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Research Article

Blockchain-Enabled Digital Twins in the Built Environment: Socio-Technical Barriers to Post-Construction Integration

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Abstract

Blockchain-enabled Digital Twins (BC-enabled DTs) offer transformative potential for enhancing the post-construction management of a building's lifecycle through real-time monitoring, improved data accessibility, and more effective decision-making, ultimately fostering trust and collaboration among stakeholders. However, the successful integration of BC-enabled DTs in the Architecture, Engineering, Construction, and Facilities Management (AEC-FM) sector is hindered by a complex interplay of barriers. This study employs a socio-technical lens in synthesising insights from academic literature and stakeholder perspectives to identify key barriers categorised across four interconnected dimensions: policy, people, process, and technology. Policy challenges include a lack of clear standards, guidelines, and regulatory clarity. People-related issues encompass insufficient awareness, limited digital skills, and resistance to change. Process barriers point to high implementation costs, lack of validated use cases, and unresolved data ownership. Technological obstacles such as inadequate system integration, energy-intensive infrastructure, and system complexities further complicate adoption. The study's contribution lies in providing an integrated, multi-dimensional framework that highlights where targeted interventions are most needed. These findings offer valuable insights for policymakers, practitioners, and researchers aiming to adopt BC-enabled DTs to promote a more sustainable, intelligent, and data-driven post-construction phase.

Keywords: blockchain; digital twins; post-construction management; barriers

Highlights

- BC-enabled DT can enable trust and real-time collaboration during post-construction asset management.
- Adoption of BC-enabled DT is hindered by socio-technical barriers across four key domains.
- Addressing people, process, policy, and tech gaps is key to enabling post-construction innovation.

1 Introduction

The social repercussions of the Architectural, Engineering, Construction and Facility Management (AEC-FM) industry's slow innovation, evidenced by high rates of worker injuries and poor working conditions, underscore the urgent need for transformation (Balasubramanian et al., 2021). To address these multifaceted challenges and maintain a competitive advantage, AEC-FM stakeholders must harness innovative strategies that enhance project coordination, ensure data integrity, and uphold sustainability and safety standards. Furthermore, as the demand for efficient, timely, and budget-conscious project delivery intensifies, the need for transformative solutions in the AEC-FM sector has become increasingly urgent (Foroozanfar et al., 2017; Shojaei et al., 2020). Implementing innovative and sustainable techniques can serve as crucial catalysts for enhancing efficiency, promoting effective information sharing, facilitating robust decision-making processes, and ultimately improving overall project outcomes (Alaloul et al., 2021; Koolwijk et al., 2018). Nonetheless, the sector still grapples with issues of mistrust, ineffective communication, adversarial relationships, and unnecessary disputes (Li et al., 2021; Rahimian et al., 2021).

The challenges in the AEC-FM sector significantly impact building lifecycle management, particularly pronounced in the post-construction phase, where asset management (AM) is often constrained by manual processes, information loss, and fragmented data (Singh & Anumba, 2024). Such inefficiencies risk critical tasks being rushed, overlooked, or improperly handled, impacting the long-term performance of built assets. As AM organisations navigate rising social responsibilities, financial constraints, and regulatory demands, there is a growing urgency to adopt digital innovations that streamline operations and enhance performance (Heaton & Parlikad, 2020).

The integration of advanced digital technologies within the AEC-FM sector offers a promising avenue for augmenting interoperability and system compatibility, thereby facilitating decentralised support and decision-making (Coupry et al., 2021). Digital Twins (DT) are particularly promising as they can enhance real-time communication and collaboration among project participants(Lee et al., 2021). However, existing literature highlights a pressing need to address concerns regarding data security, reliability, and effective collaboration (Hellenborn et al., 2023). In this context, Blockchain (BC) offers unified standards and protocols for information sharing through a decentralised peer-to-peer (P2P) framework, addressing concerns related to information security and privacy, leveraging cryptographic mechanisms (Elghaish et al., 2022).

