

## Introduction

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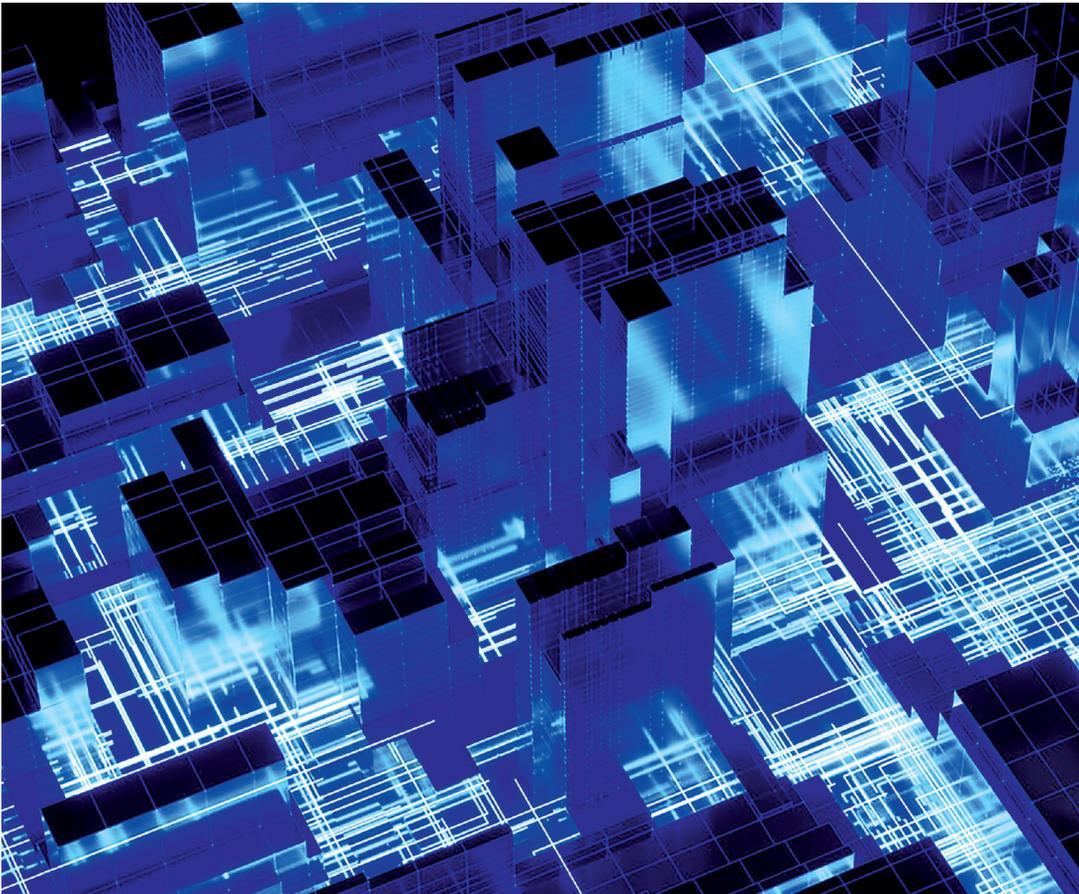
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# Blockchain, Smart Contracts and Distributed Ledger Technologies in the Built Environment

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 1

# Introduction

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The construction sector serves as a cornerstone of national and global economies, driving societal and economic development. It is intricately linked to the three pillars of sustainability: society, economy and environment, positioning it as a critical sector in shaping a sustainable future. The construction sector is a major consumer of natural resources and a significant contributor to global carbon emissions and waste.

Construction and built environment projects are typically characterised by hierarchical, interconnected supply chains and complex payment systems, often causing payment delays and financial strain for those positioned lower in the project hierarchy, frequently small and medium-sized enterprises. Many procurement delivery models used within the industry further reinforce this hierarchy, limiting collaboration and exacerbating these challenges. A persistent issue within the sector is information asymmetry and imperfect information, where stakeholders either lack equal access to critical data or rely on incomplete or inaccurate information. These challenges are intensified by the inherent complexity of construction projects, characterised by diverse stakeholders, complicated workflows and significant uncertainties. As a result, misunderstandings, disputes and delays are often the norm, hindering growth and development within the construction industry.

