

Blockchain applications in the construction industry

Vagelis Plevris

Department of Civil and Environmental Engineering, College of Engineering, Qatar University,
Doha, Qatar

12.1 Introduction to blockchain technology

Blockchain technology represents a paradigm shift in how data are collected, stored, shared, and verified across a digital network. Blockchain was initially conceptualized to support the digital currency Bitcoin (Nakamoto, 2008). It was the technology that allowed Bitcoin to pioneer the decentralized transfer of value, marking a historic milestone in human history. Remarkably, many of the highly desirable features inherent to blockchain were present in Bitcoin, despite the fact that Bitcoin merely served as the very first manifestation of this technology. Since then, blockchain has rapidly evolved beyond its financial roots to become a foundational technology with the potential to revolutionize various industries, including construction.

At its core, blockchain functions as an immutable ledger, meticulously maintained across a vast network of computers. This decentralized approach to data management marks a significant departure from traditional centralized databases, which are fully controlled by singular entities or authorities. By distributing its ledger across numerous nodes, blockchain technology ensures an unparalleled level of transparency, security, and data integrity.

In the blockchain, every transaction or data entry is recorded as a “block.” These blocks are securely linked to one another in a sequential manner, forming a chronological chain of data—a process that lends blockchain its name. What makes blockchain particularly robust is its resistance to data tampering. Altering any historical information within a block would require the consensus of the majority of the network’s participants, a feat that is practically impossible to achieve without detection. This characteristic not only fortifies the blockchain against unauthorized alterations but also establishes a trustless environment where transactions and data exchanges can occur without the need for intermediary verification.

The technology's structure fosters a transparent and verifiable record-keeping system, where each participant in the network has access to the same version of the truth. This transparency, coupled with the security measures inherent in blockchain's design, ensures that the data within the blockchain remains intact and inviolable. As a result, blockchain technology holds the potential to revolutionize a wide array of industries, offering solutions that promise enhanced efficiency, reliability, and accountability in data management and transactions.

12.1.1 Computational aspects of blockchain

Blockchain technology harnesses sophisticated computational methodologies to ensure security, transparency, and integrity within its network. At its core, it utilizes asymmetric cryptography, enabling secure communication across a public network by employing a pair of public and private keys for each user. This cryptographic approach safeguards information against unauthorized access. Additionally, blockchain employs cryptographic hash functions, which convert input data of any size into a fixed-size string of characters. This process is crucial for maintaining the integrity of data blocks, as each block in the chain is identified by a unique hash that links it to the previous block, thereby creating an immutable ledger.

Digital signatures further enhance the security of transactions on the blockchain by allowing participants to verify the authenticity of a message or document. This is achieved by using the sender's private key to sign the transaction, which can then be verified by others using the corresponding public key. Merkle trees play a crucial role in efficiently summarizing and verifying the integrity of large sets of data. They allow for quick verification of whether a specific transaction is included in a block, making them indispensable in the design of blockchain networks.

The blockchain relies on consensus mechanisms to agree on the validity of transactions without the need for a central authority. Proof of Work (PoW) and Proof of Stake (PoS) are two such mechanisms. PoW, which is used in Bitcoin, requires participants to solve complex mathematical problems to validate transactions and create new blocks, a process known as mining. PoS, on the other hand, is an energy-efficient alternative where the creation of new blocks is based on the participants' stake or ownership in the cryptocurrency.

The consensus mechanisms within blockchain architecture are engineered to navigate the intricate balance known as the blockchain trilemma, a term that encapsulates the challenge of simultaneously optimizing decentralization, scalability, and security (Tripathi et al., 2023). Each of these attributes is crucial to a blockchain's functionality and overall efficacy. According to the trilemma, a blockchain network has the inherent constraint that it can perfect, at most, two out of these three critical properties at any one time, a concept visually depicted in Fig. 12.1. This diagram illustrates that by choosing any one side of the triangle—be it A, B, or C—one effectively opts to prioritize the corresponding corner properties, potentially compromising the property at the opposing vertex.

Understanding this trilemma is essential for developing blockchain solutions that can meet diverse needs without compromising foundational principles. Both PoW and traditional PoS models offer decentralized frameworks that allow all participants the

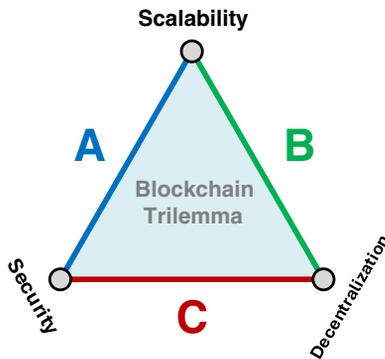


FIGURE 12.1 The blockchain trilemma.

opportunity to engage in the validation process. An alternative model known as “Delegated Proof of Stake” (DPoS) presents a more centralized approach. In DPoS, only a select group of individuals with verified identities are granted the authority to validate transactions and produce blocks, distinguishing it from its more decentralized counterparts.

Together, these advanced computational technologies form the backbone of blockchain, enabling it to revolutionize various industries by providing a secure, transparent, and decentralized platform for conducting transactions and managing data.

12.1.2 Key characteristics of blockchain technology

Blockchain technology is underpinned by a set of core characteristics that differentiate it from traditional digital systems and endow it with the potential to radically transform how we conduct transactions, manage data, and enforce agreements across various sectors. Understanding these key features is essential to appreciating the full scope of blockchain’s revolutionary impact.

Decentralization: At the heart of blockchain’s innovation is its decentralized nature. Unlike centralized systems, where control is vested in a single entity or organization, blockchain operates on a distributed peer-to-peer network. This fundamental structure ensures that no single party possesses absolute control over the entire chain. Such decentralization significantly diminishes the risks associated with data tampering, censorship, and centralized points of failure, fostering a more resilient and democratic data management system.

Transparency: Blockchain technology is synonymous with unparalleled transparency. Every transaction and piece of data recorded on the blockchain is visible to all network participants, ensuring that every action is subject to scrutiny. This level of openness is instrumental in building trust among users, as it guarantees that activities cannot be altered once they have been confirmed on the blockchain. This transparency ensures that all parties can conduct transactions with confidence, knowing that each operation is verifiable and permanent.

Security: Security is another cornerstone of blockchain. Utilizing advanced cryptographic techniques, blockchain secures data in a manner that renders it virtually tamper-proof. Each block within the chain is cryptographically linked to the previous one, creating a secure and unbreakable chain of data blocks. This structure not only protects against fraud and hacking attempts but also ensures the integrity of the entire blockchain, making it an ideal platform for secure and reliable transactions.

