Kalpa Publications in Computing
Volume 22, 2025, Pages 233–246
Proceedings of The Sixth International Conference on Civil and Building Engineering Informatics

Advancing Blockchain and Smart Contracts from Academia to Industry: Insights into the Construction Sector

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Abstract

Blockchain (BC) and smart contract (SC), known for their decentralized and secure frameworks, have been successfully applied across industries to enhance security, efficiency, and transparency in technical and engineering aspects such as automated transactions, data management, and supply chain monitoring. In recent years, the construction industry has seen significant advancements in adopting BC and SC. This review paper examines the latest BC and SC prototypes, case studies, and technical applications published over the past four years, focusing on how these academic developments can be transitioned into industry practice. By categorizing the collected studies using Technology Readiness Levels (TRLs) and conducting an in-depth analysis, the paper seeks to identify strategies for accelerating the adoption of these technologies in the construction sector. Reviewing recent advancements, this paper uncovers key trends, benefits, and challenges associated with implementing BC and SC in construction. The findings suggest that these technologies can significantly enhance project efficiency, contract management, and supply chain transparency while fostering trust among stakeholders. While these technologies offer significant potential, critical challenges, including scalability, privacy, and integration complexities, hinder their widespread adoption. Moreover, specific limitations, such as the difficulty in establishing regulatory compliance and technical barriers in data management, remain unresolved. By providing action-able insights and highlighting pathways to bridge the adoption gaps, the paper aims to accelerate the integration of BC and SC into the construction industry, driving innovation, transparency, and operational efficiency.

Keywords: Blockchain, smart contract, construction industry, technology readiness level, technology adoption, review

1. Introduction

Blockchain (BC) and smart contracts (SC) are increasingly recognized for their ability to transform industries through decentralized, secure, and transparent frameworks (Casino et al., 2019). BC, a distributed ledger technology, ensures tamper-proof data storage and process transparency, while SC automates contractual agreements using self-executing code that enforces the terms without intermediaries (Christidis & Devetsikiotis, 2016). Initially discussed as conceptual innovations, BC and SC have evolved over the past decade into tangible applications and technical prototypes. Industries such as finance and healthcare have already leveraged these technologies for enhanced security, efficiency, and transparency (Casino et al., 2019). Similarly, the construction industry—traditionally burdened with complex workflows, fragmented projects, and contractual inefficiencies—has begun to explore the potential of BC and SC over the past decade.

Several review papers have highlighted the advancements in BC and SC research specific to the construction industry. For instance, J. Li and Kassem (2021) provides a comprehensive analysis of BC and SC applications, including improving information management, enhancing transparency, and integrating with technologies like Building Information Modeling (BIM) and Internet of Things (IoT). Similarly, Rathnayake et al. (2022) focuses on SC applications for automating payment systems and contract execution, identifying strategies to overcome adoption barriers and enhance efficiency in construction projects. These studies collectively emphasize the increasing maturity of BC and SC applications in addressing the longstanding challenges of construction management. Particularly in the last five years, there has been a growing body of literature examining BC and SC applications in construction, with a noticeable shift from conceptual discussions to practical case studies and technical implementations (Sun et al., 2023). Recent research reviews the use of BC and SC for purposes such as automating contract management, streamlining payments, and enhancing supply chain transparency (B. G. Celik et al., 2024). The progression from concept to application suggests that these technologies have the potential to improve project delivery and stakeholder collaboration in construction.

However, the adoption of BC and SC technologies in construction is still in its early stages, and several barriers remain—ranging from scalability and privacy concerns to the integration with existing systems. These challenges underscore the need for a structured approach to assess the technological maturity of BC and SC innovations, which is where the Technology Readiness Levels (TRLs) framework comes into play. TRLs offer a comprehensive and objective measure of technological maturity, allowing stakeholders to gauge which innovations are ready for large-scale adoption and which require further development. Building upon our previous work (Ye et al., 2022), which provided a comprehensive review of BC-based SC applications in construction, this study seeks to extend the understanding of these technologies by examining their readiness for industrial adoption through the lens of the TRL framework.

Therefore, this paper aims to provide a review of BC and SC technologies in construction with a particular focus on their technical implementation and to investigate how BC and SC can be adapted to the construction industry. By categorizing recent studies on BC and SC based on TRLs, this paper seeks to identify which construction sub-domains derived from Ye et al. (2022) have made the most progress in adopting BC and SC, and where further development based on the technical metrics is needed to bring these technologies into mainstream industrial use. The key research questions guiding this review are: 1) Which construction sub-domains represent the greatest potential for the adoption of BC and SC technologies? 2) What aspects of the technical metrics are at the center of the studies that have achieved high TRL? 3) How could the technical solutions be adapted to the industry considering the benefits and barriers?