The sector's low productivity, especially when compared to other industries, remains a significant concern. Digital innovation holds the potential not only to address process inefficiencies but also to transform the industry by enabling new forms of organising innovative business models and new methods for value creation. Due to their anticipated value, digital transformation initiatives and digitalisation technologies are being increasingly promoted to address key challenges within construction and the built environment. Progress is being made, albeit at a measured pace, due to the industry's cautious approach to adoption. This measured pace is constrained by factors such as the evolving maturity of these technologies, disparities in technical expertise across the workforce and concerns regarding the financial investments required.

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## 2 *Blockchain, smart contracts and DLT in the built environment*

Among these digital technologies, blockchain and distributed ledger technologies (DLT) present promising opportunities for transforming construction and the built environment. Early applications of blockchain and DLT are beginning to emerge and reveal their potential not only in addressing technical inefficiencies but also in enabling novel approaches to organisation, innovative business models and value creation. While still in their infancy, blockchain and DLT are evolving rapidly, presenting substantial opportunities for the sector's future development. At this critical juncture, it is essential to evaluate the implications of these technologies to fully understand their impact.

This book comes at the right time to investigate how these technologies might shape the future of construction and the built environment. To achieve this, the book brings together leading academics and practitioners from around the world to examine the intersection of blockchain and the built environment. It explores a wide range of blockchain applications, showcasing how these innovations can transform traditional processes, enhance transparency and drive innovation across multiple domains.

The book's chapters provide a comprehensive exploration of blockchain and DLT technology, progressing from foundational technical concepts to practical implementations and offering a cohesive understanding of its role as a driver for change. Covering a wide range of themes and applications – including information security in built environment projects, tokenisation of built assets, energy management, decentralised design governance, digital building logbooks (DBLs), supply chain management, contract management, legal perspective and the macro and meso implementation roadmaps – this book presents a comprehensive and multifaceted exploration of blockchain's relevance to construction and the built environment.

To provide a clear understanding of the book's structure and scope, the following sections provide an overview of its chapters. This summary outlines the key themes, applications and insights explored in each chapter, demonstrating how they collectively contribute to a comprehensive understanding of blockchain's potential in construction and built environment sector.

Chapter 2 provides a technical yet accessible overview of DLTs, focusing on blockchain as the most prominent example. The chapter thoroughly explains the blockchain's structure, including its distributed nature, cryptographic security and consensus mechanisms. Differences between permissioned and permissionless blockchains are detailed, offering examples such as Bitcoin (permissionless) and Hyperledger Fabric (permissioned).

The chapter clarifies the concepts of smart contracts and oracles, highlighting how they extend blockchain's functionality beyond cryptocurrencies to enable secure, automated transactions and data exchanges, with applications tailored to construction such as automated payments and real-time tracking of materials. By outlining the key benefits and capabilities of blockchain – including immutability, transparency and enhanced trust – the chapter presents a conceptual model for justifying blockchain-based applications. It further examines examples from the literature to illustrate blockchain's potential in addressing inherent challenges

within the construction industry, setting the stage for a deeper exploration of its adoption at macro and meso levels and its framing as a socio-technical system (STS) in the following chapter.

Chapter 3 examines the adoption of blockchain and DLT in the construction industry, utilising STS theory to analyse the interplay between social and technical factors influencing adoption. The authors provide a historical overview of STS theory and establish its relevance to the built environment, particularly in addressing persistent challenges such as information inadequacy, unreliability and asymmetry among stakeholders.

The chapter introduces key conceptual models, including a four-dimensional framework that integrates the dimensions of technology, process, policy and society. This framework is employed as an analytical tool to evaluate blockchain applications and identify challenges and opportunities for implementation. Additionally, the authors present the “DLT Actors Model,” which maps the roles and responsibilities of stakeholders within the blockchain ecosystem, providing a structured approach to adoption strategies. Roadmaps for macro- and meso-level implementation are also proposed, offering strategic insights into the integration of blockchain and DLT within construction workflows. These roadmaps emphasise the importance of aligning technological innovation with organisational and societal needs, addressing barriers to adoption and enhancing trust and collaboration.