Immutability: Immutability refers to blockchain's ability to maintain an indelible and unalterable record of transactions or records. Once a transaction has been recorded on the blockchain, it is impossible to alter or delete it. This feature provides a robust foundation for data integrity, offering an auditable and transparent trail of transactions that can be verified by all network participants. The immutability of blockchain makes it a powerful tool for establishing trust and accountability in digital interactions.

Smart Contracts: Smart contracts represent a pivotal innovation within blockchain technology. These are self-executing contracts with the terms of the agreement embedded directly into the code. Smart contracts automatically enforce and execute the terms of a contract when predetermined conditions are met, eliminating the need for intermediaries. This automation not only streamlines the contract execution process but also introduces a level of efficiency, transparency, and security previously unattainable in traditional contract law.

These characteristics form the foundation of blockchain technology, enabling it to offer innovative solutions that are secure, transparent, and transformative. The potential applications of blockchain extend far beyond cryptocurrency, with the capability to revolutionize industries by providing a new framework for data management, transaction processing, and automated contractual agreements.

12.1.3 The importance of blockchain in various industries

Blockchain technology, characterized by its distinct features, has emerged as a transformative force in various industries, garnering significant attention for its potential to innovate and enhance operational efficiencies (Ahrum et al., 2017). Within the financial sector, blockchain serves as the foundational technology behind cryptocurrencies, facilitating secure and transparent transactions that are immutable and decentralized, thus offering a new paradigm for financial exchanges (Treleaven et al., 2017). In the realm of supply chain management (SCM), it revolutionizes how goods are tracked and authenticated, providing stakeholders with real-time visibility into the movement of goods and ensuring the integrity of the supply chain (Dutta et al., 2020).

The healthcare industry leverages blockchain to safeguard patient data, offering a secure platform for storing and sharing sensitive information while ensuring compliance with privacy regulations. Additionally, it streamlines the management of pharmaceutical supply chains, enabling the tracking of drug provenance and combating counterfeit medications (Bocek et al., 2017). In the construction sector, blockchain introduces groundbreaking opportunities for managing supply chains more efficiently, automating contract administration through smart contracts, enhancing project management with transparent

and immutable records, and revolutionizing land registry processes for more secure and efficient property transactions (Plevris et al., 2022).

Beyond these sectors, blockchain's impact extends to other fields such as digital identity verification, energy trading (Wongthongtham et al., 2021), and intellectual property (IP) rights management (Gürkaynak et al., 2018), demonstrating its versatility and potential for widespread adoption. Its ability to provide a secure, transparent, and tamper-proof ledger makes it an invaluable tool for enhancing trust, reducing fraud, and streamlining processes across a broad spectrum of industries. As blockchain technology continues to evolve, its role in driving innovation and improving industry standards is increasingly recognized, making it a critical component of the digital transformation landscape.

12.2 Bibliometric analysis

12.2.1 Papers published in the field

A cursory glance at recent scientific literature underscores the burgeoning significance of blockchain within the scientific community. In Scopus, a search for the term "blockchain" yields 59,556 documents when considering "Article title, Abstract, and Keywords" [Query string: "TITLE-ABS-KEY(blockchain)"]. Notably, 98.1% of these results (58,444 documents) were published in 2018 or later, indicating a substantial surge in interest within the past 6 years. Focusing solely on the field of engineering, the same search yields 25,309 documents (98.9% of which were published in 2018 or later), further emphasizing the widespread adoption and exploration of blockchain technology. These findings, as of March 20, 2024, are graphically depicted in Fig. 12.2, illustrating the exponential growth in scientific publications on blockchain from 2013 to 2023. Notably, the data for 2024 are excluded from the plot due to its ongoing nature, and it is important to acknowledge that indexing and adding papers to Scopus for 2023 is still underway. The sharp increase in publications reflects blockchain's expanding influence across various scientific fields, with the trend becoming apparent as early as 2019 and showing no signs of abating (Firdaus et al., 2019).

12.2.2 Bibliometric map for top keywords in the general engineering field

We conducted a co-occurrence analysis on prominent keywords sourced from both author and index keywords within the Scopus database. To execute this analysis, we initiated a search on Scopus using the term "blockchain" within "Article title, Abstract, and Keywords," limiting the search to the field of "Engineering" and focusing on publications from 2017 to 2024, encompassing an 8-year span. The complete query string, executed on March 20, 2024, reads as follows: "TITLE-ABS-KEY (blockchain) AND PUBYEAR > 2016 AND PUBYEAR < 2025 AND (LIMIT-TO (SUBJAREA, "ENGI"))". This query yielded 25,266 documents.

From this dataset, we identified the top 40 keywords associated with these papers. To ensure accuracy, similar keywords were manually merged. For instance, variations such as "block-chain," "blockchains," and "blockchain technology" were consolidated under the main keyword "blockchain." Similar adjustments were made for other keywords such as "internet of things," "smart contract," "supply chain," and "building information model."