The integration of BC with DT holds strong promise for improving post-construction AM by ensuring data integrity, security, and trustworthiness, thus enabling more effective collaboration among stakeholders (Adu-Amankwa et al., 2022). Yet, studies exploring this integration remain limited, and its adoption is likely to be influenced by a variety of socio-technical factors. Therefore, this study seeks to explore stakeholder perspectives on the socio-technical barriers that may hinder the adoption of a BC-enabled DT framework for post-construction AM. In line with the aim, the study seeks answers to the research question:

- What are stakeholder perspectives on the socio-technical barriers of a BC-enabled DT approach to post-construction asset management?

The remainder of the article is structured as follows: Section 2 gives a brief overview of related literature, Section 3 outlines the research methods, Section 4 presents the study findings and discusses related literature, and Section 5 summarises and concludes the study.

2 Related Literature

2.1 The Convergence of Blockchain and Digital Twins

In the AEC-FM domain, the intersection of BC and DT technologies remains underexplored in academic literature. Lee et al. (2021) presents a compelling case for the development of an integrated BC-DT framework designed to facilitate accountable information sharing of project-related information among stakeholders. This framework posits that the synthesis of BC and DT generates a robust mechanism through which authentic, real-time construction data can be rendered traceable and immutable, effectively enabling seamless data sharing among participants and eliminating the need for intermediaries. Moreover, emerging research suggests that a BC-enabled DT collaboration platform can cultivate a virtual environment tailored for real-time monitoring, informed decision-making, and efficient communication among a diverse array of project stakeholders (Jiang et al., 2022). Tavakoli et al. (2024) further assert that the adoption of BC-enabled DT has substantial potential to revolutionise AM practices in building operations, enhancing transparency, reliability, and performance optimisation. Additionally, Götz et al. (2020) elucidate that BC-enabled DTs are viewed as a unified collaboration solution that industry professionals can employ for decision-making and process support across a wide array of asset lifecycle management activities.

Collectively, these studies illuminate the transformative capabilities inherent in the convergence of DT and BC, particularly in the realms of real-time data monitoring, secure data exchange, and transparent decision-making processes. The integration of these technologies holds significant potential to refine and optimise workflows in post-construction AM. However, realising this promise requires navigating a multifaceted landscape of socio-technical barriers that must be explored from multiple perspectives. Therefore, exploring stakeholder viewpoints on these multifaceted barriers addresses a critical gap in the limited research surrounding BC-enabled DT for post-construction AM. This exploration lays the groundwork for developing resilient strategies that can transition BC-DT from conceptual potential to practical implementation in the AEC-FM sector, potentially revolutionising AM practices and enhancing overall project outcomes.

2.2 Socio-Technical Factors Influencing the Adoption of Digital Technologies

Digital transformation strategies for the post-construction phase signify a necessary paradigm shift in current best practices for building lifecycle management (Shen et al., 2016). Given that the AEC-FM sector is gradually adopting digital transformative strategies, it is important to examine the socio-technical factors that facilitate or hinder the engagement and adoption of these strategies. Understanding these influencing factors will provide insights for the adoption of a BC-enabled DT and its impact on the post-construction phase.

A widely accepted framework categorises socio-technical influencing factors as a complex interplay between four interdependent dimensions: People, Process, Technology, and Policy (Marocco & Garofolo, 2021). This multidimensional framework affirms that while 'People' and 'Process' serve as the primary catalysts for operational change, their success is fundamentally contingent upon the presence of robust 'Technological' infrastructures and a coherent 'Policy' environment (Shen et al., 2016).

In exploring the 'People' dimension, it is evident that human factors are foundational to the successful adoption of digital technologies. Related literature highlights key considerations, including client influence (Yang et al., 2021), stakeholder awareness (Goh et al., 2019), and the requisite skills and expertise of personnel involved (Aoun et al., 2021). In parallel, the 'Process' dimension focuses on the organisational framework necessary to generate value (Bew & Underwood, 2010) from digital initiatives, focusing on aspects such as the deployment of pilot projects (Zhang et al., 2023), financial implications (Cheng & Chong, 2022), and concerns regarding data security and privacy (Aoun et al., 2021). The ‘Policy’ dimension plays an enabling role by providing regulatory clarity and risk mitigation strategies (Shen et al., 2016). Scholarly discourse emphasises the necessity for comprehensive standards and guidelines (Cheng & Chong, 2022), government interventions (Badi et al., 2021), and well-defined ownership structures (Rasheed et al., 2020). From a ‘Technology’ perspective, digital transformation strategies rely heavily on the maturity of existing infrastructure (Kumar et al., 2021), the complexity of system integration (Perno et al., 2020), and energy consumption considerations. These factors collectively contribute to the establishment of a resilient and adaptive framework that can support ongoing technological evolution.

