Review

When Blockchain Meets the AEC Industry: Present Status, Benefits, Challenges, and Future Research Opportunities

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Abstract: Blockchain is regarded as a potential technology for transforming the architecture, engineering, and construction (AEC) industry, and the number of related publications is increasing rapidly. However, a systematic review of blockchain applications in the AEC industry is lacking. The objective of this study was to review the current status of blockchain applications via a bibliometric analysis combined with a systematic literature review. According to related articles collected from databases, the present status of blockchain was analysed with regard to the distribution of articles over publication years, journals, institutions, countries, cooperation networks between authors, keyword co-occurrence networks, and research methodologies. The results indicated that research on blockchain applications is still relatively new and fragmented with regard to several topics. Five areas of benefit were identified: (i) supply chain management, (ii) contract management, (iii) information management, (iv) stakeholder management, and (v) integration management. On the basis of the technology–organisation–environment framework, nine types of challenges were identified. Future research opportunities were proposed according to the research findings. This study contributes to the current body of knowledge and provides guidelines for further research on blockchain applications in the AEC industry.

Keywords: blockchain; AEC industry; benefits; challenges

1. Introduction

The architecture, engineering, and construction (AEC) industry is facing unprecedented challenges with the increasing investment scale, uncertainty, and complexity of such projects. Poor communication, information sharing, and workflow control among participants are the major challenges faced by the AEC industry, which cause low efficiency and poor performance [1–3]. Blockchain technology has potential for transforming the conventional AEC industry [4,5] and thus may be useful for solving these issues. Blockchain enhances the traceability, transparency, and accountability of business processes during the project lifecycle, improving information sharing, enhancing transparency, and addressing trust problems [6,7].

Blockchain has received increased interest from AEC researchers because of its potential benefits. For example, smart contracts are being deployed to facilitate payment security [8]. Novel blockchains are being used to solve information gaps in the construction supply chain [7]. Blockchain has been integrated with the building information model (BIM) to improve the BIM working environment [9,10]. However, the AEC industry still lags behind other industries [11]. To improve blockchain adoption in the AEC industry, researchers must present AEC practitioners with a comprehensive review of blockchain applications—particularly the potential benefits and challenges. There is a limited understanding of blockchain applications in the AEC industry.

Blockchain applications in the AEC industry have been reviewed in previous works. Wang et al. [12] and Dakhli et al. [13] described the potential applications of blockchain in the construction sector. San et al. [14] identified the potential uses and implications of

blockchain applications in the construction industry. Yang et al. [11] illustrated the process, benefits, and challenges of adopting private and public blockchains in the construction domain through a pilot study. Although these studies enhance our understanding of blockchain applications in the AEC industry, few rigorous and empirical academic studies have been performed on the benefits and challenges of blockchain. Perera et al. [15] summarised the potential applications and challenges of blockchain applications in the construction industry and confirmed blockchain indeed has a credible potential in the construction industry. Li et al. [4] conducted a systematic review of the use of blockchain in built environments and compiled an extensive list of challenges and opportunities presented by blockchain across four dimensions (technical, process, policy, and social). These two studies reviewed blockchain in construction as a whole. However, with the rapid development of blockchain in recent years, related research has been published but remains in a fragmented state. Additionally, previous research lacks a review of the potential advantages, challenges, and future research opportunities. Therefore, on the basis of previous studies, a mixed-method approach of bibliometric analysis and systematic review was adopted to investigate the research on blockchain applications in the AEC industry for answering the following research questions (RQs):

RQ1. What is the present status of blockchain applications in the AEC industry?
RQ2. What are the benefits of blockchain applications in the AEC industry?
RQ3. What are the challenges of blockchain applications in the AEC industry?

The objectives of this study were to (i) identify the knowledge base regarding blockchain applications in the AEC industry, e.g., information on related journals, institutions, authors, and keywords; (ii) identify the benefits of blockchain applications in the AEC industry; and (iii) identify the challenges of blockchain applications in the AEC industry. According to these objectives, future research directions for the topic were also analysed. These goals were achieved through three phases of research. The first was a bibliometric search of the literature, followed by a quantitative analysis for constructing science maps. Finally, a content analysis was conducted by presenting the benefits and challenges of blockchain applications in the AEC industry.

The remainder of this paper is organised as follows. Section 2 describes the research methodology and the results are presented in Sections 3 and 4. Sections 5 and 6 present a discussion of the results and an outline of future research opportunities, respectively. Finally, the conclusions and research limitations are summarised in Section 7.

2. Research Methodology

A bibliometric analysis combined with a systematic review was employed to map and analyse existing knowledge regarding blockchain applications in the AEC industry. Bibliometric analysis refers to the use of statistical methods to measure the quality and quantity of publications. Quantitative bibliometric tools describe the development of scientific knowledge in a field [16] and are important for analysing and predicting future research opportunities. Wallin [17] defined systematic review as a method of document identification that can identify, evaluate, and comprehensively analyse basic research to answer specific topics. The systematic review method provides a transparent and replicable selection process that can improve the validity and reliability of research results.

First, both the Scopus and Web of Science databases were used to perform a systematic search of the relevant literature. This is because they not only cover a broad range of scientific publications but also have a high indexing speed. The search continued until the end of April 2021. The formula for the search string was as follows: 'blockchain' OR 'smart contract' OR 'distributed ledger' AND 'architecture' OR 'engineering' OR 'construction' OR 'design' OR 'building'. A total of 1453 articles were initially identified in the preliminary search. Journal or conference articles written in English were retained. Duplicate literature from the two databases was then eliminated. Thus, 1012 articles were finally identified and retrieved for further analysis.