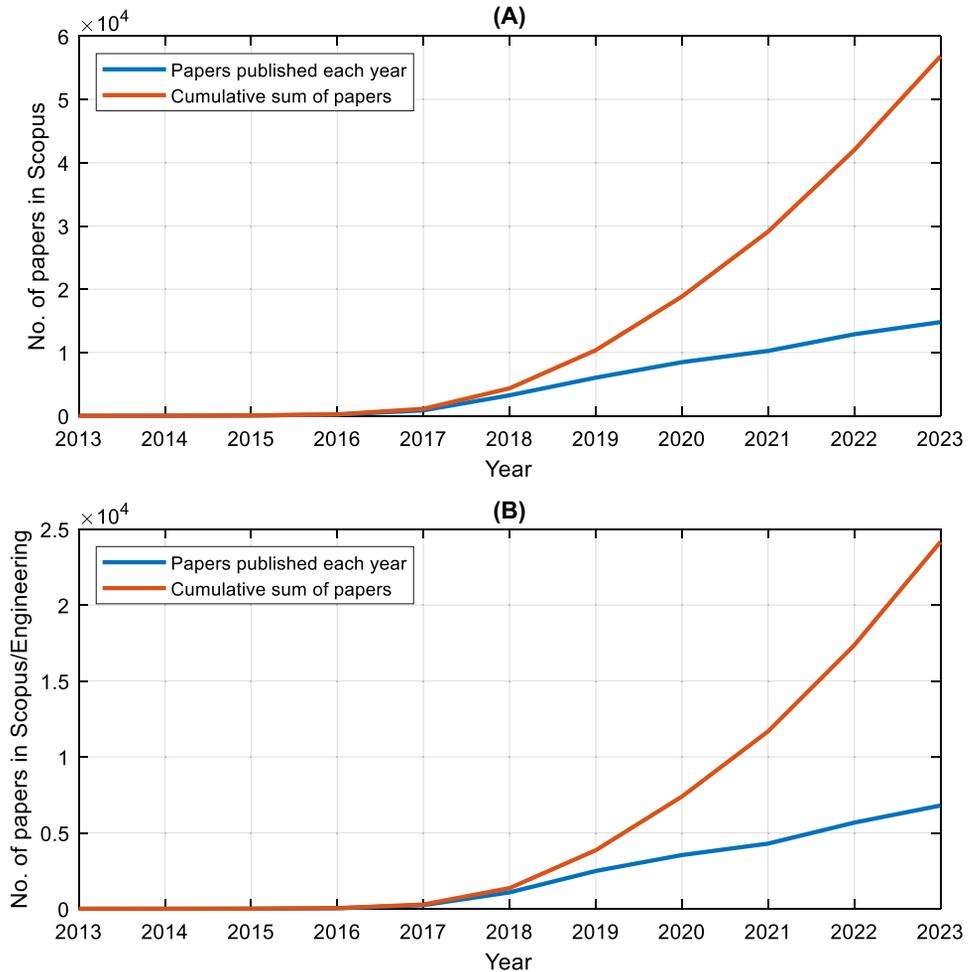


FIGURE 12.2 Papers in “blockchain,” per year: (A) search in all fields; (B) search limited within “Engineering.” Data source: Scopus.

The co-occurrence network visualization of the top 40 keywords is illustrated in Fig. 12.3. This visualization was generated using the VOSviewer software (Van Eck & Waltman, 2007), with five distinct clusters represented by different colors. A minimum strength threshold of 100 was applied to ensure clarity and relevance within the network.

In this visualization, the connections (lines) between keywords depict how often they co-occur within documents, while the size of each bubble (i.e., keyword) indicates the frequency of its occurrence. Unsurprisingly, the keyword “blockchain” occupies the central position in the network as the most prevalent term (21,474 occurrences). It is followed by “internet of things” (4325), “smart contract” (4094), “network security” (2750), “security” (2301), and “digital storage” (2179).

interconnectedness of various applications, such as the construction industry serving as a central node linking to building information modeling (BIM), architectural design, smart contract, information management, and other related domains.

12.3 Blockchain in the construction industry: an overview

12.3.1 The current state of the construction industry and its challenges

The construction sector plays a pivotal role in the global economy, contributing significantly to employment, infrastructure development, and economic growth (Pheng & Hou, 2019). However, this critical industry is besieged by numerous obstacles that impede its efficiency and overall performance. These challenges are multifaceted, ranging from fragmented communication channels and inefficient SCM to persistent delays in project completion, budgetary overruns, and frequent disputes over contracts and compliance issues. The inherently decentralized structure of construction projects, which typically involve a complex network of stakeholders including contractors, subcontractors, suppliers, and clients, adds another layer of complexity to data management and transparency.

Furthermore, the construction industry is characterized by a chronic lack of access to real-time data, which severely hampers effective decision-making and project management. This deficiency is often compounded by a continued reliance on outdated paper-based processes, which not only slow down the flow of information but also introduce significant risks related to the tracking and verification of document authenticity and transaction integrity. The slow pace at which digital technologies are adopted within the sector only serves to exacerbate these issues, leaving the industry lagging behind others in terms of technological innovation and efficiency.

The cumulative effect of these challenges is a sector that is often seen as resistant to change, struggling to meet the demands of modern infrastructure projects and facing increased scrutiny over its environmental impact and sustainability practices. In light of these issues, there is an urgent need for the construction industry to embrace innovative solutions that can tackle these endemic problems head-on. By streamlining operations, improving data transparency and access, and enhancing the reliability and security of project-related information, the industry can move toward a more sustainable and efficient future. Adopting cutting-edge technologies and reimagining traditional processes are essential steps in overcoming the current limitations and unlocking the full potential of the construction sector as a cornerstone of the global economy (Wang et al., 2023).

12.3.2 Potential of blockchain to address these challenges

Blockchain technology, with its inherent characteristics of decentralization, transparency, security, and immutability, holds significant promise for revolutionizing the construction industry (Plevris, 2022). By enabling a secure and transparent platform for transactions and data exchange, blockchain can mitigate many of the sector's challenges. For instance, its decentralized nature allows for a more democratic and reliable system of record keeping and transactions, reducing the likelihood of data

tampering and fraud. The transparent ledger ensures that all parties have access to consistent and unalterable data, fostering trust among stakeholders and improving project coordination and communication. Security features, including cryptographic hashing and consensus mechanisms, can protect sensitive information and financial transactions from unauthorized access and cyber threats. Moreover, the immutability of blockchain records ensures that every transaction or document change is permanently recorded, providing an auditable trail that can help resolve disputes and enforce compliance. Additionally, the implementation of smart contracts can automate contract management and execution, streamlining processes and reducing the need for intermediaries. This could significantly enhance efficiency in procurement, payment processes, and compliance with contractual obligations.

Plevris et al. (2022) examined the potential of Blockchain in civil engineering, architecture, and the construction industry, identifying six important application areas. The study concludes that despite the nascent stage of blockchain technology and the initial challenges it faces, it harbors significant potential to serve as a powerful catalyst for positive transformation within the construction industry. Kiu et al. (2022) explored the disruptive potential of blockchain in the construction sector. To achieve this, the study set out two primary objectives: to pinpoint the key areas within the construction industry ripe for blockchain-induced transformation and to chart a course for future research on blockchain's integration into construction processes. The study uncovered six critical domains. Among these, SCM, BIM, and contract management emerged as the three focal points of current scholarly attention. Wu et al. (2022) did a comprehensive review of the latest blockchain research within the construction industry, aiming to elucidate the rapid advancements of this emerging technology based on an examination of 141 publications from 2017 to 2021. The study offers insightful information on the progress of blockchain research, facilitating a deeper understanding of the technology's applications in construction and highlighting opportunities for further investigation.

12.3.3 Benefits of integrating blockchain into construction operations

The integration of blockchain technology into construction operations offers numerous benefits, aimed at addressing the industry's longstanding challenges:

Enhanced Transparency and Accountability: By providing a transparent and accessible ledger of transactions and documentation, blockchain technology ensures that all project stakeholders have access to the same information, fostering trust and accountability in project execution.

Improved Efficiency and Reduced Costs: Blockchain can streamline various processes, including SCM, payments, and contract execution through smart contracts. This automation reduces administrative burdens and the risk of errors, potentially leading to significant cost savings.

