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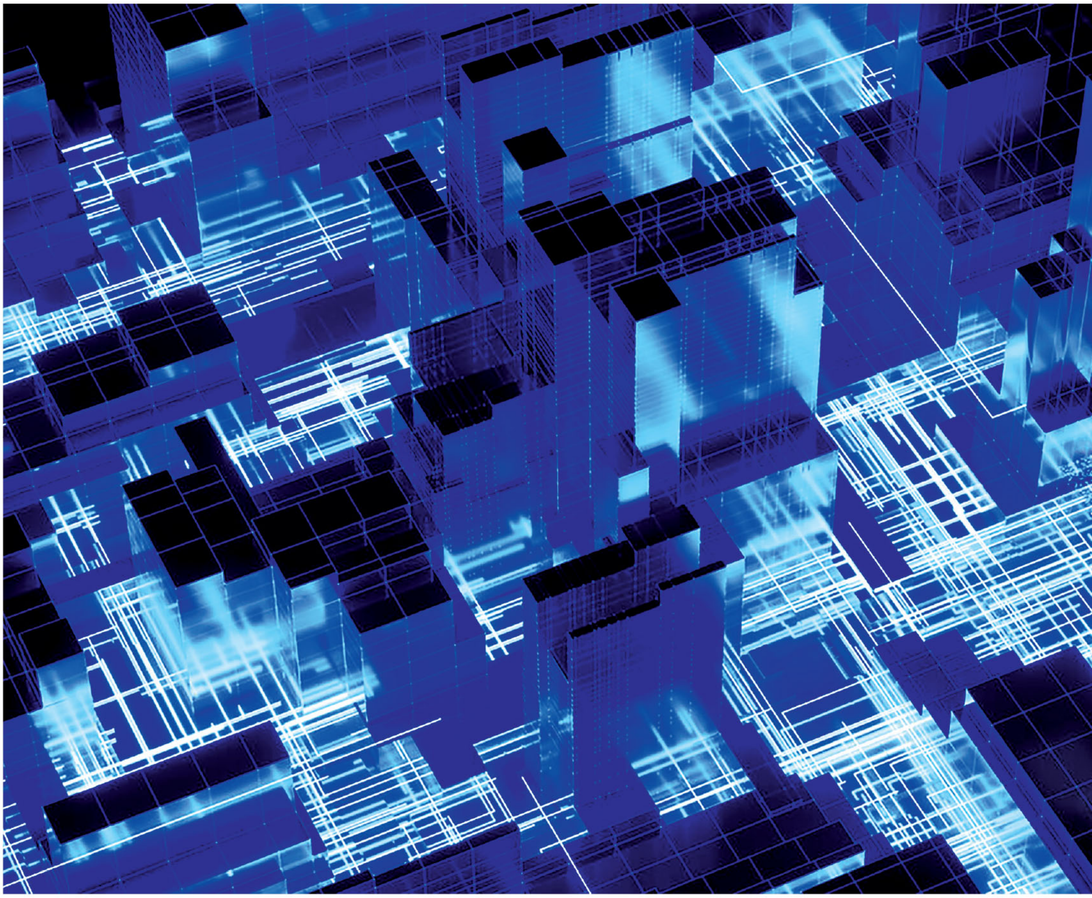
Blockchain, Smart Contracts and Distributed Ledger Technologies in the Built Environment

Key concepts, technologies, and applications

Edited by

Mohamad Kassem, Abel Maciel and Daniel M. Hall



Blockchain, Smart Contracts and Distributed Ledger Technologies in the Built Environment

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Chapter 13

Conclusions: cross-cutting themes, challenges and recommendations

Mohamad Kassem[*], *Abel Maciel*[†] *and Daniel Hall*[‡]

This concluding chapter summarises the key insights presented throughout this book, connecting individual contributions to a broader discourse on blockchain's role in addressing inefficiencies in the architecture, engineering, construction and operations (AECO) industry. It highlights blockchain's foundational principles, socio-technical dimensions and applications such as supply chain management, construction contract administration (CCA), property tokenisation and integration with digital twins and IoT systems.

Cross-cutting themes are identified, including blockchain's potential to enhance transparency, decentralise governance, support lifecycle management and enable tokenisation for inclusive and sustainable practices. This chapter also examines key challenges to adoption, such as legal and regulatory hurdles, scalability and performance limitations, integration with legacy systems and stakeholder resistance. These challenges are contextualised within the fragmented and complex nature of the built environment. Additionally, the chapter explores the dynamics of innovation ecosystems, analysing how open, closed and hybrid models influence the scalability and diffusion of blockchain in the AECO sector.

This chapter adapts recommendations from the World Economic Forum's (WEF) blockchain framework, tailoring them to support blockchain adoption within the AECO sector. These include strategies for stakeholder engagement, regulatory alignment, pilot projects and the development of interoperable and scalable systems.

Finally, the chapter calls for a collective effort among academia, industry and policymakers to position blockchain not as a standalone solution but as a catalyst for innovation, inclusivity and resilience, extending its impact beyond the built environment.

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13.1 Synthesis of chapters

This book explored the transformative potential of blockchain technology in the built environment through 11 core chapters. Each chapter addressed a distinct aspect of blockchain's application, from foundational concepts to practical implementations and sector-specific challenges. A summary of the scope and contributions of each chapter is included in the following paragraphs.

Chapter 2 provides a foundational understanding of blockchain technology and explores its application in construction projects. It provides the technical foundations of blockchain technology, defining distributed ledger technologies (DLT) and highlighting blockchain's key attributes such as immutability, transparency and security. It categorises blockchains into permissionless and permissioned types, comparing platforms like Ethereum and Hyperledger Fabric. The chapter introduces smart contracts as programmable tools for automating processes and discusses oracles as connectors between blockchain and real-world data. The chapter also discusses oracles and their significance in blockchain-based applications. It categorises oracles as human, software and hardware, providing examples of how different types of oracles are utilised in construction projects. By showcasing examples in tendering, material management and energy monitoring, it illustrates blockchain's potential to enhance transparency and efficiency in the built environment.