Chapter 4 focuses on the growing importance of data security in the architecture, engineering, construction and operations (AECO) sector, driven by the widespread adoption of digital technologies such as building information modelling (BIM), unmanned aerial vehicles (e.g. drones) and other interconnected systems. The authors identify challenges stemming from the sector’s unique contract-based and collaborative structure, often resulting in risks such as unauthorised access, data manipulation and limited information-sharing trust among stakeholders. To address these issues, the chapter introduces a decentralised framework integrating blockchain technology, inter planetary file system (IPFS) and encryption protocols to enhance data confidentiality, digital trust and utility while mitigating vulnerabilities inherent in centralised data management systems. The proposed framework combines blockchain’s immutability and transparency with IPFS’s decentralised storage capabilities and selective transparency techniques, enabling the secure sharing of sensitive information without compromising functionality. The chapter also explores the use of smart contracts to automate and secure workflows, such as request for information processes, demonstrating how distributed technologies ensure traceability, accountability and robustness against tampering. Recognising the barriers to adoption, particularly for smaller subcontractors, the authors suggest incentive-based approaches to foster inclusivity and explore future research avenues, including real-time data classification using domain-specific models. This chapter underscores the potential of decentralised technologies to transform information management practices in construction and the built environment, ensuring greater security, collaboration and resilience.

Chapter 5 investigates the transformative potential of blockchain technology and tokenisation in the real estate sector, focusing on how these innovations can

enhance liquidity, transparency and inclusivity in property markets. The authors explore the challenges of a traditionally rigid and illiquid real estate market, particularly in countries like Italy, where regulatory barriers and a lack of digital maturity hinder investment and market fluidity. The chapter emphasises the role of property tokenisation as a paradigm shift, enabling fractional ownership, reducing entry barriers for small-scale investors and fostering broader participation.

The proposed tokenisation framework combines blockchain with GIS, BIM and smart contracts to create a decentralised and transparent system for real estate transactions. Key concepts include the creation of property tokens that represent fractional ownership of assets and their management via secure smart contracts. The integration of GIS and BIM supports precise asset localisation and detailed property information, enhancing decision-making and compliance. The authors highlight the socio-economic benefits of property tokenisation, including increased financial inclusion for underprivileged groups, opportunities for energy-efficient retrofitting and mechanisms to address housing affordability. Business models such as crowdfunding platforms, fractional ownership exchanges and real estate investment services are discussed, demonstrating the potential for innovative revenue streams and market expansion. Barriers to adoption, including regulatory uncertainties, technological infrastructure limitations and resistance to change, are addressed alongside potential solutions such as standardised protocols and collaboration with legal bodies like the Notary Council. The chapter concludes with a call for further research to refine the integration of tokenisation into real estate markets, underscoring its potential to drive sustainable development, reduce transaction inefficiencies and democratise property ownership.

Chapter 6 explores the concept of DBLs as a solution for managing building lifecycle data, aligning with the European Union's twin transitions of green and digital transformation. DBLs are presented as dynamic repositories capable of capturing detailed data on material composition, energy usage and operational performance, supporting transparency, informed decision-making and regulatory compliance within the built environment. The chapter identifies several barriers to implementing DBLs, including insufficient user incentives, high administrative costs and challenges related to data interoperability, privacy and security. Existing technical approaches, such as open BIM, centralised platforms and linked data, are critically assessed, revealing limitations in addressing long-term data storage, ensuring interoperability and fostering stakeholder participation. To overcome these challenges, the authors propose a blockchain-based approach, leveraging blockchain's inherent characteristics of trust, immutability and decentralised peer-to-peer transactions. They present a conceptual architecture for a blockchain-enabled DBL system comprising three integrated layers: a decentralised data layer, a logic and services layer driven by smart contracts to automate updates and manage ownership and a user layer featuring crypto-economic incentives to encourage active participation and data contributions. By combining legacy databases with decentralised systems such as IPFS, the proposed framework is proposed as a potential solution to ensure long-term data resilience while integrating existing datasets.

The chapter emphasises the ability of blockchain-enabled DBLs to foster circular economies, streamline building retrofits and enhance data security and privacy through advanced cryptographic mechanisms. The authors propose avenues for future research, including the development of legal frameworks tailored to blockchain adoption, refinement of business models to support sustainable practices and exploration of advanced blockchain technologies, such as zero-knowledge proofs, to balance privacy and transparency.

Chapter 7 investigates the application of blockchain technology in enhancing energy management within seaport infrastructure, focusing on a microgrid case study at the Port of Milford Haven in Wales. The chapter contextualises the growing energy demands of seaports, driven by refrigeration, air conditioning and other energy-intensive activities, which collectively contribute significantly to greenhouse gas emissions. The authors examine blockchain's role in decentralising energy management, particularly using Ethereum-based smart contracts.

The chapter introduces a blockchain-enabled microgrid framework that supports renewable energy integration, leveraging smart contracts for energy transfers and pricing while ensuring tamper-proof record-keeping. Using real-world data, two scenarios are analysed to evaluate the scalability and economic feasibility of the proposed framework. Scenario 1 focuses on five buildings within the port utilising locally produced renewable energy, while Scenario 2 scales up to include 200 additional community households. The analysis highlights significant cost implications tied to Ethereum's gas prices and the computational requirements of smart contracts. Although the system demonstrates potential for reducing energy costs and enhancing local energy resilience, the volatility of gas and cryptocurrency prices presents challenges to widespread adoption.