Increased Security and Reduced Fraud: The use of cryptographic techniques ensures the security of data stored on the blockchain. The technology's inherent resistance to tampering and unauthorized alterations helps minimize the risk of fraud and cyberattacks.

Better Dispute Resolution and Compliance: The immutable record of transactions and document changes on the blockchain provides a verifiable audit trail, simplifying dispute resolution and compliance monitoring. This can reduce legal disputes and ensure projects adhere to contractual and regulatory requirements.

Innovative Project Management Tools: Blockchain enables real-time tracking of materials, equipment, and labor, improving project management and operational efficiency. This can lead to more accurate budgeting, scheduling, and resource allocation.

By addressing these key challenges and leveraging the benefits it offers, blockchain technology has the potential to significantly enhance the efficiency, reliability, and integrity of the construction industry. The adoption of blockchain could lead to a paradigm shift in how construction projects are managed and delivered, marking a new era of innovation and improved performance in the sector.

12.4 Key areas of blockchain application in construction

12.4.1 Construction supply chain management and logistics

In the realm of construction, the management of supply chains and logistics is crucial for the success and efficiency of projects, yet this sector is characterized by significant fragmentation in its processes, operations, and services. A key challenge is the disconnection between design and construction phases, largely due to the lack of reliable and accessible information throughout the supply chain. This often leads to challenges such as lack of transparency, delays in material deliveries, difficulties in tracing materials to their sources, and inefficiencies in inventory management, adversely affecting project timelines, budgets, and overall quality. Blockchain technology emerges as a promising solution to these issues by enabling open and transparent transactions, providing a robust mechanism for tracing physical objects from their origin to their destination (Qian & Papadonikolaki, 2021). Moreover, blockchain enhances various aspects of project management, including payment settlements (Hamledari & Fischer, 2021), compliance management, and materials planning. The adoption of smart contracts introduces new possibilities for automating the procurement, tracking, and verification of items within the supply chain in real-time, streamlining operations, and significantly improving efficiency and transparency across the board (Yoon & Pishdad-Bozorgi, 2022). In the following, we explore the diverse applications of blockchain technology in enhancing construction SCM and logistics.

Blockchain-Enabled Transparency and Traceability: Through the use of blockchain, every item in the supply chain can be digitally recorded on a tamper-proof ledger. This capability allows for unparalleled traceability of materials from their point of origin to their delivery on the construction site. Stakeholders can easily verify the authenticity, quality, and delivery status of materials in real-time, enhancing trust and accountability among suppliers, contractors, and clients.

Efficient Inventory Management: Blockchain technology facilitates more accurate and efficient inventory management. By providing real-time data on material availability, usage, and needs, construction projects can optimize their inventory levels, reducing excess stock and minimizing the risk of project delays due to material shortages.

Automated Smart Contracts for Logistics and Payments: The implementation of smart contracts in blockchain platforms can automate many aspects of SCM and logistics. These contracts can be programmed to execute payments automatically once certain conditions are met, such as the confirmation of material deliveries. This automation not only speeds up transactions but also reduces the potential for disputes and administrative overhead.

Enhanced Security and Compliance: The cryptographic security measures inherent in blockchain ensure that all supply chain transactions are secure and protected from unauthorized access and tampering. Moreover, the immutable nature of blockchain records provides an auditable trail of all transactions, facilitating compliance with regulatory requirements and industry standards.

Dispute Resolution and Performance Incentives: The transparent and immutable record of transactions on a blockchain provides a clear basis for resolving disputes related to material quality, delivery times, and contract terms. Additionally, smart contracts can be used to implement performance-based incentives, rewarding suppliers and logistics providers for meeting or exceeding delivery and quality expectations.

Waqar et al. (2024) provided a thorough examination of how blockchain technology can revolutionize SCM in the construction industry. Their research highlighted the transformative power of blockchain in addressing key challenges and enhancing efficiency, transparency, and sustainability across the construction supply chain. Singh et al. (2023) explored the application of the Pythagorean fuzzy analytic hierarchy process to identify and analyze the barriers hindering the adoption of blockchain technology in construction SCM. Their comprehensive literature review pinpointed 37 potential obstacles, which were subsequently narrowed down to the 15 most significant barriers. Among these, the “transparency range” emerged as the paramount challenge, with “inadequate access to institutional finance” following closely as the second most critical barrier.

Tezel et al. (2020) explored the possibilities and future prospects of employing blockchain technology within construction supply chains. The researchers gathered empirical evidence by conducting semistructured interviews with 17 industry experts. They employed a SWOT analysis to delineate the strengths, weaknesses, opportunities, and threats associated with this application and further outlined the prerequisites and procedural steps necessary for integrating blockchain technology into CSC structures. The same team (Tezel et al., 2021) subsequently delved into the practical application of blockchain technology within the construction sector. They presented an analysis of SCM applications of blockchain in construction, drawing insights from feedback on three blockchain-based models: reverse auction-based tendering for bidding processes, project bank accounts for managing payments, and asset tokenization to facilitate project financing. Through this investigation, they pinpointed a range of challenges and opportunities, both general and specific to each model, crucial for the adoption of blockchain in construction settings.

In summary, integrating blockchain technology into SCM and logistics within the construction industry can lead to significant improvements in transparency, efficiency, and reliability. This integration not only addresses many of the traditional challenges faced by the sector but also opens up new avenues for innovation and optimization, contributing to the more successful execution of construction projects.

Example: Application: Enhancing Material Sourcing and Procurement With Blockchain

Consider the implementation of a blockchain-based system designed to revolutionize material sourcing and procurement in the construction industry. In this scenario, each material batch is assigned a unique digital identifier upon its creation or extraction, which is then recorded on the blockchain. This identifier contains comprehensive details about the material, including its source, composition, date of extraction, and any certifications or environmental impact assessments associated with it. As the material moves through the supply chain—from supplier to manufacturer, and eventually to the construction site—each transaction is recorded on the blockchain, creating an indelible and transparent history of its journey.

This blockchain-enabled system offers several key advantages. First, it ensures the authenticity and quality of materials, as stakeholders can easily access and verify the history and certifications of each material batch. This capability is particularly crucial for projects requiring materials with specific standards or sustainability criteria. Second, the system streamlines the procurement process by automating order placements and payments through smart contracts, which are triggered as soon as the materials meet predefined conditions, such as successful delivery and quality inspection. This automation not only speeds up transactions but also significantly reduces administrative overhead and the potential for human error.