Chapter 3 introduces the socio-technical systems (STS) theory as a lens to explore blockchain adoption in the construction sector. It outlines how blockchain technology, characterised by its transparency, immutability and decentralised nature, addresses long-standing inefficiencies in construction. However, the chapter emphasises that blockchain adoption requires more than technical implementation – it must consider the interplay between technological and social factors. The chapter reviews STS theory's origins, its relevance to technological innovation and its application to the built environment, particularly digital technologies like building information modelling (BIM). It highlights conceptual models like the multi-level perspective (MLP) and presents a socio-technical framework tailored for blockchain adoption, combining dimensions of technology, process, policy and society. By providing a roadmap and specific models for blockchain integration, Chapter 3 establishes a comprehensive approach to navigating adoption barriers and leveraging blockchain's potential to transform construction processes and relationships among stakeholders.

Chapter 4 addresses the challenges of ensuring data security in AECO projects, particularly in the context of increasingly digital workflows and collaborative environments. It emphasises the importance of securing BIM models, given their rich visual and semantic data content. The chapter explores the principles of data security, including confidentiality, integrity and availability, outlining their relevance to AECO projects. It discusses various approaches to data storage, advocating for the use of distributed technologies like blockchain and the interplanetary file system (IPFS) to enhance data security. A universal distributed framework is proposed, integrating these technologies to facilitate secure data sharing, lifecycle transparency and selective data visibility while maintaining functionality. By addressing the interlinked facets of data confidentiality, digital trust and data utility, the chapter sets a foundation for more secure and efficient data management practices in AECO projects. It also outlines potential future research directions, including the integration of deep learning models for sensitive data classification and improved inclusivity for smaller project stakeholders.

Chapter 5 focuses on the tokenisation of property rights and its implications for the real estate sector, emphasising its ability to enhance liquidity, accessibility and efficiency. It highlights the potential benefits of tokenisation such as reduced transaction costs, increased market accessibility and fractional ownership. It outlines the steps involved in tokenising property, emphasising the need for secure data management and identity verification. The chapter proposes a property tokenisation management system, detailing its key components and functionalities. It emphasises the importance of data organisation within this system, including user accreditation, property documentation management and token and smart contract association. It also describes the system's reporting capabilities, its data warehousing functionalities and the integration of GIS tools for property visualisation and urban analytics.

Chapter 6 introduces the concept of digital building logbooks (DBLs) and their role in facilitating a circular economy within the built environment. It underscores the importance of DBLs in capturing and managing building information throughout its lifecycle, including design, construction, operation, maintenance and demolition. It discusses the challenges of DBL implementation, particularly the need for secure and reliable data storage, integration of legacy information and user-friendly interfaces. The chapter proposes a blockchain-based DBL architecture, outlining a three-layered system consisting of a data layer, a logic and services layer and a user interface layer. It advocates for a hybrid data storage system, combining decentralised storage using the IPFS with centralised databases for legacy information. The chapter concludes by emphasising the potential impacts of blockchain-enabled DBLs, including fostering circular economies, advancing energy-efficient renovations and creating decentralised data marketplaces. It also identifies future research directions such as developing standardised frameworks, integrating legacy data and aligning blockchain-based solutions with legal and regulatory frameworks. This vision positions DBLs as critical tools for driving transparency, efficiency and sustainability in the built environment.

Chapter 7 focuses on the application of blockchain technology to facilitate renewable energy integration within seaport microgrids. It provides a practical example of how blockchain can be used to manage energy trading among buildings within a microgrid, using the Port of Milford Haven in South Wales as a case study. The chapter investigates the scalability and potential viability of using Ethereum smart contracts to prioritise renewable energy trading within the microgrid, examining the impact of Ethereum gas prices on transaction costs. It describes the energy consumption and production patterns of the buildings included in the case study, detailing their specific energy needs and the presence of renewable energy sources. Results indicate that while blockchain can enhance energy efficiency and transparency, challenges such as Ethereum's price volatility, high gas fees and public adoption barriers must be addressed. The findings underscore blockchain's potential to decentralise energy systems, improve renewable energy adoption and foster community engagement. However, the chapter also calls for further research into private blockchain solutions, legal frameworks and the scalability of blockchain-enabled microgrids in energy-intensive industries.

Chapter 8 explores the application of blockchain and distributed technologies to support co-authorship and collaborative design within architectural practice. It acknowledges the shift from sole authorship to shared effort across disciplines in contemporary architectural projects, emphasising the need for effective communication protocols and knowledge-sharing mechanisms. It reviews existing research on collective authorship in architectural design, highlighting key themes such as remote collaboration, communication protocols and knowledge sharing. The chapter draws connections between stigmergic principles and collaborative design, evaluating research articles based on their incorporation of communication, feedback loops, decentralisation and the use of a shared substrate. Using practical prototypes such as blockchain-integrated BIM and DAO frameworks, the chapter illustrates how decentralised systems can facilitate design optimisation, shape grammar applications and project governance. It also addresses challenges such as trust, scalability and the need for robust data infrastructure, proposing innovative solutions like 'soulbound' tokens for skill recognition and incentivisation. By combining technological insights with socio-technical principles like stigmergy and the viable system model, the chapter proposes a vision for transforming architectural practice into a non-extractive, community-driven discipline. Finally, the chapter underscores the importance of further research and experimentation to unlock the full potential of blockchain in design governance.

