compelling benefits of digital twin technology, its widespread integration into construction project management is hindered by a complex matrix of technical, economic, and organisational barriers. Recognising and addressing these impediments is critical, as they dictate the pace of industry adoption and the ultimate scalability of digital twin solutions in real-world applications.

4.1. Interoperability and Data Integration Complexities

The construction industry employs a wide array of software platforms, file formats, and data standards, many of which are proprietary and incompatible [22]. Achieving seamless interoperability between BIM authoring tools, IoT platforms, ERP systems, and DT environments remains a formidable technical challenge. The absence of universally adopted open data standards, such as the Industry Foundation Classes (IFC) being consistently implemented across all tools, hinders the creation of integrated, end-to-end digital twin ecosystems. Furthermore, while geometric and structural data standards like IFC are prevalent, there is a critical lack of standardised ontologies and semantic web technologies to unify the vast, heterogeneous data streams generated by IoT sensors and enterprise systems. Developing unified data models that bridge proprietary IoT schemas with BIM

environments is essential to ensure that the semantic meaning of real-time, high-frequency data is preserved, contextualised, and seamlessly interpreted across the entire digital twin ecosystem.

4.2. Data Quality, Volume, and Governance

Digital twins are only as reliable as the data that feeds them. Construction sites generate vast volumes of heterogeneous data from diverse sources, including sensors, cameras, drones, and manual inputs [23]. Ensuring data accuracy, completeness, and timeliness is a persistent challenge. Furthermore, the governance of this data, including issues of ownership, access rights, privacy, and security, requires robust frameworks that are currently lacking in most construction organisations.

4.3. High Implementation Costs and Return on Investment Uncertainty

The initial investment required for DT implementation, encompassing hardware (sensors, scanners, edge computing devices), software (DT platforms, AI tools), network infrastructure, and skilled personnel, can be substantial [24]. For small and medium-sized enterprises (SMEs), which constitute the majority of the construction industry, these costs can be prohibitive. Moreover, the return on investment (ROI) of digital twin technology is often realised over the long term, making it difficult to justify upfront expenditures within traditional project budgeting frameworks.

4.4. Workforce Skills Gap and Organisational Resistance

The successful deployment of digital twin technology requires a workforce proficient in data science, AI, cloud computing, and systems integration, skills that are currently in short supply within the construction sector [25]. Additionally, organisational resistance to change, entrenched workflows, and a lack of digital culture can impede adoption even when the technology is available. Bridging this gap requires sustained investment in training, change management, and leadership commitment.

4.5. Cybersecurity and Data Privacy Concerns

As digital twins integrate increasingly sensitive project data, including structural designs, financial information, and operational parameters, they become attractive targets for cyberattacks [26]. The construction industry has historically lagged in cybersecurity preparedness, and the expanded attack surface created by IoT-connected digital twins demands urgent attention to data encryption, access controls, and incident response protocols.

5.0 STRATEGIC PATHWAYS FOR ADVANCEMENT

Overcoming the existing barriers to digital twin adoption requires a coordinated, multi-faceted approach that extends beyond mere technological deployment. Overcoming the existing barriers to digital twin adoption requires a coordinated, multi-faceted approach that extends beyond mere technological deployment. To provide a clear trajectory for industry practitioners, this section transforms strategic recommendations into a Phased Visual Implementation Roadmap (see Figure 1). This roadmap guides organisations from initial, low-risk pilot testing through to enterprise-wide scaling and ecosystem integration, ensuring that digital transformation is adopted sustainably, securely, and effectively.