To address these questions, TRL introduces a basic framework for categorizing studies in Section 2. Section 3 outlines the literature review process. Section 4 contains the descriptive analysis and in-depth analysis, offering insights into the construction industrial adoption of BC and SC. Section 5 explores the possibility of the technical solutions adaption, followed by the conclusion in Section 6.

2. TRL for Literature Analysis

To assess the development maturity of BC and SC technologies in the construction industry, the TRL framework, as defined by Mankins (1995) for NASA, provides a structured and systematic approach. This framework assesses the maturity of a technology throughout its development process. It spans nine levels, ranging from basic research and concept development (TRL 1) to fully operational and deployed technologies (TRL 9). Each level is differentiated based on the achievement of technical functions and the fulfillment of validation requirements. At the lowest level, TRL 1 focuses on observing and reporting on basic scientific research (e.g., basic BC and SC technologies), which begins the basis of designing a proof of concept and the transition to more applied research, such as its potential applications in the construction industry. Until TRL 3, the focus is on "analytical" and "experimental" approaches to prove the feasibility of a concept. From TRL 4 to TRL 6, technological components are developed and validated in controlled laboratory environments. Up to TRL 7, a system prototype is built and validated in an operational environment.

To streamline the classification of the research studies analyzed in this review, three overarching categories have been defined, derived from the overview of the TRL scale by Mankins (2009): 1) Research (TRL 1-3): This phase focuses on establishing the basic concepts of BC and SC technologies and analyzing their core ideas; 2) Development (TRL 4-6): During this phase, the BC and SC technologies are further developed, progressing from small-scale prototypes to testing in relevant operational environments; 3) Deployment (TRL 7-9): The final phase focuses on demonstrating the effectiveness of the technologies in real-world environments in preparation for full-scale system deployment. These categories allow for a simplified and systematic assignment of each research study to an appropriate TRL, thus facilitating the overall analysis of technological maturity. Even when the three overarching categories are used, effective application of TRL assessment can be challenging due to the complexity of selecting the appropriate metrics (Mankins, 2009). This is particularly true in the construction industry, which is undergoing significant digital transformation. Therefore, to determine and analyze in depth the research studies on the maturity of BC and SC technologies in this review paper, several technical aspects server as metrics are defined in the Methodology section.

3. Research Methodology

To conduct a literature review of BC and SC technical adoptions in the construction industry, the overall process of the research methodology is illustrated in Figure 1. It contains three steps: data collection, data analysis, and discussion. The design of this study borrows some aspects from the systematic review set out by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) (Moher et al., 2010). Based on the flow diagram of PRISMA, Scopus was used as the search engine and source in the data collection step to retrieve literature addressing BC and SC in the construction or more bridely in the Architecture, Engineering and Construction (AEC) industry. The papers were retrieved as a preliminary process through advanced search in the article title/abstract/keywords field combining keywords: (blockchain OR "smart contract") AND (prototype OR implement OR case) AND (construction OR AEC) for the construction industry. The data used in this review were retrieved in September 2024, and the search yielded 587 studies.

After the literature search, a series of inclusion and exclusion criteria were defined to guide the extraction of the most relevant papers. To be a follow-up study of the previous review (Ye et al., 2022), only journal articles in the last 4 years (i.e., from 2021 to 2024) focusing on technical application research are considered. Papers were excluded for the following reasons: 1) papers not available in English, 2) papers without full availability, 3) papers not as a journal article, and 4) papers not in the target fields, i.e., in the construction or AEC field. After the inclusion and exclusion process, 180 papers in construction were left. Then each of the papers was reviewed based on three quality evaluation questions: 1) Is the paper primarily focused on BC or SC technologies, rather than just mentioning them? 2) Does the paper propose a solution/framework, rather than an opinion paper based on reviews, surveys, interviews, questionnaires, and/or focus groups? 3) Does the paper provide technical insights with applications, prototypes, or implementation details? After the quality evaluation, there were 44 papers in total.