Chapter 9 focuses on applying blockchain technology to enhance construction supply chain management (CSCM). The chapter first identifies challenges within current CSCM approaches, including fragmented information sharing, lack of trust among stakeholders and the absence of a single source of truth. To address these issues, the chapter presents a blockchain-based CSCM system implemented in a real-world case study involving modular construction between Hong Kong and Mainland China. This pilot project demonstrates how blockchain improves supply chain transparency, ensures data immutability and facilitates efficient quality control processes. Additionally, the chapter provides practical guidelines for implementing blockchain systems, emphasising key considerations like stakeholder management, scalability and legal compliance. While the chapter underscores blockchain's transformative potential in CSCM, it also highlights unresolved challenges such as scalability limitations, regulatory uncertainty and resistance to change. It concludes by discussing future opportunities, including integrating blockchain with IoT, AI and DAOs, to further enhance supply chain resilience and efficiency.

Chapter 10 examines the integration of BIM, digital twins and enterprise common data environments (CDEs) to address data observability challenges in large-scale infrastructure projects. It emphasises the transition from traditional, fragmented data management approaches to comprehensive enterprise-grade solutions capable of managing diverse, interconnected data sources. It highlights the need for a transition from traditional fragmented data management approaches to comprehensive enterprise-grade solutions capable of managing diverse interconnected data sources. Blockchain and DLTs are presented as tools to enhance data integrity, traceability and security and as enablers of seamless integration within enterprise CDEs. By examining real-world case studies and theoretical frameworks, the chapter underscores the need for innovative data governance strategies and advocates for the adoption of decentralised technologies to optimise project outcomes and align with enterprise objectives.

Chapter 11 explores the potential of blockchain technology to transform CCA. The chapter maps blockchain applications to 12 core CCA functions, categorised into control, coordination and adaptation mechanisms. Examples include financial management, quality assurance, document management and dispute resolution. It demonstrates how blockchain can enhance these processes by automating contractual obligations, ensuring data integrity and fostering accountability among stakeholders. Case studies and proof-of-concept implementations are used to validate blockchain's applicability, particularly in areas like payment automation, performance monitoring and document traceability. While blockchain presents opportunities for improving CCA, the chapter also identifies challenges such as replicating complex contractual logic and ensuring the authenticity of off-chain data. It concludes by advocating for further research and collaboration to address these challenges and unlock blockchain's full potential in streamlining and enhancing CCA practices.

Chapter 12 provides a detailed analysis of the legal and regulatory considerations surrounding blockchain applications, particularly within the built environment. It highlights the importance of understanding the legal frameworks governing these applications and the need to ensure their grounding in legal reality for long-term resilience. The chapter examines the legal implications of tokenisation, considering various types of tokens and their potential to represent property rights or financial instruments. It also investigates the legal aspects of smart contracts, highlighting the distinction between 'smart contracts' and 'smart legal contracts' and the potential legal risks associated with different types of smart contracts. The chapter exposes the complexities of tokenisation and fractionalisation, and the regulatory challenges of applying existing laws like the General Data Protection Regulation (GDPR) and financial regulations to blockchain-based systems. Practical examples, such as the risks of pseudonymity, asset entanglement and data immutability highlight the need for careful planning and strategic design to navigate these challenges. Based on an analysis of international regulatory approaches, the chapter provides a roadmap for stakeholders to adopt blockchain technology responsibly. The chapter stresses the importance of collaboration between legal experts, technologists and policymakers to address gaps and foster innovation while maintaining trust and accountability.

Building on these summaries and their respective full chapter, the following section analyses cross-cutting themes that emerge across the book, connecting individual chapters to broader discussions on blockchain's role in transforming the built environment.

13.2 Cross-cutting themes

This book examines the transformative potential of blockchain and DLT in addressing systemic challenges within the construction industry and the built environment. This section highlights the cross-cutting themes that emerge across the chapters. A summary can be seen in Table 13.1.

13.2.1 Blockchain as a systematic challenge

Blockchain technology, with its inherent attributes of transparency, immutability and decentralisation, offers **transformative solutions at the system level**. The built environment is challenged by long-standing inefficiencies, fragmentation into silos and trust deficits. Blockchain can offer a novel approach to these challenges, but requires a full system's deployment, which can be quite challenging. Chapter 3 argues that blockchain can automate processes via smart contracts and help to reduce or eliminate these bottlenecks such as delays in payment processing, documentation

Table 13.1 Summary of themes found in this book

Theme	**Mechanism**	**Contributing chapters**
Blockchain as a systematic solution	Addressing systematic inefficiencies, silos and trust deficits through transparency, immutability and decentralisation	2, 3, 9, 11
Blockchain and socio-technical systems	Balancing technology with social, organisational and governance factors; reconfiguring roles in construction contract administration.	3, 8, 11, 12
Integration with digital technologies	Enhancing GIS, IoT, digital twins and common data environments for traceability, transparency and project management.	5, 9, 10
Data security and digital trust	Ensuring confidentiality, integrity and availability through decentralised systems; enhancing trust via tamper-proof ledgers and smart contracts.	4, 9, 11
Tokenisation and Democratisation	Enabling fractional ownership, broader market participation and sustainability investments through tokenised assets and systems.	5, 6, 7, 12
Collaborative and Decentralised Governance	Decentralising decision-making and enhancing stakeholder coordination, shared authorship and contract administration.	3, 8, 11
Sustainability and circular economy	Promoting green technologies, lifecycle tracking, renewable energy trading and resource efficiency through blockchain applications.	5, 6, 7

errors and misaligned projects schedules. Chapter 9 illustrates how blockchain can bridge these silos by providing a unified platform for information sharing and collaboration in supply chain management. Chapter 11 emphasises trust deficits as a critical challenge in construction, where disputes and opportunistic behaviours are common. This book shows how blockchain's transparency and immutability offer potential system's level approaches to ensure that transactions and changes are recorded and verifiable, improving integration and trust among all stakeholders.