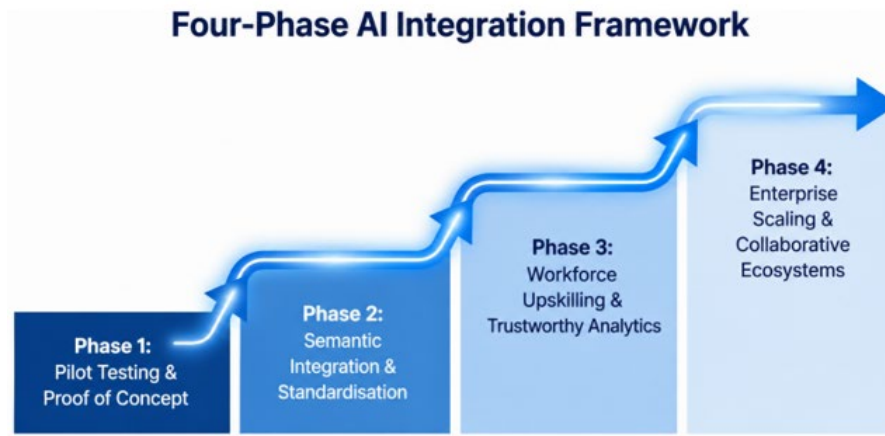


Figure 1 Phased visual implementation roadmap

The strategic pillars supporting this phased roadmap are detailed below:

Phase 1: Pilot Testing and Proof of Concept

Rather than pursuing enterprise-wide DT deployment from the outset, organisations should adopt a phased approach starting with well-defined pilot projects [27]. By targeting specific, high-value use cases, such as automated progress tracking or predictive safety monitoring on a single asset, organisations can demonstrate tangible value, build internal capabilities, and refine implementation strategies before committing to broader scaling. This phase minimises financial risk and establishes a foundational business case for DT investment.

Phase 2: Semantic Integration and Standardisation

As pilots prove successful, the focus must shift to breaking down data silos. The industry must prioritise the development and adoption of open, interoperable data standards, such as buildingSMART's openBIM framework and ISO 19650 [28]. Crucially, this phase requires the integration of semantic web technologies and unified data models to bridge proprietary IoT schemas with BIM environments. This ensures that real-time sensor data is not just geometrically aligned, but semantically understood across all integrated platforms.

Phase 3: Workforce Upskilling and Trustworthy Analytics

Technology scaling is only as effective as the human capital driving it. Closing the skills gap requires coordinated efforts among universities and industry stakeholders to integrate DT technologies and data analytics into construction management education [29]. Concurrently, as DT environments process more complex data, the integration of Explainable AI (XAI) becomes critical [30]. Ensuring that AI and ML models are transparent and interpretable builds the necessary trust among project managers and engineers, facilitating the adoption of automated, data-driven recommendations in safety-critical environments.

Phase 4: Enterprise Scaling and Collaborative Ecosystems

The final phase transitions the digital twin from a project-specific tool to an enterprise-wide and industry-wide asset. The complexity and cost of full-scale DT implementation necessitate collaborative approaches. Public-private partnerships, industry consortia, and shared digital infrastructure platforms can distribute costs and pool expertise. Furthermore, government incentives, including grants and procurement requirements that mandate digital twin adoption for public infrastructure, can catalyse this final transition, embedding DTs into the standard lifecycle management of the built environment.

6.0 CONCLUSIONS AND FUTURE WORKS

The integration of DT technology in construction project management represents a critical turning point for an industry historically constrained by fragmented workflows, cost overruns, and reactive decision-making. By establishing a continuous, dynamic link between physical assets and their virtual counterparts, DTs offer an unprecedented capacity for real-time monitoring, predictive analytics, and whole-lifecycle optimisation. However,

transitioning from isolated pilot projects to industry-wide adoption requires overcoming entrenched barriers in data interoperability, cybersecurity, and workforce readiness.

Future research and industry initiatives must therefore pivot toward developing standardised, open-source DT frameworks that seamlessly bridge Building Information Modelling (BIM), Internet of Things (IoT), and enterprise resource systems. There is a pressing need to advance explainable AI (XAI) within DT environments to ensure that automated, data-driven recommendations remain transparent, interpretable, and trustworthy for critical engineering decisions. Furthermore, exploring the convergence of DTs with emerging paradigms, such as generative AI, autonomous construction robotics, and blockchain-enabled smart contracts, will unlock new frontiers in automated, secure, and resilient project delivery.

Ultimately, the adoption of digital twin technology is not merely a software upgrade; it is a fundamental reimagining of how we conceptualise, execute, and sustain the built environment. By embracing this digital evolution, the civil engineering sector can transcend its historical limitations, transforming today's complex construction challenges into tomorrow's blueprint for a smarter, safer, and inherently sustainable world.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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