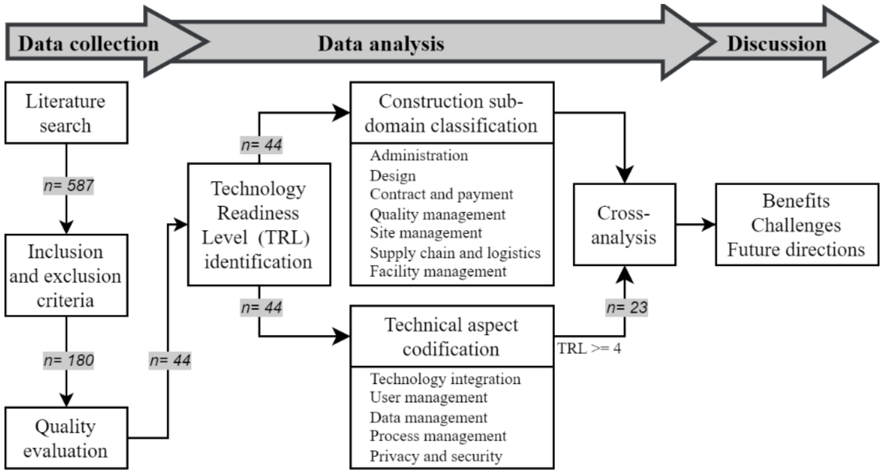

Figure 1: Overview of research methodology

In the data analysis step, the collected papers were analyzed based on three steps, namely TRL identification, construction sub-domain classification and technical aspect codification, which serves the cross-analysis. Figure 2 is drawn based on the TRL introduced in Section 2 as a guidance workflow of evaluating the TRL of BC and SC adoption readiness in each paper. It presents a logical sequence of TRLs reached and adopted that allows researchers to evaluate each BC and SC application, thus establishing its maturity.

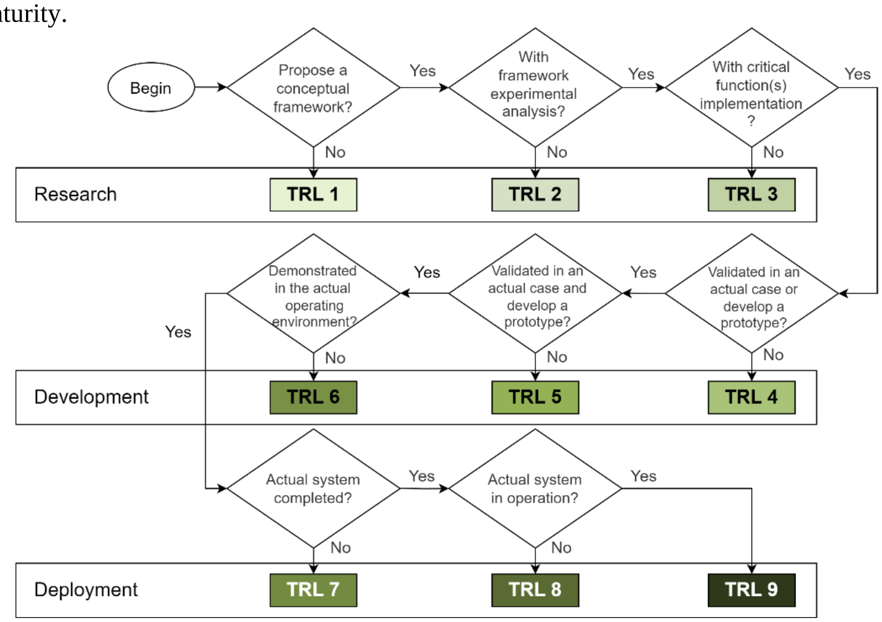

Figure 2: TRL evaluation workflow designed in this paper

As follow-up research, the classification of the construction sub-domains follows the research domain codification by Ye et al. (2022), as shown in Figure 1. To aggregate technical findings across studies, a comprehensive list of first- and second-level codes is presented in Table 1, serving as the foundation for technical aspect codification. The first-level codes are derived from frequently mentioned technical terms in the collected journal articles. These first-level codes are subsequently organized into more specific second-level codes. Through this systematic codification process, five key technical aspects for the adoption of BC and SC in the construction field have been identified from the 44 collected articles: 1) Technology Integration, 2) User Management, 3) Data Management, 4) Process Management, and 5) Privacy and Security. In the end, a comprehensive discussion can be developed by cross-analyzing the articles from multiple perspectives, including TRLs, construction sub-domains, and technical aspects.