Furthermore, the transparency provided by the blockchain reduces the risk of fraud and corruption in the procurement process, as every transaction is recorded and cannot be altered retroactively. This level of transparency also facilitates better planning and inventory management, as project managers can accurately track material flows and availability in real time, allowing for more efficient use of resources and reducing waste.

In this way, a blockchain-based system for material sourcing and procurement can significantly enhance the efficiency, transparency, and sustainability of SCM in the construction industry, leading to more reliable and cost-effective project execution.

12.4.2 Contract management and smart contracts for construction projects

A Smart Contract operates as a computer program designed on the premise of “if/then” logic. These contracts are capable of recognizing responsibilities and initiating payments upon the achievement of specific milestones (Vigliotti, 2021). Their automatic execution minimizes the need for middlemen, thereby saving both time and money. Smart Contracts facilitate the automation of agreements, thereby transforming the conventional practices of construction contracts and payments with a more efficient, modern approach. Smart contracts represent a transformative application of blockchain technology within the construction industry, particularly in the realm of contract management and execution (Li & Kassem, 2021).

The traditional method of managing contracts in construction projects is often cumbersome, prone to human error, and can lead to significant delays and increased administrative overhead. Smart contracts offer a compelling solution by automating these processes. Through the use of blockchain technology, contracts between parties—such as contractors,

subcontractors, and suppliers—are encoded into transparent, immutable, and self-executing agreements. This automation ensures that all contractual terms are met without the need for manual oversight or intervention, significantly streamlining project management and reducing the potential for disputes.

[Ahmadisheykhsarmast & Sonmez \(2020\)](#) suggested employing smart contracts to safeguard payment transactions in construction agreements. Similarly, [Nanayakkara et al. \(2021\)](#) explored the applicability of blockchain and smart contracts in addressing payment challenges within the construction sector. [McNamara and Sepasgozar \(2021\)](#) delved into the potential of blockchain and intelligent contracts (iContracts) to digitalize the construction industry. Through an analysis of 46 studies, they pinpointed nine critical factors influencing the adoption of iContracts and proposed a three-dimensional conceptual model for their implementation. [Kunkcu et al. \(2023\)](#) examined the operational barriers against the adoption of smart contracts in construction projects and explored the challenges in this process.

Example: Application: Handling Payments in Construction.

Consider the process of releasing payments in a construction project. Traditionally, this involves manual verification of work completion, invoice processing, and potential disputes over the quality or timeliness of work. Smart contracts revolutionize this process by automating payments, which are released only when specific project milestones are achieved. For instance, a smart contract can be programmed to automatically release funds to a subcontractor once digital evidence of completed work is verified against the contract terms ([Son et al., 2024](#)). This evidence might include digital signatures from project managers or photographic PoW completion, which triggers the payment process without the need for manual approval.

This system not only accelerates the payment process but also significantly reduces the likelihood of disputes ([Gupta & Jha, 2023](#)). Since the conditions for payment are predefined and encoded into the blockchain, all parties have a clear understanding of what is expected. This transparency and automation ensure that payments are made promptly upon the fulfillment of agreed-upon milestones, reducing administrative overhead and fostering a more collaborative and trustful environment among all project stakeholders ([Pham et al., 2024](#)).

To effectively implement smart contracts in construction projects, stakeholders must first agree on the specific terms and conditions that will govern their contractual relationship. These terms are then translated into code and embedded into the blockchain, creating a smart contract. Once deployed, the smart contract monitors project progress and automatically executes agreed-upon actions, such as payments, without requiring human intervention. This not only enhances efficiency but also provides a secure and immutable record of all transactions, ensuring that every party adheres to their contractual obligations.

In general, smart contracts hold the potential to dramatically improve contract management and execution in construction projects. By automating critical processes and reducing the potential for disputes, smart contracts can lead to more efficient, transparent, and equitable project outcomes. As the construction industry continues to embrace digital transformation, the adoption of smart contracts could become a standard practice, paving the way for more innovative and streamlined project management approaches.

12.4.3 Construction project management and documentation

In the construction sector, the management of projects and their associated documentation plays a vital role in ensuring projects are completed successfully. This entails handling plans, blueprints, revisions, and other crucial documents that often need regular updates and verification. Traditional approaches to managing these documents frequently suffer from issues such as errors, loss, and disputes regarding the most current versions or the legitimacy of modifications. The concept of Construction Project Management (CPM) stands to gain from adopting a more agile and decentralized approach facilitated by blockchain technology, which offers enhanced transparency and a system where participants are rewarded based on outcomes and the work they have performed. Historically, the construction industry has been identified as one of the slowest to adopt information technology innovations. In this section, we examine how blockchain technology and smart contracts can offer innovative solutions in CPM.

Secure and Immutable Record Keeping: Blockchain technology provides a platform for storing project documents in a manner that is both secure and unalterable. Each document, once uploaded to the blockchain, becomes a part of an immutable ledger. This means that every version of every document is recorded and timestamped, ensuring that changes cannot be made retroactively without a clear, auditable trail. This level of security and immutability safeguards against unauthorized alterations and potential data loss, ensuring that all stakeholders have access to accurate and up-to-date information.

Enhancing Accountability and Reducing Disputes: One of the most significant advantages of using blockchain for project management and documentation is the creation of an auditable trail of all documentation changes. This feature is invaluable for enhancing accountability among all project participants. For example, when plans or revisions are made, the blockchain records each change, who made it, and when it was made. This transparent record-keeping process drastically reduces the risk of disputes over document versions or the authenticity of changes, as there is a clear and indisputable record of every action taken.

The debate on whether blockchain technology is merely hype or a tangible asset for the construction sector was explored in a study by [Perera et al. \(2020\)](#). This research, through case studies and an extensive review of existing literature, sought to assess the potential of blockchain applications within the construction context. The findings suggest that blockchain technology holds genuine promise for the construction industry, underscored by its growing use across various sectors, significant investment flows, and the emergence of Industry 4.0. [Mahmudnia et al. \(2022\)](#) concentrated on examining the attributes of blockchain technology to assess its effectiveness in resolving disputes within construction management. Their approach involved a review of existing literature, resulting in a detailed categorization of how blockchain applications can be leveraged to address conflicts in construction projects. Their analysis pinpointed potential directions for future investigations in the realm of construction.

The study by [Turk and Kline \(2017\)](#) explored the capabilities of blockchain in enhancing construction management. The researchers emphasized that blockchain technology could significantly increase the trustworthiness and reliability of construction logbooks. Additionally, it offers a secure method for storing sensitive data. [Das et al. \(2022\)](#)

employed blockchain technology to bolster the integrity of document management in construction contexts by ensuring (1) a nonreversible and permanent approval process through the use of smart contract technology, (2) a tamper-proof record of changes to documents maintained on a blockchain ledger, and (3) the maintenance of a verifiable history of document versions via a blockchain-based data structure.