The chapter discusses key barriers, including the need for user training, hardware upgrades and ensuring the integrity of energy sources within the grid. It emphasises the importance of further research into private blockchain and centralised alternatives to overcome cost and scalability challenges.

Chapter 8 examines the potential of blockchain technology to decentralise architectural design processes by introducing innovative governance models and enabling collaborative, non-hierarchical approaches. The authors critique the traditional architectural design process as both autographic and extractive, arguing for a shift towards an allographic discipline where architecture becomes a decentralised collective endeavour. This transformation aligns with emerging technologies such as blockchain, IoT and AI within the context of the Fourth Industrial Revolution.

The chapter highlights blockchain's capacity to facilitate decentralised governance through mechanisms such as smart contracts, decentralised autonomous organisations (DAOs) and distributed data systems like IPFS. A series of prototypes are presented, demonstrating the integration of blockchain with architectural design tools like computer aided design and BIM to create systems for design collaboration, optimisation and decision-making. These include the development of shape grammars and DAOs as platforms for collaborative problem-solving and design governance. The authors discuss the application of stigmergy, a biological concept of self-organisation, to architectural collaboration, proposing decentralised

feedback loops and collective decision-making frameworks as alternatives to traditional hierarchies. Then, they introduce ArchiDAO, a blockchain-enabled organisation designed to support architectural design, research and learning, emphasising principles of equity, transparency and sustainability.

The chapter provides insights for transforming architectural practice into a more inclusive and sustainable discipline through decentralised design workflows. It highlights the potential for blockchain to address issues of trust, transparency and collaboration in architectural design while fostering innovation and democratising the creation of the built environment.

Chapter 9 investigates the role of blockchain technology in transforming construction supply chain management (CSCM) by tackling longstanding challenges, including inefficiencies, limited transparency and trust deficits among stakeholders. The authors introduce a blockchain-based CSCM system, outlining its design, architecture and workflows. A real-world case study of cross-border modular construction between Hong Kong and Mainland China illustrates the practical implementation of the system. The case study highlights how blockchain can improve data traceability, ensure the immutability of records and facilitate trust among stakeholders by creating a shared, tamper-proof ledger. Key considerations for implementing blockchain in CSCM, such as stakeholder engagement, cost-benefit analysis, scalability, interoperability and legal compliance, are also discussed in depth.

Blockchain's integration with technologies such as IoT and BIM is examined as a means to improve logistics tracking and material provenance. The chapter also identifies emerging opportunities, including digital identity management and DAOs, which have the potential to automate processes and enhance collaboration within CSCM. However, the chapter acknowledges significant barriers to blockchain adoption in CSCM, including regulatory uncertainty, resistance to change, scalability limitations and data privacy concerns. These challenges underscore the need for industry-wide collaboration, policy development and further research to unlock blockchain's full potential. The chapter concludes by emphasising the importance of stakeholder readiness, robust legal frameworks and scalable solutions for successful blockchain adoption in CSCM.

Chapter 10 explores the integration of blockchain technology within BIM, digital twins (DT) and enterprise common data environments (CDEs) to enhance data observability, traceability and governance in large-scale infrastructure projects. The chapter draws on a case study of a significant UK infrastructure initiative, using participatory observation and literature analysis to contextualise the challenges and opportunities of enterprise-level data integration. The authors highlight the limitations of traditional data management systems, particularly in handling fragmented and heterogeneous data across diverse stakeholders and systems. Blockchain technology is proposed as a transformative solution, offering immutable data lineage, enhanced transparency and decentralised control. Key applications include creating tamper-proof audit trails, managing data provenance and ensuring seamless interoperability between BIM and DT data within enterprise CDEs. A conceptual framework for enterprise data integration is presented, emphasising three core elements: decentralised data layers, logic and service layers and user layers

enabling stakeholder-specific access and collaboration. The framework integrates blockchain with legacy systems, leveraging hybrid architectures such as IPFS for distributed storage.

The chapter also introduces the concept of “golden records” to maintain consistent, authoritative data versions and discusses the importance of aligning enterprise data strategies with ISO 19650 standards for BIM and CDE workflows. Practical insights into addressing scalability, cost and user adoption challenges are provided, alongside recommendations for future research, including the integration of advanced technologies like AI and quantum computing.