First-level code	Second-level code
Internet of Things (IoT), Building Information Modeling (BIM), fog computing, electric power transmission networks, Artificial Intelligence (AI), Virtual Reality (VR), embedded systems, edge computing, deep learning, learning systems	Technology integration
human, user, stakeholder, multiple stakeholders, worker, trust, behavioral research, accountability, access control, authentication	User management
information management, digital storage, data storage, data sharing, information sharing, cloud computing, big data, data integrity, data handling, cloud storage, data sensitivity, transparency, traceability, large-sized information, off-chain data	Data management
decision making, automation, computer-aided instruction, optimization, process model, computational modeling, Business Process Model and Notation (BPMN)	Process management
network security, cryptography, security, privacy, zero-knowledge proof, permissioned, privacy-preserving, privacy protection, computer security, public key cryptography	Privacy and security

Table 1: Technical aspect codification

4. Cross-Analysis and Results

4.1. Descriptive Analysis

The distribution of collected publications from 2021 to September 2024 is illustrated in Figure 3. The noticeable annual increase in the number of publications signifies ongoing technical advancements of this research in this sector. Additionally, the TRL of these publications shows a slight annual increase. The significant rise in TRLs observed in 2024 highlights the growing recognition of BC and SC's potential, their technical implementation, and their application in real-world construction case studies. This trend suggests that this research may continue to grow in the near future.

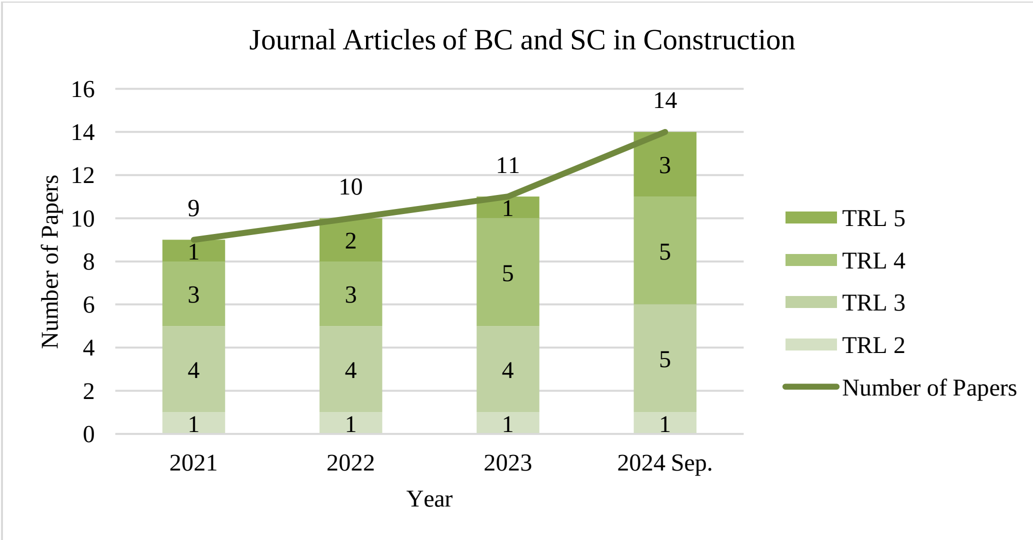

Figure 3: Year and TRL distribution of the collected journal articles in construction

Figure 4 presents the distribution of the collected publications by year, TRL, and construction sub-domain. The data highlights that supply chain, site management, payment, and contract are the most researched areas in BC and SC studies within the construction sector, particularly about technological adoption. Notably, publications on-site management are characterized by higher TRLs, indicating more advanced, ready-to-implement solutions. Both supply chain and site management stand out as the domains with the highest TRLs, reflecting their maturity for practical application. In contrast, technical advancements in facility management and administration are limited, while research on quality management remains predominantly theoretical.

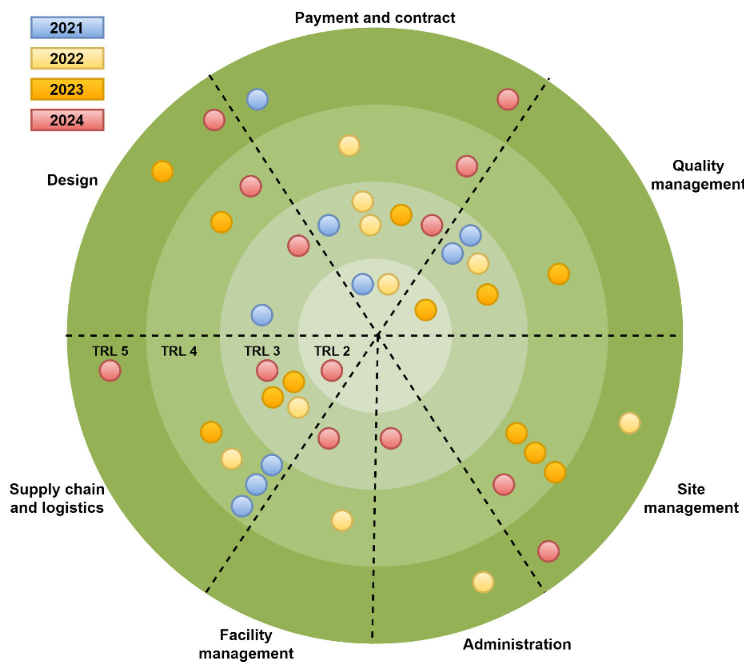

Figure 4: Year, TRL, and construction sub-domain distribution of the collected journal articles in construction