Next, we implemented a two-stage selection strategy based on the following criteria: (a) blockchain is the main research theme in the article (because some articles mentioned the concept of blockchain although it was not the focus of the study); and (b) the application field of blockchain is related to the AEC industry. For the first stage, we carefully checked the title, abstract, and keywords of each article. Next, we carefully reviewed the content of the selected articles to ensure that they were closely related to the RQs. A total of 137 articles were selected for the analysis. Finally, we downloaded and read the full text of these articles. Among them, 7 articles were incomplete, and 35 were inconsistent with the research topics. Additionally, 15 articles were obtained from other databases through snowball sampling. Finally, a total of 116 articles were retained. The process is illustrated in Figure 1.
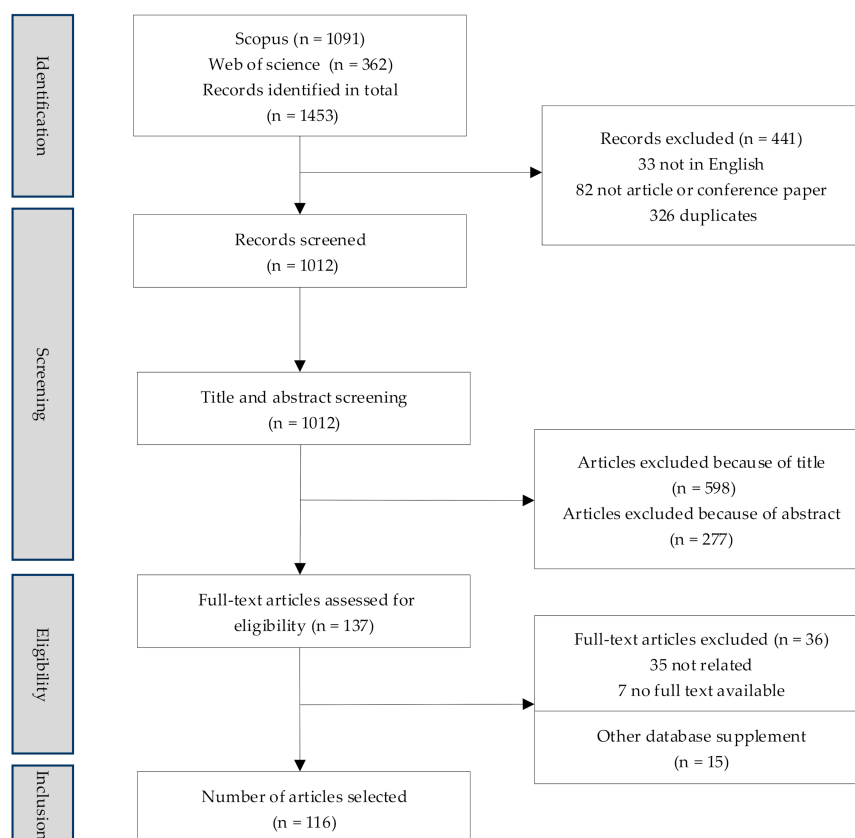

Figure 1. Overall flow of the review process and strategy.

3. Results of Bibliometric Analysis

To answer RQ1, a bibliometric analysis was conducted for constructing science maps regarding the publication years, journals, countries, institutions, authors, research methods, and author keywords.

3.1. Chronological Publication Trend

The publication trend of blockchain applications in the AEC industry is shown in Figure 2. The first related paper was published in 2015, indicating that blockchain research is relatively new. Between 2008 and 2020, the total number of publications increased significantly, reaching 45 in 2020. This reflects the popularity of this research topic. Additionally, the number of published conference papers was almost double the number of journal papers between 2017 and 2019. This gap narrowed from 2019 to 2020; in 2020, journal papers outnumbered conference papers for the first time. This may be because preliminary research results and general concepts were reported at the early stage.
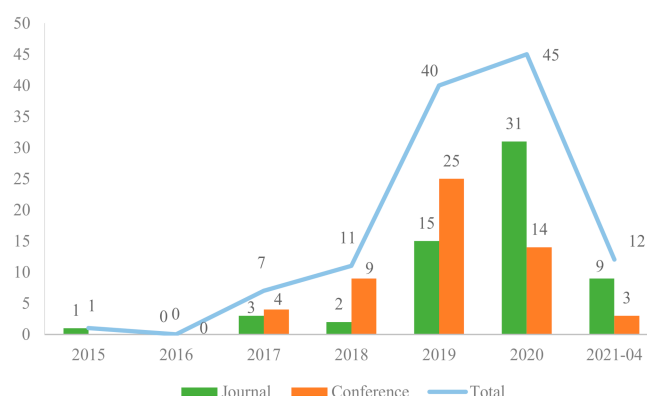
Figure 2. Paper distribution based on publication years.

3.2. Journals

A total of 36 journals were identified from the selected articles. Figure 3 presents the top eight journals with regard to the total number of publications. The largest number of publications (12 articles) came from Automation in Construction. The impact factor of this journal is 7.7, indicating its high impact. Frontiers of Engineering Management and Journal of Legal Affairs and Dispute Resolution in Engineering and Construction published five and four articles, respectively. *Buildings* had the fourth-most published articles, with a total of three articles. Therefore, these journals are crucial in the blockchain-based AEC industry, attracting scholars worldwide to submit their manuscripts.
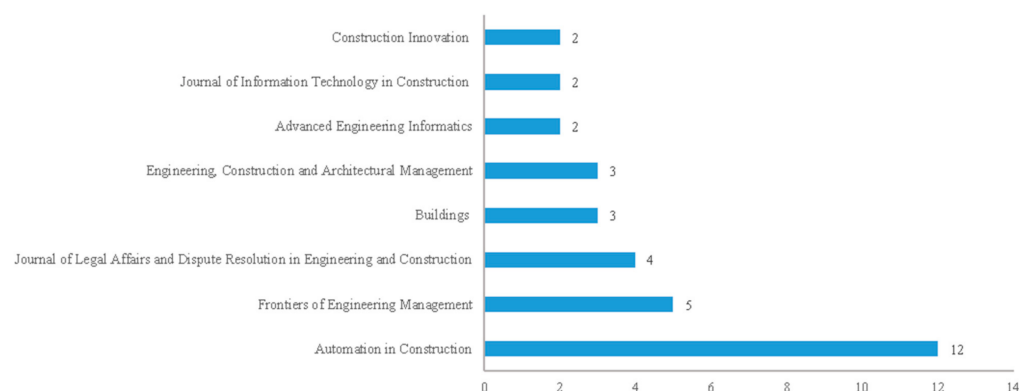

Figure 3. Top eight journals with regard to the number of articles published.

3.3. Countries

In Figure 4, the colours represent clusters and the three main clusters are illustrated. As shown, the collaboration network of countries forms a cluster of academic cooperation with Australia, the United Kingdom, and China as the core. Cluster 1 (red) includes three countries, cluster 2 (green) includes three countries, and cluster 3 (blue) includes two countries. Each node represents a country, and its size reflects the number of papers contributed by the authors in that country.

According to the node sizes shown in Figure 4, scholars from China were ranked first in terms of the number of publications (26 articles). This may be related to the Chinese government's regard for blockchain as a national strategy. Chinese scholars were followed by those from the United Kingdom and Australia, who contributed 23 and 19 articles, respectively. Thus, it can be considered that blockchain in the AEC industry has received significant attention in these countries. The United Kingdom ranked first among the countries in terms of article citations; articles published in the United Kingdom were cited 321 times. Developing countries, such as Slovenia, Lithuania, and Finland, published only one or two articles. However, the average number of citations for these countries was

large. For example, only one article was published in Slovenia, but it was cited 94 times; thus, Slovenia ranked fifth for citations, following South Korea. The results indicated that developing countries are gradually asserting their influence in this area.
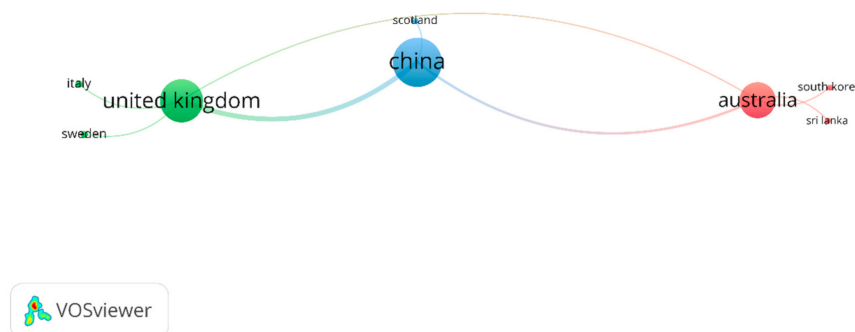

Figure 4. Network of cooperation between countries.