In summary, these socio-technical dimensions reveal that the successful adoption of BC-enabled DT for post-construction AM transcends mere technological challenges; it embodies a multifaceted transformation requiring a holistic approach. Thus, understanding and addressing these socio-technical variables comprehensively is imperative for realising the full potential of BC-DTs in the post-construction phase, ultimately fostering enhanced efficiency, sustainability, and value throughout the building lifecycle.

3 Methodology

This study adopted a qualitative methodological framework centred on semi-structured interviews to capture in-depth stakeholder perceptions regarding DT and BC technologies within the AEC-FM sector. The choice of this approach is grounded in its efficacy for eliciting comprehensive and nuanced insights (Bryman, 2016), allowing participants to articulate their perspectives drawn from their professional knowledge and expertise.

Purposeful sampling was utilised, primarily leveraging online platforms such as LinkedIn and recommendations from peers to identify and recruit participants. Following the recommendations of Saunders et al. (2019), a sample size of 5 to 25 participants is considered optimal for qualitative interviews. As a result, this study engaged 32 AEC-FM professionals and scholars across diverse regions, including Asia, Europe, North America, and Africa.

The interviews were conducted via Microsoft Teams, employing open-ended questions designed to elicit meaningful dialogue and in-depth responses (Yin & Campbell, 2018). This approach enhanced the authenticity and richness of the data captured during the sessions. The transcriptions of these interviews underwent rigorous analysis using NVivo, where responses were systematically categorised into self-descriptive groups and thematically coded to identify the scope or variety of relevant constructs (Saldaña, 2021). This analytical process revealed emerging themes that underscore the socio-technical barriers to the adoption of BC-enabled DT for post-construction AM. These themes were shaped by the study's central focus, as suggested by Bryman (2016).

4 Results and Discussion

Participants’ perspectives provide a nuanced understanding of the socio-technical barriers that may hinder the adoption of a BC-enabled DT approach for post-construction AM. These “barriers” refer to factors that may hinder the effective implementation and use of BC-enabled DT in this context (Neto et al., 2020). Key themes from the interviews were categorised under the socio-technical dimensions of people, policy, process, and technology.

4.1 Policy Barriers

Policy-related barriers highlight the absence of standards, definitional clarity, and ownership frameworks, which can further exacerbate the obstacles to the widespread adoption of BC-enabled DT for post-construction AM.

Absence of Standards, Policies and Guidelines

Participants underscored the lack of standardised protocols, regulations, and frameworks for a BC-enabled DT, noting that this ambiguity complicates system selection and risks promoting inconsistent or undefined asset usage. Previous literature corroborates this perspective, suggesting that emerging technologies often raise unresolved policy issues, underscoring the need for clear regulations and standards (Aoun et al., 2021; Wu et al., 2022). Specifically regarding DT, the lack of internationally recognised data standards impedes the integration of facilities management systems, Internet of Things (IoT) devices, and real-time as-built data (Seaton et al., 2022).

Lack of Clear Definition

The absence of a precise and universally accepted definition was identified as a significant barrier, contributing to communication gaps and varying interpretations among stakeholders. Participants emphasised that such definitional ambiguity fuels uncertainty in implementation, complicates stakeholder engagement and inhibits the development of a cohesive strategy for adoption. Findings from related studies underscore the confusion surrounding DT and BC, where inconsistent definitions and unclear goals hinder their integration into existing business processes (Akinradewo et al., 2022; Koeleman et al., 2019). According to Jang and Collinge (2020), the challenge of unclear requirement definitions can lead to escalated project costs and diminished operational efficiencies.

Ownership Concerns

Issues of ownership and responsibility surfaced as a concern, particularly regarding data, costs, liabilities, and accountability. Participants described disputes over data rights and model control as deterrents to collaboration and document sharing. Literature reinforces this notion, highlighting the complexities of data ownership arising from the multi-stakeholder dynamics of construction processes (Li et al., 2019). Furthermore, Jones et al. (2020) emphasise that ownership challenges carry notable social and cultural implications, particularly given the extensive collection, storage, and sharing of data through DT technologies.