4.2. Detail analysis and results

To provide a targeted analysis of the current state of technical adoption and derive insights from academic research within the construction sector, this section focuses on the detail analyzing publication achieved at least TRL 4 to discover the technical status of this research. In total, 23 articles were analyzed (15 at TRL 4 and 8 at TRL 5), with their findings summarized in Table 2. These articles are evaluated based on their specific construction sub-domain, the selected BC platform, whether a prototype is developed or a case study is included, and the extent to which each technical aspect is thoroughly addressed.

Reference	**Construction sub-domain**	**BC platform**	**Case study /Prototype**	**Technical aspects**					
				TI	**UM**	**DM**	**PM**	**P&S**	**Sum**
TRL 4									
X. Li et al. (2021)	SC&L	HLF	Both	○	◐	◐	○	○	**1**
Lu et al. (2021)	SC&L	HLF	Both	◐	◐	◐	○	○	**1.5**
Tezel et al. (2021)	SC&L	Ethereum	Prototype	○	●	○	○	●	**2**
X. Li et al. (2022)	SC&L	HLF	Both	◐	◐	◐	○	○	**1.5**
van Groesen and Pauwels (2022)	Facility management	Ethereum	None	◐	◐	◐	○	○	**1.5**
L. Wu et al. (2022)	Payment and contract	HLF	Prototype	○	◐	◐	◐	○	**1.5**
Y. Celik et al. (2023)	Design	Ethereum	Prototype	◐	◐	◐	○	◐	**2**
Chen et al. (2023)	Site management	Ethereum	Both	◐	○	◐	◐	○	**1.5**
Lu et al. (2023)	SC&L	HLF	Both	○	◐	○	◐	◐	**1.5**
Naderi et al. (2023)	Site management	Ethereum	Prototype	◐	●	◐	○	○	**2**
H. Wu et al. (2023)	Quality management	HLF	Prototype	◐	◐	◐	◐	○	**2**
Xiao et al. (2023)	Site management	Ethereum	None	◐	◐	◐	○	○	**1.5**
Bahnas et al. (2024)	Site management	Ethereum	Prototype	◐	○	◐	◐	○	**1.5**
Liu et al. (2024)	Design	HLF	Prototype	◐	◐	◐	◐	○	**2**
Pham et al. (2024)	Payment and contract	Ethereum	Case study	◐	◐	◐	◐	○	**2**
Percentages of technical aspects in TRL 4 (%)				***36.67***	***50.00***	***43.33***	***23.33***	***13.33***	***33.33***
TRL 5									
Sigalov et al. (2021)	Payment and contract	GoQuorum	Both	◐	◐	●	○	◐	**2.5**
Adel et al. (2022)	Administration	IBM BC	Prototype	●	◐	●	○	○	**2.5**
Yang et al. (2022)	Site management	HLF	Case study	◐	◐	●	○	●	**3**
Tao et al. (2023)	Design	HLF	Prototype	◐	◐	●	○	◐	**2.5**
Bao et al. (2024)	Site management	Ethereum	Prototype	●	◐	●	◐	○	**3**
Ding et al. (2024)	SC&L	HLF	Prototype	◐	◐	●	○	◐	**2.5**

Lu and Wu (2024)	Design	HLF	Both	◐	◐	●	○	◐	**2.5**
Ye et al. (2024)	Payment and contract	Ethereum	Prototype	●	●	◐	●	○	**3.5**
Percentages of technical aspects in TRL 5 (%)				***68.75***	***56.25***	***93.75***	***18.75***	***37.50***	***55.00***

SC&L = Supply chain and logistics; BC = Blockchain; HLF = Hyperledger Fabric; TI = Technology integration, UM = User management, DM = Data management, PM = Process management, P&S = Privacy and security; ○ = Not addressed, ◐ = Theoretically/Partially addressed, ● = Technically/Fully addressed.