Concerning research linkages, the United Kingdom has the largest number of links (eight), indicating that it has collaborations with other countries. Next, China and Australia have seven and five links, respectively. The links in Figure 4 represent the existing cooperation between countries, and their thicknesses indicate the strength of cooperation between the two countries. The China–United Kingdom links were the strongest (4). Weak United Kingdom–Australia and Australia–South Korea linkages existed. Table 1 presents the top 10 countries with regard to the total number of published papers.

Table 1. Top 10 countries with regard to the total number of published papers.

No.	Countries	Documents	Citations	Average Citations
1	China	26	172	6.62
2	United Kingdom	23	321	13.96
3	Australia	19	220	11.58
4	United States	12	89	7.42
5	Sweden	5	21	4.20
6	Malaysia	5	13	2.60
7	Italy	4	13	3.25
8	India	4	4	1.00
9	Russian	2	18	9.00
10	Scotland	2	2	1.00

3.4. Analysis of Collaborative Networks of Institutions and Authors

A total of 110 institutions were identified from selected articles. The size of the node reflected the number of articles published by the institution [18]. As shown in Figure 5, Northumbria University had the largest node size, with 105 citations of the 6 published studies. Western Sydney University was ranked second, with 84 citations of 6 articles. The University of Florida was ranked third, with 63 citations of 5 articles. However, the distribution of the cooperation network of author institutions was relatively scattered. This is because blockchain research in the AEC industry is still in its infancy, and cooperation between institutions is not yet close. A feature of VOSviewer is that it groups the institutions into coloured clusters. Different clusters are represented by different colours. Cooperation exists between the institutions within the cluster. For example, as indicated by cluster 1 (red), six institutions (Central China Normal University; Curtin University; Hong Kong University of Science and Technology; Huazhong University of Science and Technology; Hubei Engineering Research Center for Virtual, Safe, and Automated Construction; and Kyung Hee University) have forged collaborative relationships with each other.
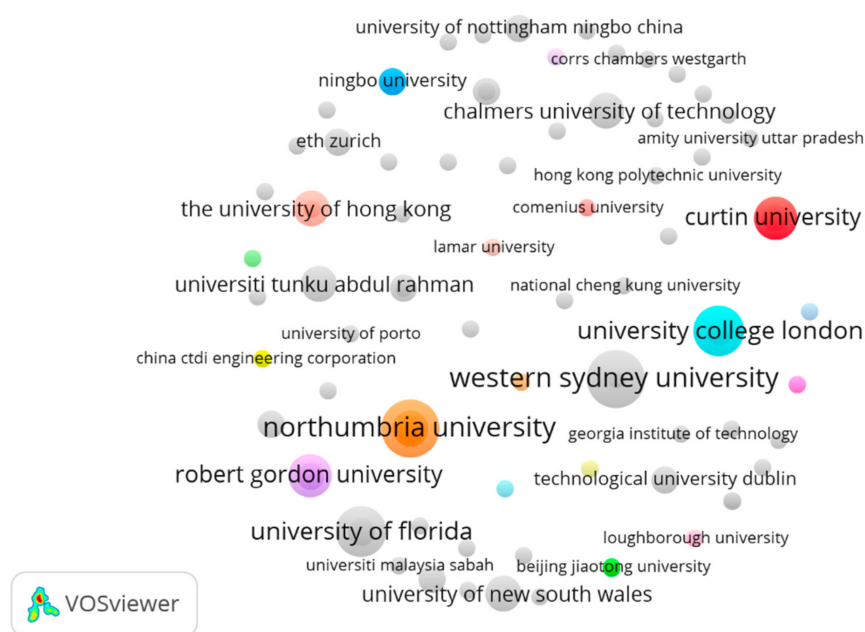
Figure 5. Network of cooperation between institutions.

A total of 278 researchers were identified from selected articles related to blockchain research in the AEC industry. The nodes were coloured according to the network links of the researchers. As shown in Figure 6, different clusters were represented by various colours, with each cluster being established around 1–3 core authors. The author cooperation network exhibited a decentralised layout. The largest author collaborative network cluster (red) was centred on Shou, WC., Cheng J.C.P., and Chen J., with a total of 13 authors. Among these authors, Li J. has published six articles, which were cited 105 times, making outstanding contributions to blockchain-related research in the AEC industry. Kassem M., Perera, S., Cheng J.C.P., and Das M. have published four articles each.

Figure 6. Author cooperation network.