13.2.2 Blockchain and socio-technical environments

Blockchain implementation requires a holistic approach that **balances technological innovation with social, organisational and governance factors**. Chapter 3 explicitly situates blockchain adoption within STS theory, emphasising the interplay between technology, processes and societal factors. It advocates for a MLP that integrates dimensions such as policy, organisational culture and stakeholder dynamics alongside technical capabilities.

Chapter 11 examines blockchain's impact on CCA through a socio-technical lens, highlighting how the technology reconfigures traditional roles and interactions among stakeholders. Blockchain's transparency and immutability enhance trust and accountability, reducing opportunistic behaviours and facilitating smoother coordination. The chapter also stresses the importance of aligning blockchain solutions with existing organisational processes to ensure successful integration.

Chapter 12 contributes to the STS theme by examining how blockchain adoption in construction must align with legal and regulatory frameworks to address jurisdictional inconsistencies, operational risks and data protection laws. It highlights the integration of technological innovations such as smart legal contracts and tokenisation with solutions like cryptographic protocols and identity segregation to balance automation with compliance. The chapter explores cross-border regulatory challenges and financial frameworks, emphasising the importance of adapting blockchain applications to diverse legal and cultural contexts for operational resilience.

By framing blockchain as a STS, these chapters collectively highlight the importance of integrating human, organisational and technological dimensions to unlock the full potential of blockchain in the built environment.

13.2.3 Blockchain integration with digital technologies

The integration of blockchain with key digital technologies in construction and the built environment elevates it from a standalone solution to a *foundational element of a connected and interoperable digital ecosystem*.

Blockchain's integration with GIS is highlighted in Chapter 5, particularly in the context of property tokenisation and urban analytics. Blockchain enhances GIS by providing a secure platform for managing geospatial data linked to property assets. This integration supports applications such as urban planning, infrastructure visualisation and environmental impact assessment. Tokenised property systems benefit from this synergy as blockchain ensures the integrity of ownership data while GIS provides spatial insights for decision-making. Chapter 9 demonstrates how IoT-enabled sensors combined with blockchain enhance traceability and transparency in modular construction supply chains. Chapter 10 explores the integration of blockchain with digital twins and CDEs, highlighting the importance of real-time data observability and enhanced project management in large-scale infrastructure projects. By providing immutable data trails and ensuring secure access control, blockchain enhances the functionality of CDEs in managing complex, multi-stakeholder infrastructure projects. This integration addresses challenges such as data fragmentation, version control and unauthorised access, creating a more robust data management ecosystem.

These synergies highlight blockchain's potential as a key component of integrated digital ecosystems. This theme further underscores two key aspects: the necessity of interdisciplinary approaches to technology adoption and the imperative to address the challenges of technological complexity and scalability inherent in the integration of diverse technologies.

13.2.4 Data security and digital trust

Data security and trust enhancement are key advantages of a blockchain-based system. Chapter 4 critiques centralised data security models and advocates for decentralised systems using blockchain and encryption technologies to ensure data confidentiality, integrity and availability in AECO projects. By removing reliance on single points of failure, blockchain enhances the resilience of data systems, particularly in projects involving sensitive BIM models or other high-value data assets. Chapter 9 applies blockchain's tamper-proof ledger to enhance trust among supply chain stakeholders. Blockchain's immutability ensures that all transactions and records are verifiable, creating a single source of truth for stakeholders. This is particularly valuable in cross-border modular construction projects, where trust is often compromised due to inconsistent or inaccessible data. By providing a transparent ledger of material provenance and movement, blockchain enables seamless collaboration and reduces the risk of fraud or miscommunication. Chapter 11 highlights how blockchain-based smart contracts improve trust in CCA by automating compliance and reducing disputes. Self-executing agreements can enforce terms and conditions and enhance compliance. Securing contractual obligations on an immutable ledger can also help in reducing opportunistic behaviours and fostering reliable stakeholder relationships.

This theme suggests that blockchain can bring some key contributions to the built environment, including decentralised resilience (i.e. addressing vulnerabilities in centralised systems by decentralising control and ensuring data confidentiality, integrity and availability, Chapter 4), trust in supply chains (fostering collaboration and reducing risks through tamper-proof auditable records, Chapter 9), automated compliance (streamlining contract administration by automating obligations and reducing disputes, Chapter 11), accountability and transparency (recording actions and transactions on an immutable ledger to promote stakeholder accountability, Chapters 9 and 11) and balancing transparency and privacy (using encryption and selective visibility to ensure data privacy while maintaining secure collaboration, Chapter 4).

13.2.5 Tokenisation and democratisation of access

Blockchain has the potential to *make ownership and investment more accessible and inclusive* across the built environment, through tokenisation and democratisation of access. Blockchain can be used to reduce financial barriers and foster broader participation in markets traditionally dominated by larger investors.

Chapter 5 discusses fractional ownership of real estate assets through blockchain-based tokens, making investment accessible to a broader demographic. By converting property ownership into blockchain-based tokens, investments can be divided into smaller tradable units, making them accessible to a broader demographic. This approach reduces entry barriers for small-scale investors and promotes more inclusive participation in real estate markets. Tokenisation also enhances liquidity by creating secondary markets for trading these digital assets, aligning with the broader goals of democratising property ownership. Chapter 7 extends this concept to renewable energy microgrids, enabling community participation in energy trading through tokenised systems. Tokenised systems allow individuals and organisations to trade renewable energy units, prioritising sustainability and local energy use. Chapter 6 incorporates tokenisation into the framework of DBLs, proposing it as an approach to incentivise investment in energy retrofitting and other sustainability initiatives. Blockchain tokens linked to DBLs can represent credits for energy savings or funding opportunities for green upgrades, aligning financial incentives with environmental goals. Chapter 12 examines legal and regulatory challenges for fractional ownership can be addressed. It highlights conflicts between blockchain's immutability and data protection laws, proposing solutions like cryptographic protocols to ensure compliance. The chapter explores tokenised asset classification under financial regulations, focusing on frameworks like the EU's MiCA and addressing risks such as anti-money laundering and know your customer compliance.