Example: Application: Implementing a Blockchain for Document Integrity and Auditability.

Imagine a construction project that encounters a series of unexpected changes, requiring multiple adjustments to the original architectural plans. Such alterations could stem from a variety of factors, including unforeseen site conditions, regulatory changes, or modifications requested by the client. In a traditional setting, managing these revisions could lead to confusion, miscommunication, and potential disputes over the authenticity and approval of changes.

Blockchain technology will offer a systematic approach to maintaining a transparent and immutable record of every modification made to the project plans. Each time a revision is proposed, detailed information, including the nature of the change, the rationale behind it, and the approval status, is securely recorded on the blockchain. This digital ledger serves as a chronological and unalterable history of the project's development, capturing every action from inception to completion.

Should any disagreements or questions arise concerning the details of a specific plan revision or the sequence of modifications, the blockchain provides a verifiable and auditable trail. This trail meticulously documents each step, including who made the change, when it was made, and who approved it, offering clear evidence that can be referenced to quickly resolve disputes.

The advantages of such a system extend beyond dispute resolution. By fostering a level of transparency and trust previously unattainable, all parties involved in the project, from architects and contractors to clients and regulatory bodies, gain access to a reliable source of truth. This not only facilitates smoother communication and collaboration but also significantly reduces the risk of costly delays and legal challenges. Moreover, the adoption of blockchain for document integrity and auditability underscores a commitment to ethical practices and accountability, enhancing the reputation of those involved and setting a new standard in project management and execution.

Such an application of blockchain technology in project management and documentation can transform how the construction industry handles critical information. By ensuring secure, transparent, and immutable record keeping, blockchain technology enhances accountability, reduces the risk of disputes, and promotes a more efficient and collaborative project environment. As the industry continues to recognize the benefits of digital innovation, the integration of blockchain into project management and documentation practices is poised to become a standard, driving further improvements in project delivery and stakeholder satisfaction.

12.4.4 Land registry and real estate transactions

The real estate sector is recognized as a pivotal component of the global economy, significantly impacting individuals worldwide. In 2022 the value of real estate assets managed

professionally worldwide was approximated to be \$13.3 trillion, with the Americas accounting for 43.9% of this global market share (Patkar & Neshat, 2023). Investments in real estate are often seen as offering more favorable returns compared to the stock market, with less associated volatility and potential tax advantages in numerous instances. Despite its considerable importance and the technological progress transforming other industries, real estate has remained relatively unchanged over the past few decades. The sector predominantly operates with outdated practices, heavily relying on manual record keeping and transaction processes. This archaic approach has led to various issues, including restricted market participation due to high entry barriers, inefficient and expensive verification processes that involve numerous intermediaries, and a scarcity of foreign investments, among other challenges.

The processes involved in land registry and real estate transactions have long been criticized for their lack of transparency, efficiency, and security. Traditional systems are often mired in bureaucratic red tape, susceptible to fraud, and burdened with a slow and cumbersome paper trail that can lead to significant delays and increased costs. Blockchain technology presents a revolutionary approach to these issues, offering a way to streamline and secure land registry and real estate transactions in a manner previously unattainable.

Blockchain technology introduces a level of transparency, security, and efficiency to land registry and real estate transactions that significantly improves upon the traditional methods. By leveraging a decentralized ledger, all records of property transactions become immutable and easily verifiable. This not only reduces the potential for fraud but also simplifies the process of verifying ownership and the history of a property. With blockchain, every transaction related to a piece of land or property—including sales, mortgages, and leases—can be recorded in a manner that is transparent to all parties involved and secure from tampering or unauthorized alterations.

The immutable nature of blockchain technology ensures that once a transaction is recorded, it cannot be altered or deleted. This characteristic is particularly beneficial in the context of land registries and real estate transactions, where the risk of fraud and document tampering is a significant concern. Blockchain's secure and transparent ledger means that every change in ownership, every lien, and every encumbrance is accurately and permanently recorded, providing a clear and unassailable record of the property's history.

Plevris et al. (2023) analyzed the present conditions and associated issues with the registration of land and real estate property records, particularly in developing nations. They discussed the challenges and prospects presented by the application of blockchain technology in this domain. Zhang et al. (2023) introduced a blockchain-driven model for real estate investment and offered an in-depth explanation of the model's real estate registration and authentication features. Utilizing blockchain technology, the model ensures the creation of tamper-proof records for real estate transactions, alongside providing robust authentication and verification mechanisms for informal real estate dealings.

Saari et al. (2022) sought to grasp the latest advancements in blockchain research, particularly within the real estate domain, by gathering empirical data from various blockchain studies. They aimed to assess the real-world applications and implications of blockchain technology. According to their findings, while many of the theoretical benefits of blockchain are yet to be empirically validated, the practical applications gathered from the studies indicate that blockchain technology has the potential to enhance efficiency, diminish time consumption, and offer verifiability, transparency, and automation. Wouda and Opendakker (2019)

delved into how Blockchain technology could impact commercial real estate transactions, particularly focusing on the challenges associated with defining property characteristics during the transaction process of an office building. A key issue they highlighted was the difficulty in specifying property features, attributed to inadequate data structure and quality.

Integrating blockchain technology into land registry and real estate transactions holds the promise of transforming these critical aspects of the construction and real estate sectors. By ensuring secure, transparent, and immutable recordkeeping, blockchain can mitigate fraud, streamline transactions, and enhance the overall reliability and efficiency of property dealings. As the construction industry and related sectors continue to evolve with technological advancements, the adoption of blockchain in land registry and real estate transactions stands out as a beacon of innovation, paving the way for more secure, efficient, and transparent processes.

Example: Application: A Blockchain-Based Land Registry System.

Envision a sophisticated land registry system powered by blockchain technology, where each piece of real estate is represented by a distinctive digital token. This token encapsulates all pertinent details regarding the property, such as the identity of its current owner, a history of past transactions, and any existing liens or encumbrances. Upon the sale of the property, the transaction is recorded on the blockchain, facilitating the transfer of the digital token to the new owner. This ensures a transaction that is not only secure but also marked by unparalleled transparency.

This innovative system offers a marked improvement over traditional methods by streamlining the transaction process. It eliminates the cumbersome need for physical documentation exchange and verification, significantly expediting the overall process. Moreover, the inherent security features of blockchain technology drastically reduce the potential for fraudulent activities. Each transaction and property detail is recorded on a tamper-proof ledger, making it nearly impossible to alter information illicitly.