3.5. Co-Occurrence Analysis of Keywords

Author keywords were used to describe the co-occurrence network. Keywords with the same meaning or similar meanings were integrated, such as 'smart contracts' and 'smart contract'. The threshold value for keyword occurrence was set as two to improve the representativeness and comprehensiveness of the clustering results. As a result, 39 of 226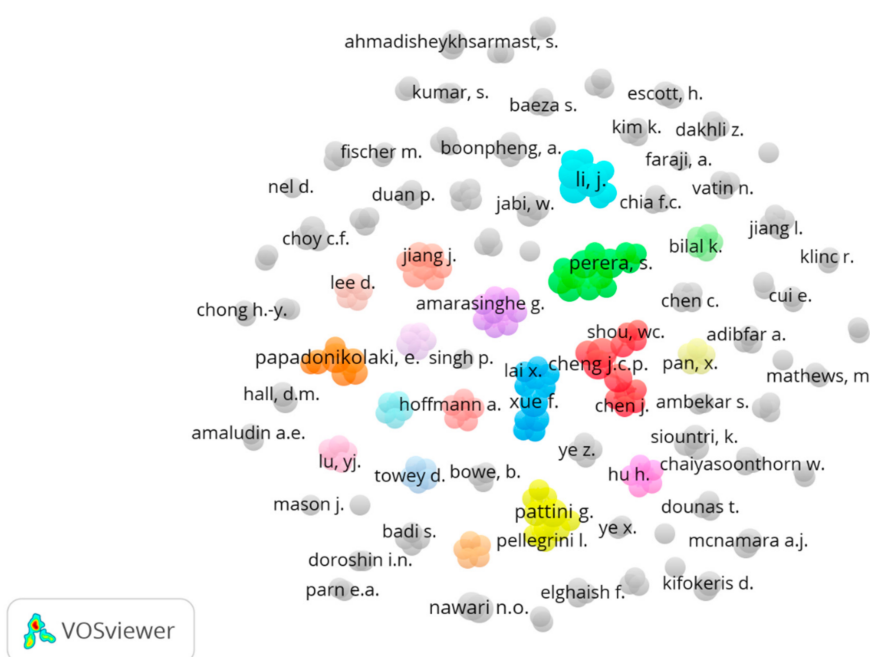 keywords reached the threshold value. Different colours represented different keyword clusters obtained using VOSviewer, and each cluster illustrated the corresponding association network. As shown in Figure 7, the co-occurring keywords were grouped into 10 clusters of different colours. For example, cluster 1 (red) refers to 'smart contract', and the main keywords were 'construction automation', 'construction contract', 'distributed ledger', 'information trust', 'procedure', and 'security of payment'. Cluster 2 (green) refers to 'BIM', and the main keywords were 'application', 'building information management', 'contract management', 'experience', 'supply chain management' (SCM), and 'trust'.
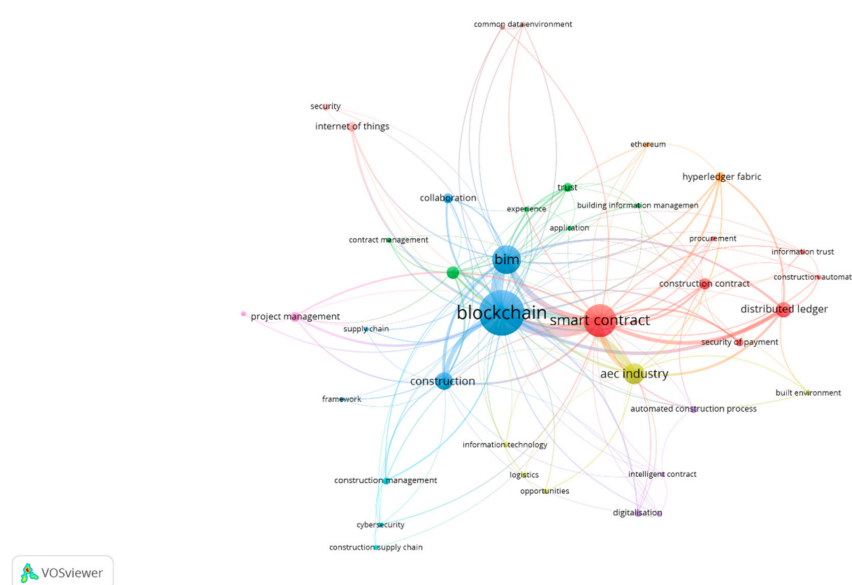
Figure 7. Keyword co-occurrence network.

In Figure 7, the node size indicates the occurrence frequency of each keyword. A larger node indicates that the keyword occurs more frequently in the literature. A thicker line between two keywords indicates a stronger association between their respective research areas [19]. As shown in Figure 7, 'BIM' and 'AEC industry' were the most frequently occurring keywords, excluding 'blockchain' and 'smart contracts'. A BIM is defined as a virtual three-dimensional building model that integrates a database of building elements [20]. Thus, the results indicate that the integration of BIM and blockchain has attracted considerable attention in the AEC industry. Moreover, SCM, construction contract management, construction automation, information management, and stakeholder management are research hotspots for blockchain in the AEC industry. However, few studies have addressed the challenges of blockchain applications in the AEC industry.

3.6. Research Methodologies

By reviewing selected articles, nine research methods were identified: general description, literature review, case study, questionnaire, expert interview, analytical hierarchy process (AHP), simulation modelling, interpretive structural modelling, and framework description. Conceptual analysis was used in 40% of the studies, which is consistent with the development of emerging research fields. This was followed by framework description (23%) and literature review (13%), as shown in Figure 8.

- General description
- Literature review
- Case study
- Questionnaire
- Expert interview
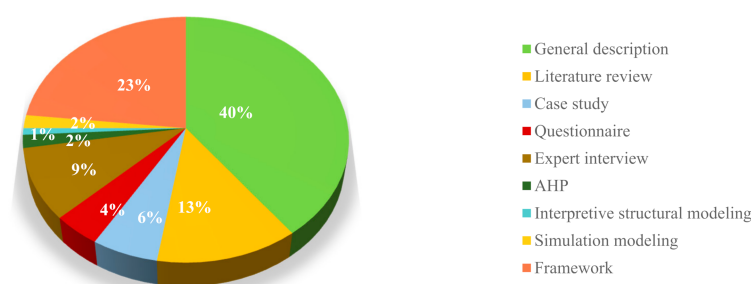- AHP
- Interpretive structural modeling
- Simulation modeling
- Framework

Figure 8. Classification of studies using different research methodologies.

4. Results of Systematic Review

In this section, we answer RQ2 and RQ3.

RQ2. What are the benefits of blockchain applications in the AEC industry?

By analysing and comparing the selected publications, the main benefits of blockchain in the AEC industry were summarised. Figure 9 illustrates the benefits of blockchain applications in five areas: SCM, contract management, information management, stakeholder management, and integration management. For detailed information about the selected articles, see Appendix A.

Figure 9. Benefits of blockchain applications in five areas.

4.1. SCM

There have been many studies on the construction supply chain (22 articles). SCM involves design documents, purchased equipment, materials, human resources, and engineering equipment. The construction industry has a complex supply chain, and blockchain can enhance the present SCM process through the use of public licenses [11]. The construction industry routinely relies on documents or centralised platforms to manage relevant information, from project procurement to final delivery. Information security is one of the main challenges faced by construction SCM, because of transparency and trust issues [21]. Blockchain can address these challenges by enhancing the transparency and traceability of the construction process. For example, Wang et al. [7] constructed a blockchain-based framework to improve supply chain traceability and information sharing during precast construction. Similarly, Zhang et al. [22] proposed an integrated framework based on blockchain that can effectively achieve decentralisation and openness. Additionally, the influence mechanism of blockchain on trust has received attention. Qian and Papadonikolaki [6] examined how blockchain affects trust in construction SCM according to industry experience. The results indicated that blockchain benefits trust relationships through system- and cognitive-based trust, reducing the demand for establishing trust. Sun and Wang [23] used an analytic hierarchy process to analyse the relationship between blockchain and trust.

Through an empirical investigation, De La Peña and Papadonikolaki [24] identified nine intrinsic blockchain attributes that promote customer trust in contractors.

4.2. Contract Management

There were 25 articles on contract management. Most of them discussed the potential benefits of blockchain in construction contracts, and some focused on the general concepts. For example, Dakhli et al. [13] and Shou et al. [12] discussed the potential application of smart contracts in the construction industry and confirmed their advantages for improving time efficiency and cost savings. According to these studies, the benefits of smart contracts include the reduction of paperwork and the resolution of non-payment, late payment, and trust issues in construction contracts. Furthermore, the design of the smart-contract secure payment framework was investigated. Froese et al. (2007) emphasised that problems related to project payment are common in the construction industry. The application of smart contracts in the AEC industry can alleviate these problems. For example, Ahmadisheykhsarmast and Sonmez [25] designed a payment security system based on smart contracts and demonstrated its utility in making construction payments using actual engineering cases. A smart construction contract framework for automating construction payments was proposed by Luo et al. [26]. Ye and König [27] proposed an automatic billing framework that combines a BIM with smart contracts to simplify the payment and construction processes. Chong and Diamantopoulos [28] found that smart contracts are recognised as an advanced technology for solving construction payment security problems, and they developed a DFD framework that integrated blockchain and other advanced technologies to support the implementation of automated payment systems.