These contributions suggest the potential role of blockchain in transforming traditional economic models in the built environment and contributing towards more inclusive and sustainable systems.

13.2.6 Collaborative and decentralised governance

Blockchain can enhance collaboration, accountability and shared decision-making by *decentralising traditional hierarchical processes and transforming governance structures* in the built environment.

Chapter 8 illustrates how blockchain enables decentralised governance in architectural design workflows. By decentralising authority, blockchain empowers diverse stakeholders to contribute equitably to design processes, enabling shared authorship and reducing reliance on traditional, top-down governance structures.

Chapter 3 situates decentralised governance within the broader STS framework for blockchain adoption. It highlights the importance of governance as a socio-technical dimension, particularly in BIM-integrated systems where multiple stakeholders interact. Blockchain's ability to establish decentralised data ownership and transparent decision-making mechanisms is presented as key to overcoming challenges in stakeholder coordination and trust.

Chapter 11 extends the concept of decentralised governance to CCA. Blockchain's transparency and immutability enable the decentralisation of contractual functions, such as financial management, progress tracking and quality control. This decentralised approach is expected to reduce disputes, streamline coordination and enhance compliance, transforming traditional contract administration practices.

13.2.7 Sustainability and circular economy

Blockchain can play a key future role in a more sustainable and circular built environment, by aligning financial and operational practices with environmental goals.

Chapter 5 discusses how tokenisation of real estate assets can promote energy-efficient retrofitting by facilitating investment in green technologies. Chapter 6 introduces blockchain-enabled DBLs to track building lifecycle data and support circular economy principles. Chapter 7 explores blockchain's role in renewable energy trading within seaport microgrids, emphasising its potential to decarbonise energy systems and reduce operational emissions.

These cross-cutting themes demonstrate blockchain's multifaceted impact across the built environment. They connect blockchain's applications and technical features, such as data security and interoperability, with broader societal goals, including sustainability, inclusivity and collaborative governance. By addressing these recurring aspects across the chapters, this book establishes a transformative and innovative technology within the built environment. However, the adoption and implementation of blockchain are accompanied by significant challenges that are examined in detail in the following section.

13.3 Key challenges

Although blockchain demonstrates significant potential for the built environment, as previously discussed, its widespread adoption faces some critical challenges. These challenges encompass legal and regulatory constraints, scalability and performance, integration with legacy systems, data quality and reliability, fragmentation of standards and protocols, ethical and social concerns, and stakeholder resistance and adoption barriers. These challenges underline the intricate nature of implementing blockchain in a fragmented and highly regulated sector. The following subsections provide a detailed examination of these challenges.

13.3.1 Legal and regulatory challenges

Legal and regulatory considerations constitute a significant barrier to the adoption of blockchain technology, both broadly and in relation to the specific applications discussed in this book. The implementation of tokenisation and fractional ownership, as discussed in Chapter 5, faces jurisdictional inconsistencies and the lack of standardised property and financial laws across regions. Similarly, Chapter 11 highlights the uncertainties surrounding the enforceability of smart contracts in CCA, including issues related to digital signatures, liability and dispute resolution. Chapter 12 further expands on broader regulatory concerns, including compliance with data protection laws such as GDPR, token classification and financial reporting obligations. These legal complexities underscore the importance of harmonising regulatory frameworks to support technology adoption while preserving accountability and compliance.

13.3.2 Scalability and performance limitations

Blockchain systems are often challenged by efficient scalability, particularly in applications requiring high transaction throughput or real-time data updates. Chapter 2 outlines the technical limitations of existing blockchain platforms, such as slow transaction speeds and high operational costs, which are also evident in supply chain applications (Chapter 9) and energy microgrids (Chapter 7). Improving blockchain scalability and reducing associated costs are critical steps for enabling its adoption in large-scale time-sensitive projects.

13.3.3 Integration with legacy systems

The integration of blockchain with existing legacy systems presents significant technical and operational challenges. Chapter 6 highlights difficulties in incorporating blockchain into traditional data management systems, such as DBLs, while Chapter 10 emphasises the need for interoperability between blockchain, BIM and digital twin systems. Additionally, Chapter 5 points to the challenges of aligning blockchain-based tokenisation platforms with legacy property registries and financial systems. Ensuring seamless integration is essential to leveraging blockchain's full potential while maintaining its interface with existing processes and practices.

13.3.4 Data quality and reliability

The effectiveness of blockchain systems depends heavily on the accuracy and reliability of data inputs that are often provided through external oracles (software, hardware, humans). Chapter 2 highlights the challenges of ensuring trustworthy oracle connections between off-chain sources and blockchain systems, emphasising that the accuracy of data feeds directly impacts the integrity of blockchain processes. Similarly, Chapters 9 and 11 identify data quality issues as potential risks in supply chain management and CCA, respectively, where inaccurate inputs can undermine the integrity of smart contract automation. Developing reliable oracle solutions is critical to addressing these vulnerabilities. Chapters 2 and 9 raise the need for AEC-specific oracles capable of validating and verifying data from diverse sources such as IoT devices, project schedules and material inventories.