Furthermore, the blockchain acts as an immutable source of truth, openly accessible to all stakeholders involved, including buyers, sellers, regulatory bodies, and financial institutions. This accessibility ensures that all parties have a consistent and accurate view of property information, leading to transactions that are smoother and more reliable.

The implementation of such a blockchain-based land registry system revolutionizes property transactions. It not only enhances the efficiency and security of these transactions but also fosters a level of transparency and trust among participants that was previously unattainable. Through the elimination of fraud and reduction in transaction times, this system stands as a testament to the transformative potential of blockchain technology in the realm of real estate transactions and beyond.

12.5 Challenges and considerations in adopting blockchain

12.5.1 Technical challenges and limitations of blockchain technology

While blockchain technology offers a host of benefits, its adoption, especially in industries like construction, comes with a set of technical challenges and limitations.

Understanding these hurdles is crucial for organizations considering integrating blockchain into their operations. The successful implementation of blockchain technology requires navigating through these challenges, which include scalability, energy consumption, interoperability, and the need for standardization.

Scalability: One of the most significant technical challenges facing blockchain technology is scalability. As blockchain networks grow in size and usage, the amount of data that needs to be processed and stored on every node of the network increases. This can lead to slower transaction times and higher costs, making it challenging to scale blockchain solutions for large-scale applications. In the construction industry, where projects can involve thousands of transactions and documents, scalability issues could limit the effectiveness of blockchain solutions.

Energy Consumption: Blockchain technology, particularly those networks that use PoW consensus mechanisms, is notorious for its high-energy consumption. The mining process, which involves solving complex mathematical puzzles to validate transactions and create new blocks, requires significant computational power and, consequently, electricity. This high-energy demand raises concerns about the environmental impact of adopting blockchain technology on a large scale, especially in industries committed to sustainability goals.

Interoperability: Interoperability refers to the ability of different blockchain systems and networks to work together seamlessly. In the construction industry, where projects often involve multiple stakeholders with their own systems and processes, the lack of interoperability between different blockchain platforms can be a significant barrier. Without standards to ensure that systems can communicate and exchange data efficiently, the potential benefits of blockchain technology may not be fully realized.

Need for Standardization: The blockchain industry is still in its early stages, and the lack of standardization is a challenge for its broader adoption. Without universally accepted standards and protocols, it can be difficult for organizations to choose the right blockchain solution for their needs. This uncertainty can lead to compatibility issues, increased costs, and delays in project timelines. In the construction industry, where projects often require collaboration between various parties, the need for standardization is particularly acute to ensure seamless integration and adoption of blockchain technology.

While blockchain technology holds great promise for transforming the construction industry and beyond, addressing its technical challenges and limitations is crucial for its successful implementation. Scalability, energy consumption, interoperability, and the need for standardization are significant hurdles that must be overcome. As the technology matures and solutions to these challenges are developed, the potential for widespread adoption of blockchain in construction and other industries becomes increasingly feasible. Recognizing and addressing these technical challenges early on will be key to leveraging blockchain technology's full potential and ensuring its sustainable integration into industry practices.

12.5.2 Legal and regulatory considerations

The integration of blockchain technology into the construction industry, while promising in terms of efficiency and transparency, raises a myriad of legal and regulatory considerations.

These considerations stem from the technology's novelty, its decentralized nature, and the global inconsistency in blockchain regulation. As construction companies navigate the adoption of blockchain, understanding and addressing these legal and regulatory challenges is crucial for ensuring compliance and mitigating risk.

Navigating a Complex Regulatory Landscape: Blockchain technology operates across a decentralized network, often spanning multiple jurisdictions. This global nature can complicate compliance with local laws and regulations, which may vary significantly from one country or region to another. For construction companies operating internationally, the challenge lies in adhering to a mosaic of regulatory standards concerning data privacy, security, and transactions. The lack of clear legal frameworks specifically addressing blockchain technology in many jurisdictions adds to the complexity, making it difficult for companies to ensure their blockchain applications are fully compliant.

Data Privacy and Security: Data privacy regulations, such as the General Data Protection Regulation (GDPR) in the European Union, pose specific challenges for blockchain implementations. For instance, the immutability of blockchain, while a key feature for security and transparency, conflicts with the GDPR's requirements for data to be deletable under certain conditions. Finding a balance between leveraging the benefits of blockchain and adhering to strict data privacy laws is a significant challenge for the construction industry, which often handles sensitive project and client information.

Smart Contracts and Legal Recognition: Smart contracts are a hallmark of blockchain technology, offering automated contract execution based on predefined conditions. However, the legal status of smart contracts is still under debate in many jurisdictions. Questions regarding their enforceability, the resolution of disputes arising from smart contract executions, and the applicability of traditional contract laws to these digital agreements are yet to be fully resolved. For the construction industry, where contracts are complex and disputes are not uncommon, the legal uncertainties surrounding smart contracts necessitate careful consideration and potentially bespoke legal frameworks.

Intellectual Property Issues: Blockchain technology enables the sharing and storing of a vast amount of digital information, raising concerns about IP rights and protection. In the construction industry, where proprietary designs, techniques, and other forms of IP are valuable assets, ensuring that IP rights are respected and protected when using blockchain platforms is essential. The decentralized and open nature of many blockchain systems can complicate IP protection, requiring companies to implement robust mechanisms to safeguard their assets.

In conclusion, legal and regulatory considerations are among the foremost challenges in adopting blockchain technology within the construction industry. The evolving regulatory landscape, concerns about data privacy and security, the legal status of smart contracts, and IP protection are critical areas that require attention. As the technology and its applications in the construction sector mature, it is anticipated that legal frameworks and regulations will evolve to better accommodate the unique characteristics of blockchain. Until then, construction companies must remain vigilant, ensuring that their use of blockchain technology aligns with current legal and regulatory requirements while preparing for future changes.

12.5.3 The cost of implementing blockchain solutions

The adoption of blockchain technology, while offering numerous benefits, is accompanied by various costs that organizations need to consider. These costs are not just financial but also include investments in time and resources required for successful implementation. For industries such as construction, where the potential for blockchain to streamline operations and enhance efficiency is significant, understanding and planning for these costs is crucial.

Initial Investment Costs: The initial costs of implementing blockchain technology can be substantial. This includes the expenses associated with developing or purchasing blockchain software, hardware acquisition for running the network, and integrating the blockchain solution with existing systems. Given that blockchain is a relatively new technology, finding the right expertise and solutions tailored to the specific needs of the construction industry can also add to the initial costs.