4.3. Information Management

There were 21 articles on information management. They mainly discussed the application of blockchain to construction documents, particularly for resolving transparency and trust issues. Owing to the complexity of construction projects, a large amount of data must be recorded and stored during project implementation. Additionally, such projects face various changes over time, requiring multiple revisions of construction information. Thus, there may be trust issues, information errors, and difficulties in regulation. Blockchain is a key solution that provides a reliable information-management infrastructure at all project stages. It improves the security and timeliness of data storage and recording during construction [9,29,30] and facilitates efficient and traceable data changes [31,32]. Furthermore, construction projects involve many stakeholders. Therefore, information sharing and integration are critical to the success of such projects. However, poor collaboration is common in the AEC industry. Blockchain is useful for solving these problems. For example, to address the problem of automated information sharing in a prefabricated supply chain, Wang et al. [7] designed and evaluated a blockchain-based BIMF-PSC model. Jo et al. [33] proposed a distributed architecture and evaluated its effectiveness of the model for data security and transparent information sharing. Yang et al. [11] found that blockchain can record and track transaction information. Moreover, they reported that information-integration benefits reduce the fragmentation and complexity of the industry and ensure transparent, traceable information sharing. Scholars have also studied the quality of information management in construction projects. For example, Sheng et al. [34] performed construction quality information management with blockchains and achieved a consistent, safe, and high-quality information management system. Zhong et al. [35] proposed a blockchain-based framework to realise a distributed, encrypted, secure database record and support automated compliance checks, promoting construction quality management.

4.4. Stakeholder Management

There was a total of 13 articles related to stakeholder management research. Most of them stated that blockchain can achieve its potential by enhancing collaboration among stakeholders. Goh et al. [36] and Shi et al. [37] proved that blockchain can improve the

efficiency of stakeholder collaboration and enhance construction quality. Other researchers examined the needs and opinions of stakeholders regarding blockchain adoption in the AEC industry. For example, Nanayakkara et al. [38] investigated the views of stakeholders regarding blockchain applications in the Australian construction industry and identified 18 unique views. The most prominent factors were efficiency, trust, fairness, safety, transparency, accountability, compliance, and standardisation. Chaveesuk et al. [39] used an extended TAM model to analyse the determinants of the Thai construction industry's intention to adopt blockchain. Specifically, the perceived financial costs, convenience, trust, and readiness directly affected the behavioural intentions and had an indirect effect on perceived usefulness and ease of use. Although many studies have indicated that stakeholders have a positive attitude towards the adoption of blockchain, there are opposing opinions. For example, Mason and Escott [40] investigated stakeholder attitudes towards technology and concluded that the full realisation of automation is doubtful.

4.5. Integration Management

Many papers (up to 39) focused on the theme of integration. Table 2 presents the integration of blockchain with the Internet of Things (IoT), BIM, and other emerging technologies. Among them, the integration of blockchain with BIM has been most widely explored. For example, Xue and Lu [41] developed an innovative semantic difference transformation model that can capture continuous and synchronous changes, minimising information redundancy and supporting BIM and blockchain integration. Only one study focused on the integration of blockchain with Big Data to optimise the management of architectural employees. Integrating blockchain with BIM and IoT has attracted the attention of scholars in the AEC industry. This is because blockchain can solve many problems in the industry, e.g., enhancing trust in automatic payment, efficient procurement, transformation of the construction process, and design information management. Additionally, the integration of blockchain with multiple emerging technologies has attracted the interest of scholars. Lokshina et al. [42] investigated the application of integrated BIM, IoT and blockchain technologies in system design of a smart building. These technologies are complementary and can be combined to enhance information security management and improve the provision of IoT services. However, the integration of blockchain with artificial intelligence (AI) and machine learning (ML) is mostly at the conceptual stage. For example, Mathews et al. [43] introduced the integration of blockchain with AI and ML but did not conduct an in-depth study.

RQ3. What are the challenges of blockchain applications in the AEC industry?

Although blockchain offers many potential benefits to the AEC industry, several challenges must be addressed. The nine types of blockchain application challenges are presented in Figure 10. These were divided into technical (45 articles), organisational (29 articles), and environmental (27 articles) challenges. Details regarding the identified challenges are discussed below.

4.6. Technology-Related Challenges

A total of 45 articles dealt with challenges related to blockchain that hinder its application. The challenges described in the literature include those pertaining to throughput and latency, scalability limitations, technical interoperability issues, speed and data storage limitations for large amounts of data, and smart-contract coding and deployment. Hunhevicz and Hall [5] summarised the use cases of blockchain in the construction of distributed-ledger technologies (DLTs), arguing that throughput, data storage, and interoperability may be constraints related to the final DLT design. Sheng et al. [34] and Kiu et al. [73] reported that smart-contract coding and deployment in the construction industry are challenging because construction contracts involve complex clauses and many participants. Li et al. [4] presented a forward-looking framework based on smart contracts and determined that DLT scalability and interoperability between systems are the main technical barriers. Additionally, some studies revealed that privacy and security are inter-

related technical issues. According to the reports of Tezel et al. [74] and Hamledari and Fischer [75], blockchains are vulnerable to cyberattacks, wherein attackers gain control of most of the blockchain network. Fragmentary research has been performed on other challenges associated with integration, such as system integration challenges. Hijazi et al. [76] analysed 69 peer-reviewed studies and found gaps in addressing, checking, and verifying the availability and limitations of BIM–blockchain integration.

Table 2. Integrating blockchain with other technologies.