Table 2: Comparative analysis of papers with TRL 4 and 5 according to the technical aspects

As shown in Table 2, for the TRL-4 articles, 5 out of 15 focus on "Supply Chain and Logistics", while 4 are centered on "Site Management". In the TRL 5 papers, 2 out of 8 cover topics related to "Design", "Site Management", and "Payment and Contract", respectively. Regarding BC platforms, Hyperledger Fabric (HLF) and Ethereum are the most frequently used. Specifically, all the TRL-4 articles use either HLF or Ethereum. In TRL 5, 50% of articles use HLF, and 25% use Ethereum. Other BC platforms, such as GoQuorum and IBM Blockchain, are occasionally used in TRL 5 studies, indicating a shift toward broader platform exploration at higher TRLs. When evaluating the technical aspects of each article, a full solid circle (●) represents that the target technical aspect is fully addressed in the article (counted as 1), a half solid circle (◐) denotes partial or theoretical consideration (counted as 0.5), and an empty circle (○) means the aspect is not addressed (count as 0). Papers at TRL 4 typically score between 1 and 2 across all five technical aspects, while those at TRL 5 score between 2.5 and 3.5. In terms of practical implementation, 12 of the 15 TRL-4 articles have developed a prototype, and 6 have tested their framework in a use case. Only two TRL-4 articles neither developed a prototype nor tested their frameworks. At TRL 5, 7 out of 8 papers have developed a prototype, with 3 having tested their frameworks in real-world case studies. According to the percentages of technical aspects, most of the aspects in TRL 5 are higher than TRL 4, except for the process management aspect. In the following sub-sections, articles that fully address the technical aspects are analyzed in detail aspect by aspect to assess the current state of technical development and to extract key insights from their findings.

4.2.1 Technology Integration

Technology integration is a critical aspect of advancing the construction sector through the adoption of BC and SC. In TRL 4, numerous articles have explored the potential of integrating BC and SC with other advanced technologies such as BIM, IoT, Artificial Intelligence (AI), and digital twins. However, it is noteworthy that none of these articles have provided technical or practical validation of their proposed concepts. This indicates a gap between theoretical exploration and practical implementation at this TRL, highlighting the need for more empirical research and real-world applications.

Conversely, in TRL 5, the discussion around integrating BC and SC with other technologies is more advanced, with seven studies fully addressing the aspect. For instance, Adel et al. (2022) proposed a blockchain-based chatbot system for information management in construction firms, specifically targeting work progress tracking in construction projects. The chatbot leverages IBM Watson Assistant, and the blockchain network is built using the IBM Blockchain Platform, while the connection between the chatbot and the network is via IBM Cloud Functions and IBM Cloudant Databases. This solution reduces the technical difficulty of using blockchain for construction stakeholders. Bao et al. (2024) proposed a token-based incentive framework for Virtual Reality (VR) safety training and tested it via prototype development (uploading the VR model to the cloud, and safety scenario metadata to the blockchain). Ye et al. (2024) developed a generation tool that converts Business Process Model and Notation (BPMN) to Solidity, which is open-sourced on GitHub (2024c) and implemented a decentralized application (DApp) to visualize a real-time payment process via a BPMN diagram. These examples demonstrate the practical applications and benefits of integrating blockchain with other technologies in the construction sector, paving the way for more innovative solutions.

4.2.2 User management

User management refers to the control of user roles, user collaboration, permissions, and access in BC and SC systems. It is frequently discussed in the collected articles, although it often lacks technical depth. At TRL 4, Tezel et al. (2021) proposed three BC and SC-based models for supply chain management, which are project bank accounts (PBAs) for payments, reverse auction–based tendering for bidding, and asset tokenization for project financing with role configuration and access control. The source code of these three models is available as open source on GitHub (2024b). Naderi et al. (2023) proposed a method to combine computer vision, InterPlanetary File System (IPFS) with BC and SC, and tested the user management component through the SafetyCredit DApp, also open-sourced on GitHub (2024a). At TRL 5, Ye et al. (2024) advanced user management by integrating BPMN with SC to control the user role for task execution with source code available on GitHub (2024c). These advancements underline the importance of secure and scalable user control mechanisms in BC and SC-based applications within the construction industry.