13.3.5 Fragmentation of standards and protocols

The absence of standardised blockchain protocols creates fragmentation, impeding interoperability and scalability across platforms. Chapter 5 discusses the challenges posed by inconsistent standards in tokenised property systems. Token classification, data structures and smart contract functionalities often vary across platforms, making it difficult to establish a unified marketplace for tokenised real estate. Chapter 10 highlights similar issues facing the integration of blockchain with BIM and digital systems. Chapter 12 discusses the broader implications of fragmented standards on regulatory compliance. Blockchain systems operating under varying protocols may struggle to meet legal requirements for data protection, financial reporting and auditability (e.g. classification of tokens and smart contracts differing across jurisdictions create regulatory uncertainty and complicate cross-border implementations).

13.3.6 Ethical and social implications

Blockchain adoption raises important ethical and social considerations including issues of privacy, equity and unintended consequences. Chapter 8 highlights potential inequities in decentralised governance models, where power dynamics may still favour certain stakeholders. The chapter calls for equitable governance in decentralised governance models to ensure fair participation and prevent the consolidation of power among a few dominant stakeholders. Chapter 3 identifies the broader ethical responsibility of balancing technological innovation with social equity. Blockchain, as a STS, can inadvertently exclude stakeholders who lack access to necessary resources such as technological infrastructure, funding or expertise. The chapter calls for a socio-technical approach to blockchain adoption that prioritises education, capacity-building and stakeholder engagement to bridge these gaps and foster inclusive participation. Chapter 12 discusses the risks of privacy breaches and data misuse in blockchain systems, identifying the need for privacy-preserving technologies such as zero-knowledge proofs and selective encryption to address these risks and ensure ethical data management.

13.3.7 Stakeholder resistance and adoption barriers

Resistance from stakeholders is another critical barrier to blockchain adoption. Chapter 3 identifies the lack of pervasive awareness and the limited technical understanding of blockchain systems as a barrier causing hesitation and resistance to adoption among project participants. Chapter 11 highlights the trust deficits and competitive concerns that often accompany the introduction of blockchain. Traditional stakeholders may view blockchain systems, especially smart contracts, as disruptive to their roles or authority (e.g. loss of control and fear of transparency). Addressing these adoption barriers requires targeted education, demonstration projects and clear communication of blockchain's value propositions.

These challenges collectively highlight the multifaceted barriers to blockchain adoption in the built environment. The complexities of legal and regulatory frameworks, limitations related to scalability, challenges associated with integration and resistance from various stakeholders necessitate a unified endeavour among technologists, policymakers and industry leaders. Tackling these challenges through targeted research, collaborative efforts and the development of flexible and responsive frameworks – that respond dynamically to the unique and changing needs of the built environment – will be crucial for unlocking blockchain's potential.

13.4 Ecosystem barrier to blockchain diffusion in the built environment

Blockchain is a systemic innovation that affects entire ecosystems rather than isolated entities [1]. As a result, its success will heavily depend on the ecosystem dynamics and the effectiveness of orchestrators within the prevalent ecosystem. For instance, Papadonikolaki *et al*. [1] found that the innovation ecosystem for construction blockchain is moving towards the open innovation ecosystem. In an open innovation ecosystem, open-source consortia are identified as the preferred orchestrators due to their ability to facilitate collaboration and innovation by providing a platform for various stakeholders to contribute and share resources [1]. However, the study also identified elements of closed and hybrid innovation ecosystems for construction blockchain. In the closed ecosystem, contractors were identified as key orchestrators with responsibility for managing and controlling the innovation processes within a more restricted and controlled environment. However, contractors' effectiveness as orchestrators is challenged by: (1) narrow profit margin which makes it challenging for them to invest in and lead the blockchain innovation ecosystem. They need to ensure that any orchestration efforts lead to efficiency gains and quicker processes to justify the investment [1]; (2) inability to exert influence over the entire ecosystem [1]; and (3) they are often seen as traditional stakeholders who may view blockchain systems and smart contracts as disruptive to their roles or authority (e.g. loss of control and fear of transparency), as identified in Chapter 11. In between, the two ecosystems (i.e. closed and open), there is the hybrid ecosystem that requires orchestrators to switch between different modes of orchestration – ranging from more controlled, closed approaches to more open, collaborative ones – depending on the challenges and needs of the network [2]. While hybrid ecosystems for blockchain have challenges such as managing the balance between open and closed efforts to ensure that the ecosystem remains dynamic and responsive to changes, they offer the opportunity for orchestrators to leverage diverse capabilities and resources from both internal and external sources, fostering innovation and growth [2]. Within the hybrid construction blockchain ecosystem, Papadonikolaki *et al*. [1] identify contractors, software vendors, consortia, SMEs and insurance companies as key orchestrators, with each playing a role based on their strengths and capacities to manage and facilitate innovation.

Another significant hurdle for blockchain adoption in the AECO sector is the weak ecosystem of start-ups. Start-ups are uniquely positioned to address the complexities of technology adoption in the AECO industry [1] due to their agility in rapid prototyping and iteration of solutions. Start-ups are also best positioned to address the specialised and niche blockchain applications tailored to the intricate workflows of AECO projects. To date, research on which blockchain innovation ecosystem is best for fostering the growth of construction blockchain start-ups is insufficient. However, emerging evidence suggests that closed systems – found to be prevalent in the current construction blockchain innovation ecosystem [1] – deter the development of a vibrant start-up ecosystem. For instance, Papadonikolaki *et al.* [1] observed that although hybrid elements exist within construction blockchain innovation ecosystems, the predominant inclination towards closed systems restricts the potential for start-ups to thrive. Blockchain technologies rely on interconnected networks of developers, infrastructure providers and end-users, where start-ups play a critical role in amplifying network effects. Sadeghi *et al.* [3] suggest that establishing a supportive ecosystem, particularly one that includes active participation from start-ups, could significantly accelerate the adoption and diffusion of blockchain in the built environment. Start-ups accelerate the development of interoperable tools, standardisation efforts and shared knowledge. However, the current predominantly closed innovation ecosystem for construction blockchain appears to undermine its potential within the built environment.