| Reference	Digital Technology						
	BIM	IoT	AI	BDA	ML	RFID	Sensors
Jennifer Li [31]	✓	✓					
Dounas and Lombardi [44]	✓						
Li et al. [45]	✓	✓					
Xue and Lu [41]	✓						✓
Shojaei et al. [46]	✓	✓				✓	✓
Wei and Cui [47]				✓			
Lokshina et al. [42]	✓	✓				✓	✓
Ilin et al. [48]						✓	
Zheng et al. [49]	✓						
Mason [50]	✓						
Mathews et al. [43]	✓	✓	✓		✓		
Singh [51]		✓					
Chew [52]	✓						
Liu et al. [9]	✓						
Ye et al. [53]	✓	✓					
Siountri et al. [54]	✓	✓					
Pellegrini et al. [55]	✓						
Shinde et al. [56]	✓		✓		✓		
Shojaei [29]	✓	✓				✓	
Dounas et al. [57]	✓						
De La Peña and Papadonikolaki [24]		✓					
Jo et al. [33]		✓					
O'Reilly and Mathews [58]	✓	✓					✓
Safa et al. [59]	✓						
Elghaish et al. [60]	✓						
Chong and Diamantopoulos [28]	✓					✓	✓
Hill [61]		✓					
Amaludin and Bin Taharin [32]	✓						
Dounas et al. [62]	✓						
Cardeira [63]	✓						
Di Giuda et al. [64]	✓						
Li et al. [65]	✓		✓				
Hargaden et al. [66]	✓						
Heiskanen [67]		✓					
Siountri et al. [68]	✓	✓					
Dounas et al. [69]	✓						
Lee et al. [70]	✓	✓					
Das et al. [71]	✓						
Parn and Edwards [72]	✓						
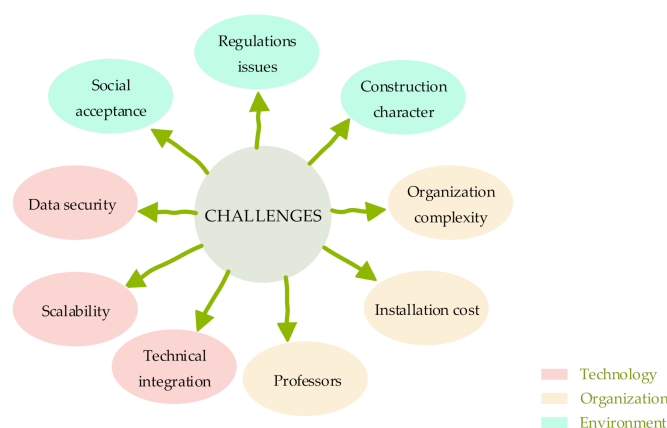
Figure 10. Challenges of blockchain applications in the AEC industry.

4.7. Environmental Challenges

The majority of the literature indicates that social acceptance is an important challenge faced by blockchain applications. Shojaei [29] and Dounas et al. [57] claimed that the blockchain application environment was not fully formed, owing to a lack of empirical cases. Li et al. [4] and Kifokeris and Koch [77] showed that the application of blockchain in the AEC industry remains in its infancy. These articles emphasised the absence of clear legislation in smart-contract management and enforcement. Moreover, research has been conducted on the characteristics of construction projects. For example, Wang et al. [7] investigated blockchain applications in the supply chain of prefabricated components. They found that it may be difficult to reuse existing blockchain networks, owing to the one-time nature of construction projects. Li et al. [45], McNamara and Sepasgozar [78], and Shojaei et al. [46] emphasised that smart contracts are suitable, owing to the high uncertainty and long-term nature of construction projects.

4.8. Organisational Challenges

A total of 29 articles dealt with the organisational challenges of blockchain technology. Most documents emphasised the absence of experts with the necessary technical skills and experience pertaining to blockchain, which limits the extent to which blockchain can be developed, deployed, and utilised. As blockchain application in the AEC industry remains in its infancy, most operators have not received adequate training and education [58]. Zhong et al. [35] reported that most construction-industry participants lack an understanding of the basic concepts and benefits of blockchain. Similar studies suggested that managers are hesitant to adopt blockchain and lack high-level planning [39,79]. Another factor to consider is the transition of the processes. Pattini et al. [80] reported that it is difficult to transition from physical documents (i.e., orders and invoices) to digital documents (i.e., smart contracts). Zhong et al. [35] claimed that there are few successful case references available, which limits blockchain's widespread adoption. A review of the literature reveals that the installation cost is high, which may reduce the willingness of decision makers to adopt blockchain. Additionally, as blockchain brings a way of thinking significantly different from that pertaining to traditional architecture, a reform of the culture and governance model may be a significant change for the AEC industry. Several studies have revealed the challenges faced by blockchain applications due to stakeholders' reluctance to share private information. Related challenges include organisational complexity and the imbalance caused by blockchain applications. The existence of many stakeholders may result in conflicting goals, with the potential for various intermediaries to disappear, which causes divergence and increases the complexity. For example, Kifokeris and Koch [81] reported that, in the social material construction logistics environment, where contractors dominate, blockchain application will disrupt the existing balance of power; contractors must give up a certain degree of control.

5. Discussion

Blockchain applications in the AEC industry have attracted considerable attention. However, the summary and prospects of the RQ-related topics are still insufficient. To respond to the main RQ, we designed three RQs. In this section, the response is described.

RQ1. What is the present status of blockchain applications?

The descriptive analysis included publication years, journals, institutions, countries, cooperation networks between authors, keyword co-occurrence networks, and research methodologies. An analysis of the number of annual publications revealed that, since 2016, the number of publications in the AEC industry has been increasing. A global analysis indicated that China was the main contributor to the topic, providing the largest number of publications. However, with regard to the paper citation rate, the United States far exceeds China, ranking first. This is because research in America started earlier than that in China. Li J., Kassem M., Perera S., Cheng J.C.P., and Das M. have made outstanding contributions to research related to blockchain applications in the AEC industry. Keyword analysis indicates the importance of contract management, stakeholder management, and SCM. Analysis of research methods revealed that general concepts are used most frequently, which are typically insufficient in empirical research and case studies.

RQ2. What are the benefits of blockchain applications in the AEC industry?

In-depth research of the identified themes revealed that blockchain can solve a series of problems in the AEC industry. The main benefits are divided into SCM, contract management, information management, stakeholder management, and integration management. Integration management—particularly the integration of BIM and blockchain—has received widespread attention. Regarding contract management, automated payment is the most promising area for blockchain to address problems in the AEC industry. With regard to information management, blockchain promotes information recording, storage, sharing, and integration owing to its traceability, disintermediation, and transparency. However, research on stakeholder management is insufficient.

RQ3. What are the challenges of blockchain applications in the AEC industry?

Despite the potential benefits, several challenges must be overcome. The selected publications mainly focused on the benefits; few studies have focused on the challenges. Our research findings confirmed the technology–organisation–environment (TOE) framework. Nine challenges were identified, which were divided into technological, organisational, and environmental challenges. The research results indicated that the complexity of the technology (i.e., privacy, security, and scalability) presents a challenge. Additionally, enhanced flexibility, clarity, and responsiveness to regulations and taxation may affect the application of blockchain in the AEC industry [82,83]. The decision to adopt blockchain is not only a technical decision but also a commercial one [84]. This is because it requires a series of conditions, such as the support of senior leaders and an innovative organisational culture.

6. Future Research Opportunities of Blockchain in AEC Industry

6.1. Future Research Opportunities Based on Benefits

The benefits of blockchain applications in the AEC industry have broad future research opportunities. Future research opportunities related to the benefits are discussed in this section.

In previous studies on the benefits of blockchain applications in the AEC industry, researchers mainly used qualitative methods, such as a conceptual framework. However, to address the actual situation, the adoption and implementation of blockchain require the correct analysis and quantification of the effects of different variables, which can be accomplished by encouraging researchers and practitioners to conduct empirical and case-based research, e.g., investigating the key drivers of blockchain application in the AEC industry. Additionally, there may be complex relationships between the various benefits. However, researchers have not yet clarified the relationships between these advantages.