4.2 People Barriers

People-centric barriers underscore the challenges posed by limited awareness, insufficient expertise, and stakeholder resistance, which can collectively hinder the successful implementation of BC-enabled DT for post-construction management.

Lack of Awareness

Participants observed that unfamiliarity with adoption pathways and a limited awareness of benefits hinder effective implementation. They emphasised that the lack of technological awareness among industry stakeholders underscores the necessity of highlighting these benefits to dispel the misconception that digital initiatives are transient trends. This aligns with findings showing that AEC-FM firms have low digitalisation maturity, often dismissing digital initiatives as lacking tangible value due to insufficient understanding (Chong & Diamantopoulos, 2020; Goh et al., 2019). Moreover, literature indicates that while many AEC-FM firms assert they are digitally transforming, there is still a significant lack of awareness regarding the new processes and structures involved, which challenges the creation of a work environment conducive to digital innovation within firms and across the industry (Chong & Diamantopoulos, 2020).

Limited Skills and Knowledge

Participants' perspectives indicated that the lack of skilled and knowledgeable experts, as well as insufficient manpower can be barriers to the utilisation of a BC-enabled DT approach. Additionally, views expressed highlighted the lack of technology-focused education, insufficient workforce training, and an overall scarcity of capacity-building efforts. These insights align with findings of Neto et al. (2020) and Saberi et al. (2019), who identify insufficient expertise as a critical bottleneck in both DT and BC adoption. Similarly, Marocco and Garofolo (2021) emphasise the persistent deficit of technical skills necessary to manage advanced technologies in post-construction activities, where new processes demand specialised knowledge, competencies, and methodologies that are not yet widely accessible.

Stakeholder Attitude

Stakeholder attitudes, particularly resistance to change, were recognised as significant barriers to the adoption of new practices. Participants noted that, despite the recognised benefits of technology, behavioural inertia, particularly among senior leadership, can impede technological advancement. Literature evidence suggests that factors such as perceived costs, convenience, trust, and readiness play a crucial role in shaping behavioural intentions, which can subsequently influence stakeholder attitudes towards technology adoption and realisation (Cheng et al., 2021). Furthermore, Neto et al. (2020) note that stakeholders often resist innovative technologies due to the rapid pace of technological advancements, which can outstrip the capacity of both workers and managers to absorb and comprehend these changes.

4.3 Process Barriers

Process-related obstacles, which may hinder adoption, predominantly manifest as the absence of demonstrable use cases, significant cost implications, and concerns surrounding data privacy and security.

Absence of Use Cases

Participants emphasised the dearth of practical, real-world applications and pilot projects that showcase the efficacy of BC-enabled DT systems. They further noted that this deficiency in implementation evidence fosters a climate of scepticism, thereby hindering the broader adoption within the industry. Empirical studies corroborate that a lack of exemplar projects reduces confidence and slows innovation (Coupry et al., 2021; Dasaklis et al., 2022). Seaton et al. (2022) further highlight that the scarcity of case studies and exemplar projects impedes efforts to illustrate the comprehensive advantages of these systems in the industry.

Cost Implications

Participants also recognised high initial investments, alongside long-term maintenance expenses and significant training costs, as a key obstacle to implementing BC-enabled DT. While there is a recognition of the potential for returns on investment, participants considered high implementation costs as prohibitive, particularly for smaller organisations with limited resources. Prior research amplifies these concerns, indicating that uncertainty regarding financial returns often deters firms from investing in emerging technologies (Aoun et al., 2021). Within the built environment, various stakeholders view the current slate of emerging technologies as excessively costly to implement, while simultaneously grappling with ambiguity regarding the perceived benefits (Ebekozien et al., 2023).

Data Privacy and Security Concerns

Participants raised concerns regarding data privacy and security in the implementation of a BC-enabled DT approach. Given the volume and sensitivity of data processed by BC-enabled DTs, participants expressed concerns about safeguarding intellectual property and sensitive documents, which, if compromised, could undermine the transparency and efficacy of data exchange. These concerns are echoed in the literature, particularly with the rise of Internet-of-Things-driven systems in Industry 4.0, which introduces new cybersecurity risks (Aoun et al., 2021; Parn & Edwards, 2019). Additionally, while BC technology offers secure, decentralised data exchange (Coupry et al., 2021), it simultaneously introduces intricate issues related to regulatory compliance, cross-border data governance, and susceptibility to evolving cyber threats (Dasaklis et al., 2022).