4.2.3 Data management

Data management involves the organization, storage, and handling of data within blockchain networks, including on- and off-chain strategies. In the reviewed papers, it is primarily addressed through two approaches: 1) on- and off-chain data handling, and 2) BC network configuration and SC coding for data management. At TRL 4, Adel et al. (2022) proposed a chatbot system that integrates on-chain and off-chain data management for tracking construction progress, simplifying BC and SC adoption for construction stakeholders. The chatbot is built using IBM Watson Assistant, and the blockchain network is constructed using the IBM Blockchain Platform. This solution simplifies the technical complexities associated with blockchain adoption for construction stakeholders.

In TRL 5, most of the studies have provided technical insights into the data management aspect. The BIMcontracts approach proposed by Sigalov et al. (2021) integrates blockchain and smart contracts with Common Data Environment (CDE) and payment services for payment automation and contract management. In this approach, the smart contract is initialized firstly by a billing container using the Information Container for Linked Document Delivery (ICDD) technology, then configured in JSON format, and deployed to the blockchain. Billing information is securely stored on the blockchain, enhancing payment accuracy and transparency. Tao et al. (2023) manage to store a BIM model fingerprint, user ID, and process status on the HLF blockchain to handle BIM data sharing and issue management by implementing corresponding smart contracts. Bao et al. (2024) proposed a token-based incentive framework for VR safety training and tested it via a prototype development with a configuration of Avalanche primary network and subnet for different data storage. Ding et al. (2024) focused on information sharing by channel controlling and data access control via smart contracts in HLF blockchain and IPFS. Lu and Wu (2024) proposed a blockchain-based framework to protect building design intellectual property rights in the AEC industry. Each BIM design version is hashed as a Non-Fungible Token (NFT), with data stored in CouchDB and IPFS. These approaches demonstrate innovative solutions for secure and efficient data management in the construction sector.

4.2.4 Process management

Process management refers to the coordination, monitoring, and execution of tasks and workflows in construction projects, particularly how they are governed through blockchain and smart contracts. It remains a challenging but vital aspect of the construction sector. At TRL 4, seven papers address the topic theoretically, but none provide significant technical insights, signaling a substantial gap in practical process management solutions at this stage. This gap highlights the need for more research and development to bring theory into practice in process management. At TRL 5, only two papers address process management, with just one offering technical insights. Ye et al. (2024) developed a solution for real-time process monitoring by integrating BPMN with smart contracts, providing a practical method for managing complex construction processes in real time. Process management remains a challenging topic in construction due to the complexity and uniqueness of each project. Future research could focus on developing more robust and practical solutions for process management in the construction industry.

4.2.5 Privacy and security

Privacy and security in blockchain systems for construction focus on enhancing data protection (both on-chain and off-chain) and ensuring secure access control to different sensitive levels of construction data. Although less frequently discussed than data management in general, each TRL (4 and 5) includes at least one paper with technical insights in this area. In TRL 4, Tezel et al. (2021) proposed models for supply chain management that incorporate role configuration and access control to enhance data privacy and security. These models are available as open-source resources on GitHub (2024b), encouraging further exploration and development. In TRL 5, Yang et al. (2022) developed a JavaScript and Chaincode-based solution to verify scaffolding work by comparing parameters such as location and quantity throughout various stages—ordering, procurement, and installation. This approach enhances the accuracy and security of scaffolding processes, ensuring the reliability of construction projects. These advancements underscore the importance of robust privacy and security measures in BC and SC-based construction applications, ensuring the system access control and the integrity of construction processes.

5. Discussion

The reviewed articles show diverse applications of BC and SC at different TRLs. Based on the analysis and results, the three research questions proposed in the introduction can be answered. The construction sub-domains “Supply chain and logistics” and “Payment and contract” showcase the greatest potential for the adoption of BC and SC technologies. At TRL 4, most studies focus on supply chain and logistics or site management, while TRL 5 broadens to include design and payment management. HLF and Ethereum are the dominant platforms in TRL 4, but TRL 5 studies explore other platforms like GoQuorum and IBM Blockchain, reflecting increased technical diversity. TRL 5 papers generally address technical aspects more thoroughly, scoring higher in areas like data handling and process management. While TRL 4 studies remain more theoretical, both levels demonstrate practical progress, with most TRL 5 studies developing prototypes and testing them in real-world scenarios. This shift from theory to practice highlights the growing maturity of BC applications in construction. The integration of BC and SC presents numerous advantages, such as increased trust between parties, streamlined payment processes, and improved supply chain management. BC and SC can enhance contract execution by automating tasks and enforcing compliance through coded agreements, reducing disputes and delays. Additionally, these technologies improve data integrity and transparency across project lifecycles, enabling better decision-making and reducing inefficiencies. The integration of BC and SC presents numerous advantages, such as increased trust between parties, streamlined payment processes, and improved supply chain management. BC and SC can enhance contract execution by automating tasks and enforcing compliance through coded agreements, reducing disputes and delays. Additionally, these technologies improve data integrity and transparency across project lifecycles, enabling better decision-making and reducing inefficiencies.