Finally, blockchain adoption in the construction sector is significantly hindered by a lack of readiness for business model transformation. Challenges identified earlier in this chapter, such as legal and regulatory uncertainties and the absence of standardised frameworks, further exacerbate this issue [4,5]. Additionally, the construction sector's traditional competitive culture and inadequate levels of collaboration contribute to an environment that perpetuates the currently prevalent closed-ecosystem model, as previously discussed. Consequently, many blockchain applications remain in the early stages of prototype development. However, with the ongoing shift towards open and hybrid innovation models [1], greater scaling and commercialisation are anticipated in the near future [6].

13.5 Recommendations

Building upon the challenges and barriers identified throughout the book and synthesised in this chapter, this section presents a structured set of recommendations. These recommendations are adapted from the WEF blockchain framework [7]. While the original framework is not explicitly tailored to construction, its recommendations have been refined to address the specific context of the AECO sector (Table 13.2).

13.6 Final reflection

As blockchain technology matures, its integration into the built environment has the potential to reshape how we design, construct and manage our buildings and infrastructure. Building a functional and effective blockchain ecosystem for the AECO industry necessitates a collective effort to move beyond proof-of-concept stages.

Table 13.2 Recommendations for blockchain adoption in the AECO sector

Theme	**Action items**
Strategic alignment	• Identify clear objectives and use cases for blockchain implementation, ensuring the technology addresses specific challenges or pain points such as inefficiencies, lack of trust or manual errors in AECO processes. • Explore opportunities where blockchain can drive systemic and disruptive transformations such as redefining procurement models, enabling decentralised decision-making or fostering new collaborative business models that challenge traditional practices. • Conduct thorough feasibility assessments to ensure blockchain is the appropriate solution for the challenges identified.
Stakeholder engagement	• Involve relevant stakeholders including clients/employers/owners, designers, contractors, regulators and end-users early in the adoption process to align and understand expectations and foster trust. • Facilitate open discussions to ensure alignment on the value blockchain brings to each stakeholder's operations.
Regulatory and legal readiness	• Engage with regulators to clarify legal uncertainties and encourage supportive policies for blockchain adoption (e.g. evaluate existing regulatory frameworks that govern data privacy, smart contracts and blockchain usage in the AECO sector). • Collaborate with policymakers to support the development of regulations that support blockchain while ensuring accountability and data security.
Technology and interoperability	• Prioritise interoperability to ensure the blockchain system can interact seamlessly with other digital technologies (BIM and IoT) and legacy systems. • Develop standardised protocols and interoperability frameworks for oracles that can feed verified AECO data (e.g. from supply chains, construction schedules and performance monitoring systems) into blockchain platforms. • Select a blockchain platform based on specific use-case requirements such as scalability, security, data throughput and ease of integration with existing technologies like BIM and IoT.
Governance framework	• Establish governance structures tailored to blockchain networks in the AECO sector, incorporating decision-making protocols, conflict resolution mechanisms and defined participant roles. • Ensure transparency, accountability and equitable participation while enabling the alignment of network rules with existing regulatory and contractual requirements in AECO projects.

(Continues)

Table 13.2 (*Continued*)

Theme	Action items
Pilot projects and prototyping	• Implement pilot projects to test blockchain applications in controlled low-risk environments but real-world scenarios (project bidding, procurement or compliance tracking). • Use these pilots to identify potential barriers and refine the system.
Risk and impact assessment	• Conduct comprehensive risk assessments to identify technical, operational and reputational risks associated with blockchain deployment. • Use impact metrics (e.g. improved supply chain transparency, reduced payment delays or enhanced compliance tracking) to evaluate blockchain's contributions to operational efficiency, cost reduction and trust-building in AECO processes.
Collaboration and ecosystem building	• Foster collaboration among AECO industry stakeholders to share resources, knowledge and best practices for blockchain adoption accelerating the identification of use cases, streamlining implementation efforts and reducing duplication of resources. • Promote the development of industry consortia or working groups to drive standardisation and collective innovation in blockchain for AECO.
Performance monitoring	• Establish clear key performance indicators (e.g. measuring improvements in supply chain visibility, reduction in payment processing times, enhanced data security and compliance with project requirements) to track the blockchain system's efficiency, transparency and cost-effectiveness over time. • Collect feedback from stakeholders in AECO projects to improve and adapt the blockchain system to establish whether the blockchain solution aligns with evolving industry needs and expectations.
Scaling and long-term strategy	• Develop a long-term roadmap (with milestones, timelines and resource allocation) for scaling blockchain applications in the AECO sector, transitioning from pilot projects to broader implementation across the value chain (e.g. a staged approach implementing the system gradually to selected applications such as supply chain management, project collaboration and compliance tracking). • Use insights from pilot projects to identify best practices, address common barriers and refine strategies for deployment. Focus on building scalable, interoperable and user-friendly systems that deliver measurable benefits across all stages of the AECO value chain.

While the applications discussed in this book were primarily at the proof-of-concept stage, many were tested with real-world industry data and case studies, demonstrating significant positive impacts across several key areas: enhanced transparency and traceability (Chapters 5 and 9); improved efficiency and automation (Chapters 7 and 11); data security and reliability (Chapters 9 and 10); inclusivity and democratisation (Chapters 5, 6 and 8); lifecycle and sustainability management (Chapter 6); and trust and accountability (Chapters 9 and 11).

To translate these promising initial results into widespread industry transformation, a coordinated and collaborative approach is essential. Collaboration among industry professionals, policymakers and academic researchers – through initiatives such as fostering partnerships, developing standardised interoperability protocols, piloting projects and addressing regulatory challenges – will be crucial for successful blockchain adoption and long-term integration of blockchain technology into the built environment.