Construction projects involve a complex network of stakeholders, such as contractors, owners, subcontractors, and governments [85]. There are various differences in the goals and needs of these stakeholders [86]. For example, contractors may prefer the advantages of safe payment, while owners pay more attention to the processes of transparency and information sharing to reduce contractors' opportunistic behaviour. Understanding the needs of different stakeholders is critical for project success [87]. The existing advantages are mostly considered from a holistic perspective, and the stakeholders in the AEC industry are not classified and compared. In the future, comparative research between stakeholders can be conducted to identify the key driving force for blockchain applications.

6.2. Future Research Opportunities Based on Challenges

The literature regarding the challenges of blockchain applications in the AEC industry lacks quantitative research. In the future, an integrated ISM-DEMATEL method should be considered for an in-depth investigation of the challenges of blockchain applications in the AEC industry.

Nevertheless, future research must be able to address technical issues related to blockchain applications, such as throughput, security, scalability, and interoperability. Such work is limited, and relevant quantitative research on these topics remains scarce. Thus, investigations must focus on addressing these challenges. Data privacy is a critical issue in information science, but the AEC industry has not paid sufficient attention to this issue. Owing to participants' concerns about data theft during the process of transferring data to external systems, data security and privacy issues affect the accuracy of the process. Additionally, a certain degree of data control is critical for blockchain applications in the AEC industry. This is because project participants may be unwilling to share all the relevant information with competitors. Potential solutions for hiding multi-party transaction information should be investigated in future research. Blockchain is a relatively young and rapidly developing technology, and its applications in the AEC industry remain limited. Additionally, most of the research focuses on the application of mature blockchain technology rather than method improvements. Compared with blockchain research in other industries, research on blockchain applications in the AEC industry is lagging, with considerable room for further development and exploration.

Most previous studies focused on the technical challenges; the organisational and environmental challenges have been insufficiently covered. From a sustainable-development perspective, the relationship between project partners is vital. Organisations differ with regard to SCM analysis and transaction tracking. Additionally, before proceeding with implementation, it is necessary to understand the applicability of blockchain in a cultural context. For example, the barriers to blockchain application in the AEC industry in China may differ from those in other countries. These issues need to be explored further.

As research on blockchain applications in the AEC industry is still in its early stage, there is no standard to regulate the behaviour of practitioners. Researchers should perform scientific studies from theoretical and empirical perspectives to formulate standards and policies for the AEC industry. For example, by examining the role of blockchain in the AEC industry, we were able to develop corresponding standards.

7. Conclusions

A mixed-method review of existing research related to blockchain applications in the AEC industry was conducted to understand its current status, benefits, challenges, and future research opportunities. The results indicated that research on the application of blockchain is still relatively new. The main contributions and limitations of the study are summarised in this section. Additionally, according to the inductive method of data analysis, future research opportunities are suggested.

Our first contribution was the construction of science maps of the understudied 'blockchain and AEC industry' area, which include the top contributors, institutions, publication journals, and author keywords. These structured insights will assist researchers

in understanding the present status of the research and lay a foundation for future research in the field.

Second, we presented a conceptual framework (Figure 9) that summarises and classifies the benefits of blockchain applications in five areas. This framework makes a novel theoretical contribution to help blockchain adoption by enhancing awareness of the potential advantages of blockchain for organisations.

Third, we provided up-to-date information related to the challenges of blockchain applications in the AEC industry by presenting a TOE framework. The challenges presented in Figure 10 offer opportunities for researchers and practitioners to eliminate technological (e.g., solve data security issues), organisational (e.g., provide relevant training to staff), and environmental (e.g., formulate relevant laws and regulations) barriers to blockchain adoption.

Fourth, we proposed future research opportunities for the application of blockchain in the AEC industry. These easily accessible reference points help researchers and practitioners to rethink and expand on current work. This methodological contribution of the present study lies in providing accurate quantitative information, specific characteristics, and functional limitations of blockchain applications in the AEC industry.

Despite these contributions, this study has limitations. First, when the benefits and challenges of blockchain applications in the AEC industry were discussed, some scattered research was not explored in detail. These studies are interesting and should be considered in future research. Second, with the increasing number of publications and depth of blockchain applications in the AEC industry, research results may be dynamic. Therefore, a similar review should be conducted in the next few years. Third, the search query was not comprehensive enough to capture all the literature related to blockchain. Therefore, Delphi studies that overcome these limitations should be conducted in the future. Finally, the Boolean query that was formulated for the search should be extended by including the keyword derivatives to more accurately reflect the topic.

Appendix A

Table A1. The selected articles and their characteristics.

No	Authors	Year	Publication Type	Methods	Findings	
					Benefits	**Threats**
1	Jennifer Li [31]	2020	Conference	Framework description	Increase traceability of a digital record	Scalability issues, interoperability issues, initial cost, digitalisation
2	Dounas and Lombardi [44]	2018	Conference	Framework description	CAD + blockchain	Technology problem

Table A1. *Cont.*

No	Authors	Year	Publication Type	Methods	Findings	
					Benefits	Threats
3	Kifokeris and Koch [81]	2020	Journal	Simulation modelling	Complement well-established technologies, shared ledger structure, reduction of accounting rework	Data unavailability, lack of wide awareness, power balances, security issues, potential implementational constraints
4	Xiong et al. [88]	2019	Journal	Framework description	Construction supply chain	Extra weaknesses in security
5	Li et al. [45]	2019	Conference	Framework description	Speed up the process of payment authorisation, trust, cooperation	Technical integration, legislation, limited skills, the complexity of the contract network, security issues
6	Das et al. [89]	2021	Journal	Framework description	Facilitate document approval workflows, data confidentiality and integrity, validate the authenticity of document search results	
7	Kim et al. [90]	2020	Journal	Questionnaire	Address the security issues, achieve a faster approval process	Lack of real case, processing time consuming, data security issues
8	Owusu et al. [91]	2020	Conference	Literature review	Contract management, enhanced communication, ensure transparency, secured copyrighted, automated contracting.	Cyber threats, complex structure
9	Fitriawijaya et al. [92]	2019	Conference	Simulation modelling	Construction supply chain	
10	Li et al. [93]	2021	Journal	Framework description	IoT + blockchain	Capacity issue, QR codes, skilled personnel
11	Xue and Lu [41]	2020	Journal	Framework description	BIM + blockchain	
12	Ahmadisheykhsarmast and Sonmez [25]	2020	Journal	Framework description	Security of payment	Security threats
13	Danielle [94]	2020	Journal	General description	Contract management, information management	
14	Shojaei et al. [46]	2020	Conference	Framework description	BIM + blockchain	Scalability, complex project
15	Lokshina et al. [42]	2019	Journal	Framework description	BIM + blockchain + IoT	
16	Ilin et al. [48]	2018	Conference	General description	RFID + blockchain	
17	Wei and Cui [47]	2020	Conference	General description	Construction document management	
18	Zheng et al. [49]	2019	Journal	General description	BIM + blockchain	Security, high power consumption, time-consuming verification, and transaction
19	Mason [50]	2019	Journal	General description	BIM + blockchain	