Training and Development Costs: Another significant expense is related to training and development. For blockchain technology to be effectively integrated into construction operations, employees and stakeholders need to understand how to use the system. This requires comprehensive training programs and ongoing support to ensure all users are competent and comfortable with the new technology. Additionally, as blockchain technology evolves, continuous learning and development efforts will be necessary to keep pace with advancements and updates.

Operational and Maintenance Costs: Once a blockchain solution is implemented, there are ongoing operational and maintenance costs to consider. This includes the cost of electricity and computing power needed to run the blockchain network, especially for systems that rely on energy-intensive consensus mechanisms like PoW. There are also costs associated with maintaining the security of the blockchain, updating the system to accommodate new features or address vulnerabilities, and providing technical support to users.

Scalability and Upgradation Costs: As construction projects and operations grow, the blockchain system may need to scale to accommodate increased transaction volumes, more users, and additional types of transactions or data. Scaling a blockchain solution can involve significant upgrades to infrastructure and software, potentially leading to substantial costs. Furthermore, as technology advances, organizations might need to invest in newer blockchain solutions to stay competitive, adding to the overall cost of maintaining an up-to-date blockchain infrastructure.

Cost-Benefit Analysis: Despite these costs, the long-term benefits of blockchain technology, such as improved efficiency, enhanced security, and reduced risk of fraud, can outweigh the initial and ongoing expenses. However, conducting a thorough cost-benefit analysis is essential for organizations in the construction industry to ensure that the investment in blockchain technology is justified. This analysis should consider not only the financial implications but also the potential for blockchain to drive innovation, improve project outcomes, and enhance stakeholder satisfaction.

The cost of implementing blockchain solutions in the construction industry encompasses a wide range of expenses, from initial investments in technology and training to

ongoing operational and maintenance costs. While the financial commitment can be significant, the potential for blockchain to transform construction operations and deliver long-term benefits makes it an investment worth considering. Careful planning, budgeting, and a clear understanding of both the costs and the expected returns are crucial for successfully integrating blockchain technology into construction practices.

12.6 The future of blockchain in construction

The integration of blockchain technology into the construction industry is poised to revolutionize how projects are managed, executed, and delivered. As we look toward the future, it is clear that blockchain holds the potential to address many of the industry's longstanding challenges, including inefficiencies in project management, supply chain vulnerabilities, and issues of transparency and trust among stakeholders. The future of blockchain in construction is not just about the evolution of technology itself but how it can be harnessed to drive innovation, improve sustainability, and reshape the industry landscape.

12.6.1 Driving innovation and efficiency

The ongoing development of blockchain technology is expected to spur innovation across the construction sector. By enabling more secure, transparent, and efficient processes, blockchain can streamline project management, enhance collaboration among stakeholders, and reduce time and costs associated with construction projects. Innovations such as smart contracts and decentralized applications (DApps) are set to automate and simplify complex processes, from procurement and supply chain logistics to contract management and compliance. As these technologies mature, their adoption will likely become more widespread, leading to significant efficiency gains and a more competitive industry.

12.6.2 Enhancing sustainability

Blockchain's potential to improve traceability and accountability in the supply chain also supports the construction industry's growing focus on sustainability. By providing an immutable record of the origin, movement, and quality of materials, blockchain can help ensure that sustainable practices are followed throughout the supply chain. This capability could be instrumental in reducing waste, ensuring the ethical sourcing of materials, and facilitating the use of green building practices. As environmental concerns continue to gain prominence, the role of blockchain in promoting sustainability in construction is expected to expand.

12.6.3 Reshaping industry collaboration

The decentralized nature of blockchain fosters a more collaborative and transparent environment for all parties involved in construction projects. By providing a single source

of truth, blockchain technology can minimize disputes, enhance trust, and streamline communication among contractors, suppliers, clients, and regulatory bodies. This shift toward greater collaboration and transparency could lead to a fundamental reshaping of industry relationships, with a focus on shared goals and mutual benefits.

12.6.4 Overcoming challenges for wider adoption

The path to widespread blockchain adoption in the construction industry will require overcoming the current technical, legal, and regulatory challenges. As the industry continues to familiarize itself with blockchain technology, efforts to standardize practices, develop interoperable systems and address concerns related to scalability and energy consumption are crucial. Moreover, the establishment of clear legal and regulatory frameworks will be essential to facilitate the adoption of blockchain and ensure that its benefits can be fully realized.

In general, the future of blockchain in construction promises a shift toward more efficient, transparent, and sustainable practices. As the industry navigates the challenges of adoption and integration, the potential for blockchain to transform construction processes and outcomes is immense. Looking ahead, the construction sector's willingness to embrace blockchain technology and drive innovation will be key to unlocking these benefits and securing a competitive edge in a rapidly evolving industry landscape. The journey toward the widespread adoption of blockchain in construction may be complex, but the potential rewards for the industry and its stakeholders are significant and far-reaching.

12.7 Conclusion

The exploration of blockchain technology in the construction industry reveals a landscape ripe for transformation. As detailed in this chapter, blockchain holds the promise of addressing many of the sector's most pressing challenges, including issues related to inefficiency, transparency, and trust. By decentralizing data management, enhancing security through cryptography, and streamlining processes with smart contracts, blockchain offers a pathway to significant improvements in how construction projects are managed and delivered.

The journey toward integrating blockchain into construction operations is not without its challenges. Technical hurdles, legal and regulatory considerations, and the costs of implementation are significant barriers that need to be navigated. However, the potential benefits of blockchain technology—from improved efficiency and reduced costs to enhanced transparency and accountability—present compelling reasons for its adoption.

Looking forward, the construction industry stands on the brink of a digital revolution. Blockchain technology, with its capacity to facilitate immutable recordkeeping, secure transactions, and automate contract enforcement, is at the forefront of this transformation. As the industry grapples with the complexities of adoption, the focus must remain on collaboration, innovation, and a commitment to addressing the technical and regulatory challenges that lie ahead.

The future of blockchain in construction is not merely about the adoption of new technology but about reimagining the foundations upon which the industry operates. By embracing blockchain, the construction sector can unlock unprecedented levels of efficiency, transparency, and trust, paving the way for a more sustainable, reliable, and innovative future.

The integration of blockchain into the construction industry represents a significant leap forward, promising to reshape the landscape of project management, supply chain logistics, and stakeholder relations. As the industry continues to evolve, the continued exploration, experimentation, and implementation of blockchain technology will be key to realizing its full potential. The journey is complex and filled with challenges, but the destination—a more efficient, transparent, and accountable construction industry—is well worth the effort.

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