Despite the potential benefits, there are several barriers to the widespread adoption of BC and SC in the construction industry. A key issue is the lack of sufficient technical insights in many studies. For instance, while many studies offer comprehensive solutions addressing various construction engineering aspects, a key limitation remains the lack of focus on fundamental challenges such as further improving privacy and security to fit construction practices in BC and SC applications. This issue is particularly critical for high-potential areas like the construction sub-domain “Payment and contract”, where secure data handling (especially for off-chain data) is essential. Addressing this gap requires advanced development in BC and SC technology to ensure robust privacy and security measures are in place, enhancing their reliability and adoption in the construction industry. While BC and SC show great promise, there is still significant room for improvement in the depth of technical understanding and practical applications. Current solutions tend to lack realism and are not sufficiently developed to address the industry’s specific needs, limiting their practical utility. The adoption of BC and SC in the construction industry is further hindered by industry fragmentation, insufficient digital infrastructure, and resistance to technological change. This fragmentation limits collaboration among industry players, making it challenging to develop standards and share valuable information that could facilitate widespread implementation. Achieving standardization across the construction sector is crucial for the scalable adoption of these technologies. Additionally, transitioning from academic research to practical industry applications presents significant challenges, including the need for regulatory alignment and the development of industry-specific, scalable solutions.

Looking forward, the integration of BC and SC with emerging technologies such as AI, IoT, and digital twins is anticipated to play a pivotal role in overcoming these barriers. These integrations could enable advanced predictive analytics, enhance real-time data sharing, and improve operational efficiencies across construction projects. Future trends also suggest a growing focus on decentralization, with applications in autonomous supply chain operations and enhanced stakeholder collaboration through distributed decision-making frameworks. Furthermore, as the construction industry increasingly adopts green building practices, blockchain could support sustainability efforts by offering transparent systems for tracking carbon footprints and verifying eco-friendly materials. Process management, an area where technical insights are currently limited due to the complexity and uniqueness of construction workflows, represents another promising avenue for future research and development. Addressing these challenges while capitalizing on emerging trends will be essential for unlocking the full potential of BC and SC in the construction sector. While BC and SC offer significant potential for transforming the construction industry, especially for supply chain, payment, and contracts, there is a clear need for deeper technical exploration, improved collaboration, and practical solutions tailored to industry challenges. Addressing these barriers will be critical for enabling the successful adoption of these technologies in the construction sector.

6. Conclusion

This paper provides a comprehensive review of blockchain and smart contract (BC and SC) implementations in the construction industry, exploring their potential benefits and challenges. By analyzing 44 journal articles published between 2021 and 2024, this study identifies key technical aspects essential for BC and SC adoption, including technology integration, user management, data management, process management, and privacy and security. The findings reveal that while BC and SC hold significant promise for transforming the construction industry, much of the research remains in early stages, with many solutions still conceptual or experimental. Advanced technological maturity is evident in areas like supply chain, site management, and payment systems, but other domains such as quality and facility management remain underexplored. This indicates a need for more targeted, industry-specific solutions that address construction’s unique challenges, including process complexity and data security.

Future research should focus on bridging the gap between theoretical models and real-world applications of BC and SC in the construction industry. One critical area is the further development of practical, industry-specific solutions that can address issues like the complexity of construction processes and off-chain data security. More detailed investigations into process management could help translate theoretical advancements into scalable, implementable systems. Furthermore, exploring cross-sector collaborations to develop unified standards and protocols for BC and SC in construction will help promote broader industry adoption. These efforts should focus on creating interoperable systems that can streamline operations across diverse project environments. Another promising avenue for future development is incorporating emerging technologies like BIM, IoT, and AI with BC and SC. This integration can improve automation, transparency, and efficiency in construction processes. However, challenges around scalability, standardization, and implementation must be addressed before these technologies can be widely adopted. While the potential of these integrations is often overstated, a strategic combination of BC, SC, and these tools offers the possibility of more streamlined, secure, and data-driven construction workflows. Advancing privacy and security measures within BC and SC systems is crucial, especially as construction projects involve large-scale data with complex hierarchy and multiple stakeholders. Addressing these issues will enable the development of robust, practical applications that move beyond theoretical discussions, positioning BC and SC as key enablers of digital transformation in the construction sector.

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