Chapter 11 examines the integration of blockchain technology into construction contract administration (CCA) to address critical issues associated with traditional contract management, including inefficiencies, disputes and the mismanagement of contractual obligations. The chapter conceptualises CCA as a multi-functional system critical for project success, focusing on its core mechanisms: control, coordination and adaptation. Highlighting the challenges of poor CCA – including delays, cost overruns and disputes – the authors highlight the potential of blockchain to mitigate these issues through traceability, immutability and automation.

The authors perform a structured analysis of the blockchain’s applicability to key CCA functions, such as financial management, performance monitoring and document handling, using examples from the *FIDIC Red Book* (2017 edition). They propose blockchain-enabled smart contracts to automate payment processes, improve transparency in decision-making and ensure accurate real-time data for contract provisions. Use cases such as automated interim payments and performance monitoring with integrated IoT and blockchain systems demonstrate the technology’s potential to streamline workflows and minimise disputes.

The chapter identifies barriers to adoption, including technical challenges, the complexity of encoding contractual logic and the need for alignment with existing procurement frameworks. It recommends prioritising future research that fosters collaboration between scholars and contract drafting committees to develop scalable and context-specific solutions.

Chapter 12 presents a detailed legal perspective for the application of blockchain in construction and built environment applications. The chapter focuses on the intersection of physical assets, such as real estate and construction, with digital innovations like blockchain and tokenisation. The author acknowledges blockchain’s transformative potential but argues that its adoption is limited by jurisdictional inconsistencies, evolving regulatory landscapes and operational risks. The author distinguishes between smart contracts (automated execution) and smart legal contracts (binding agreements with coded elements), addressing challenges like ambiguity in contract formation and confidentiality risks.

The chapter examines tokenisation’s implications for fractional ownership, asset entanglement and intellectual property rights, highlighting conflicts between blockchain’s immutability and data protection laws such as the General Data Protection Regulation. To address compliance challenges, the author proposes solutions including cryptographic protocols and segregated identity systems. The chapter examines financial regulations applicable to cryptocurrencies, tokenised assets and

payment systems, with a focus on frameworks such as the UK's Financial Services and Markets Act and the EU's Markets in Crypto-Assets Regulation. It also addresses legal risks associated with token classification and compliance with Anti-Money Laundering and Know Your Customer regulations. Finally, the chapter explores cross-border legal challenges by comparing regulatory practices in jurisdictions such as Switzerland and Singapore. It examines practical applications of blockchain in areas like payment systems, DT and supply chain management, highlighting its potential to enhance transparency, automate compliance and ensure data authenticity.

The chapter provides practitioners, developers and legal professionals with guidance on integrating legal compliance into blockchain applications to achieve operational resilience and long-term success.

This concluding chapter summarises the key insights presented throughout this book. It identifies and analyses recurring themes, challenges and opportunities that emerge from the preceding chapters, aiming to connect individual contributions to a broader discourse on blockchain's role in addressing inefficiencies in the AECO industry.

The chapter begins by summarising the key contributions of each chapter, highlighting blockchain's foundational principles, its socio-technical implications and its application in domains such as supply chain management, CCA, property tokenisation and integration with DT and IoT systems. By doing so, the chapter underscores how this book bridges theoretical frameworks with practical applications.

The chapter identifies several cross-cutting themes, including blockchain's capacity to enhance transparency, decentralise governance, support lifecycle management and enable tokenisation for inclusive and sustainable practices. Challenges to blockchain adoption are analysed in detail, including legal and regulatory hurdles, scalability and performance limitations, integration with legacy systems and stakeholder resistance. These barriers are contextualised within the fragmented and complex nature of the built environment, underscoring the need for coordinated efforts to address them. The chapter also explores the dynamics of innovation ecosystems, identifying how open, closed and hybrid models influence the scalability and diffusion of blockchain in the AECO sector.

The chapter concludes with actionable recommendations adapted from the World Economic Forum's blockchain framework, tailored to the AECO sector. These include strategies for stakeholder engagement, regulatory alignment, pilot projects and the development of interoperable and scalable systems.

Ultimately, the conclusion calls for a collective effort among academia, industry and policy to realise blockchain's potential in the AECO sector. It positions blockchain not as a standalone solution but as an integral component of a broader effort to modernise the built environment. The chapter concludes with a reflection inviting stakeholders to regard blockchain as an enabler for fostering innovation, inclusivity and resilience in the AECO sector.