This book encourages stakeholders to regard blockchain not as a standalone solution but as an integral component of a broader collaborative effort to modernise the design, construction and operation of the physical built environment. While challenges persist, the opportunities for improvement through blockchain technology are considerable, as explored throughout this book.

This book also makes important contributions to the field of digitalisation in the AECO industry. Its originality lies in effectively bridging theoretical frameworks with practical applications of blockchain in the AECO. Key contributions include:

- **Novel frameworks** such as the socio-technical blockchain adoption frameworks (Chapter 3), decentralised governance models (Chapter 8), legal and regulatory frameworks (Chapter 12) and tokenisation frameworks (Chapters 5 and 6).
- **Emerging applications** of blockchain-enabled supply chain systems (Chapter 9), energy microgrids and renewable energy trading (Chapter 7), CCA (Chapter 11), data security in BIM and digital twins (Chapter 10), collaborative design in architecture (Chapter 8) and property tokenisation (Chapter 5),
- Detailed exploration of **legal risks and compliance challenges** (Chapter 12).
- **Novel technical approaches** involving blockchain integration with IoT, BIM and microgrid systems demonstrating the potential of the resultant solution in transforming existing practices and enabling new business models and organisational paradigms.

Finally, the findings of this book extend *beyond the scope of blockchain and the built environment*, providing valuable insights into broader discussions on digital transformation and sustainable development. These implications include fostering circular economies, enabling inclusive investment through tokenisation, enhancing trust and collaboration and promoting broader participation.

While many still argue that *blockchain is a solution in search of a problem*, this book seeks to provide a balanced perspective by integrating evidence-based insights from practical applications with acknowledgement of its limitations and challenges. In doing so, it avoids speculative claims and focuses on the real-world potential of blockchain, which, although slowly emerging, shows promise.

We hope this book motivates stakeholders across academia, industry and policy to engage actively with blockchain's potential, not just as a technology but as a future catalyst for innovation, inclusivity and resilience.

References

[1] Papadonikolaki E, Tezel A, Yitmen I and Hilletofth P. Blockchain innovation ecosystems orchestration in construction. *Industrial Management & Data Systems*. 2022;123(2):672–694. https://doi.org/10.1108/IMDS-03-2022-0134.

[2] Reypens C, Lievens A and Blazevic V. Hybrid orchestration in multi-stakeholder innovation networks: practices of mobilizing multiple, diverse stakeholders across organizational boundaries, *Organization Studies*. 2019; 42(1):61–83. https://doi.org/10.1177/0170840619868268.

[3] Sadeghi A, Vafadarnikjoo A, Borrmann A and Kerschbaum F. A framework for trustworthy data management using blockchain in construction ecosystems. *IEEE Access*. 2023;11:61034–61048. Available from: https://ieeexplore.ieee.org/document/10125997.

[4] Xu Y, Chong HY and Chi M. Modelling the blockchain adoption barriers in the AEC industry. *Engineering, Construction and Architectural Management*. 2023;30(1):125–153. https://doi.org/10.1108/ECAM-04-2021-0335.

[5] Wu H, Zhong W, Zhong B, Li H, Guo J and Mehmood I. Barrier identification, analysis and solutions of blockchain adoption in construction: a fuzzy DEMATEL and TOE integrated method. *Engineering, Construction and Architectural Management*. 2025;32(1):409–426. https://doi.org/10.1108/ECAM-02-2023-0168.

[6] Nguyen B, Buscher V, Cavendish W, Gerber D, Leung S, Krzyzaniak A and Flapper T. *Blockchain and the Built Environment*. London: Arup; 2019.

[7] World Economic Forum. *Redesigning Trust: Blockchain Deployment Toolkit*. Geneva: World Economic Forum; 2020 [cited 2024 Dec 4]. Available from: https://widgets.weforum.org/blockchain-toolkit/pdf/WEF_Redesigning_Trust_Blockchain_Deployment%20Toolkit.pdf [accessed 1 December 2024].

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Blockchain, Smart Contracts and Distributed Ledger Technologies in the Built Environment

Key concepts, technologies, and applications

The built environment, encompassing the spaces we inhabit, the infrastructure that connects us, and the systems that sustain our societies, is foundational to human progress. It shapes how we live, work and interact, serving as a fundamental for social and economic prosperity. Yet, despite its importance, the sector faces enduring challenges: inefficiencies, insufficient collaboration, significant environmental impact, and a slow pace of transformative innovation, particularly in areas such as value creation, business model evolution, and major sector-wide transformations.

Digitalisation and digital transformation, driven by technologies such as building information modelling (BIM), the internet of things (IoT), artificial intelligence, and immersive technologies, have become essential in helping the sector address these issues. More recently, distributed ledger technologies (DLT), such as blockchain and self-executing contracts like smart contracts, have emerged, offering further opportunities for the built environment.

Emerging evidence, as explored in this book, highlights DLT's capabilities in transparency and trust (immutable records and enhanced accountability), efficiency and automation (smart contracts and streamlined processes), data security (decentralised integrity), collaborative governance (shared decision-making), tokenisation (democratised ownership), integration (synergy with digital twins, BIM and IoT), and sustainability (circular economies, renewable energy). However, adoption in the built environment faces several challenges, including legal, technical, ethical and stakeholder barriers.

Combining theoretical and practical perspectives, this book examines the potential of blockchain and DLT in both the delivery and management of the built environment, addressing their adoption frameworks, applications and associated benefits and challenges.

Intended for researchers, practitioners, students, technology developers and policymakers, *Blockchain, Smart Contracts and Distributed Ledger Technologies in the Built Environment: Key concepts, technologies, and applications* is a comprehensive guide to the adoption and integration of DLT in the built environment.

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