4.4 Technology Barriers

Technology-related barriers highlight the limitations of existing technological infrastructure, concerns over energy consumption, and the complexities of system integration, all of which can hinder implementing BC-enabled DT for post-construction AM.

Limitations with Technology Infrastructure

A predominant barrier identified by participants revolves around inadequate technological infrastructure. Participants pointed specifically to deficiencies in network capacity, cloud infrastructure, and the necessary system support needed to facilitate seamless integration. This observation underscores a broader issue: the lack of industry focus on addressing the infrastructural demands posed by emerging technologies, despite continual advancements in research and development. Prior studies corroborate these findings, highlighting the absence of tailored wireless networks and the pressing need for high-bandwidth cloud computing as significant obstacles, particularly in FM applications (Naji et al., 2024). Similarly, Xu et al. (2021) delineate how inadequate IT infrastructure and server limitations remain critical impediments to the successful implementation of BC technologies in the AEC-FM sector.

Energy Consumption Concerns

The high energy demands associated with the large-scale implementation of BC-enabled DTs emerged as another significant barrier. Participants expressed concern regarding the substantial power requirements for the operation of numerous sensors and gateways, which raises pressing environmental issues, particularly in regions where the energy infrastructure is unreliable. These findings resonate with observations made by Naji et al. (2024), who highlight the continuous energy demands of data centres driven by large-scale data storage and processing. Similarly, Li et al. (2019) note that such energy consumption may strain grid systems and increase emissions, negatively impacting the built environment.

Complexities of the Approach

Participants noted that integrating BC-enabled DT systems can be excessively complex, highlighting challenges related to system interoperability, permission management, and software limitations. While the concept of using sensors to collect real-time data appears straightforward in theory, participants emphasised that the practical execution of ensuring seamless operation among all system components is considerably more intricate, primarily due to the overarching system complexity. Prior research underscores that such complexities can deter the acceptance of innovative technologies, particularly when they are perceived as difficult to implement or manage (Badi et al., 2021; Li et al., 2022). In particular, Aoun et al. (2021) emphasise that emerging technologies introduce additional constraints, such as stringent reporting requirements, transparency obligations, and extensive data management obligations, further complicating their widespread adoption.

5 Conclusions

This study explored stakeholder perspectives on the socio-technical barriers to adopting a BC-enabled DT approach to post-construction AM. Through qualitative insights derived from industry professionals and academics across multiple regions, the findings highlight that while the integration of these technologies holds significant potential for enhancing data integrity, transparency, and real-time collaboration, their adoption can be hindered by a complex interplay of socio-technical challenges across policy, people, process, and technology dimensions. Key barriers identified include the absence of regulatory standards and definitional clarity, limited awareness and expertise among stakeholders, high implementation costs, lack of demonstrable use cases, data privacy concerns, and the technical complexity of integrating BC-enabled DT systems. The results underscore that the adoption of BC-enabled DTs is not solely a technical endeavour but a socio-technical transformation that requires coordinated action across multiple domains.

This study contributes to the limited but growing body of research on the convergence of BC and DT in the context of post-construction management, offering a structured socio-technical lens through which adoption challenges can be better understood. Practically, the findings provide actionable insights for industry professionals, policymakers, and change agents seeking to advance digital transformation strategies in post-construction AM. These insights can inform digital roadmaps, guide regulatory development, and support the design of targeted training and capacity-building programmes to facilitate implementation readiness.

While the qualitative approach offers rich insights, the findings are based on a purposive sample and may not be generalisable across all contexts. Future research should examine context-specific strategies for overcoming these barriers, explore cross-disciplinary collaborations to build digital capacity, and evaluate real-world pilot implementations to demonstrate value and feasibility. Addressing these dimensions holistically is critical to realising the full potential of BC-enabled DTs in supporting more secure, efficient, and resilient post-construction AM.

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Conflicts of Interest
The authors have no competing interests to declare that are relevant to the content of this article.

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