Table A1. *Cont.*

No	Authors	Year	Publication Type	Methods	Findings	
					Benefits	Threats
20	Mathews et al. [43]	2017	Conference	General description	BIM + blockchain	
21	McNamara and Sepasgozar [78]	2018	Conference	Literature review	Optimising payments and reducing delay	Data security, industry confidence, front-end work, cultural shift
22	Hijazi et al. [76]	2019	Conference	Literature review	Construction supply chain	Integration issues, data privacy, cost, change management, supervision, lack of practical applications
23	Raslan et al. [95]	2020	Conference	Literature review	Information management	Experts, cost
24	Perera et al. [15]	2020	Journal	Literature review	Security, anonymity, decentralisation, anti-fraud, immateriality, and financial incentives	Data privacy, data storage, scalability limitations, demand for high computing power
25	Nawari and Ravindran [96]	2019	Journal	Literature review	BCT + BIM + blockchain	
26	Nawari and Ravindran [97]	2019	Journal	Literature review	BIM + blockchain	
27	Pattini et al. [80]	2020	Journal	General description	Information management	Training, process transition, uniform rules
28	Shemov et al. [98]	2020	Journal	Case study	Verification of documents, automated procurement and payment, CSC traceability	High cost, time lag, size and bandwidth, business-related and operational challenges, vulnerability attacks
29	Singh [51]	2020	Conference	General description	IoT + blockchain	Regulatory ambiguity, trust, cost, governance, inconsistent standards
30	Rodrigo et al. [99]	2018	Conference	Literature review	Construction supply chain	
31	Kifokeris and Koch [100]	2019	Conference	Expert interview	Digital building logistics	Cybersecurity, integration issues, technical interoperability issues, work practices and organizational changes
32	Hamma-adama et al. [101]	2020	Conference	Literature review	Contract management, stakeholder management	Awareness, knowledge
33	Kifokeris and Koch [77]	2019	Conference	General description	Stakeholder management	Trust and safety issues, experts
34	Sivula et al. [102]	2018	Conference	General description	Construction supply chain	Integration challenges, experts, security issues
35	Li et al. [103]	2019	Conference	General description	Technology, social politics	Technical architecture, social impact

Table A1. *Cont.*

No	Authors	Year	Publication Type	Methods	Findings	
					Benefits	**Threats**
36	Kassem et al. [104]	2018	Conference	Framework description	Improve financing channels, automate construction activities, simplify verification processes, resolve ownership and rights verification, proof of origin, and construction payments	Adequate bandwidth and capacity, legal issues; lack of technical staff, social awareness
37	Li et al. [4]	2019	Journal	Literature review	Enhance cooperation, digital twins, disintermediation, efficiency, low transaction costs, ownership and right certification, provenance, reduction of human error, smart contracts, social benefits, traceability, workstream improvement	Data authentication, broadband and connectivity, smart-contract coding, energy consumption, exchange rate fluctuations, interoperability, laws, malicious attacks, preparation for adoption, skills, resistance to change, industry technology status
38	Goh et al. [36]	2019	Journal	General description	Stakeholder management	Security, social awareness, technical defects
39	Nawari and Ravindran [105]	2019	Journal	General description	BIM + blockchain	Privacy, security, centralised management entities, attack risk, cost, scalability
40	Nanayakkara et al. [106]	2019	Conference	Literature review	SCM	
41	Wang et al. [7]	2020	Journal	Framework description	Improve the traceability of prefabricated components	Throughput and latency, lack of awareness, initial cost, difficulty in reuse
42	Hewavitharana et al. [107]	2019	Conference	General description	Contract management	
43	Chew [52]	2019	Journal	General description	Payment, SCM, BIM, smart contract, effective carbon tracking	
44	Boonpheng et al. [108]	2020	Journal	General description	Data management	
45	Liu et al. [9]	2019	Journal	Framework description	BIM+ blockchain	
46	Luo et al. [26]	2019	Conference	Framework description	Construction payment automation	
47	Chen et al. [109]	2020	Conference	Case study	Information management	
48	Sheng et al. [34]	2020	Journal	Framework description	Information management	Cost, capacity, coding and deployment of smart contracts, industry conflicts
49	Ye et al. [53]	2018	Conference	General description	BIM + IoT+ blockchain	
50	Adibfar et al. [110]	2020	Journal	Literature review	BIM + blockchain	
51	McNamara and Sepasgozar [111]	2020	Journal	Literature review	Automated payment	Social awareness

Table A1. *Cont.*

No	Authors	Year	Publication Type	Methods	Findings	
					Benefits	**Threats**
52	Siountri et al. [54]	2020	Journal	Framework description	BIM + IoT+ blockchain	
53	Pellegrini et al. [55]	2020	Journal	Case study	BIM + blockchain	
54	Prakash and Ambekar [112]	2020	Journal	Expert interview	Construction payment automation, SCM, BIM	
55	Hunhevicz and Hall [5]	2020	Journal	Case study	Construction automation	Throughput, data storage, interoperability, privacy, cost
56	Shinde et al. [56]	2020	Conference	General description	Contract management	
57	Shojaei [29]	2019	Journal	General description	Contract management, SCM, BIM, facility management, sustainability	Lack of feasibility
58	Kiu et al. [73]	2020	Journal	Literature review	SCM, BIM, construction management, document management, real estate management and fund management	Lack of empirical work
59	Ye and König [27]	2020	Conference	Framework description	BIM + blockchain	Limited storage and slow transactions
60	Dounas et al. [57]	2020	Journal	Framework description	BIM + blockchain	Industry awareness
61	De La Peña and Papadonikolaki [24]	2019	Conference	Expert interview	IoT + blockchain	Industry awareness
62	Zhong et al. [35]	2020	Journal	Framework description	Information management	Lack of cases, lack of understanding, initial costs, construction companies' unwillingness to privatise, technical issues, policy environment
63	Graham and Hailer [113]	2019	Conference	General description	Risk management, SCM	Lack of standardization, full participation, technical limitations
64	O'Reilly and Mathews [58]	2019	Conference	Framework description	BIM + blockchain	Cultural change, education
65	Safa et al. [59]	2019	Journal	General description	Information management	
66	Li and Kassem [114]	2019	Conference	Expert interview	Contract management	smart-contract coding, technical capabilities, laws, and regulations
67	Elghaish et al. [60]	2020	Journal	Case study	Construction payment automation	Technical issues
68	Chong and Diamantopoulos [28]	2020	Journal	Questionnaire	Payment security	Blockchain platform type selection, algorithm development

Table A1. *Cont.*

No	Authors	Year	Publication Type	Methods	Findings	
					Benefits	Threats
69	Mason [115]	2017	Journal	General description	BIM + blockchain	Reliability and interoperability, creating coding codes
70	McNamara and Sepasgozar [116]	2021	Journal	Framework description	Contract management	Lack of technical personnel, lack of successful cases, cultural barriers
71	Singh and Ashuri [117]	2019	Conference	General description	Information management	Speed under massive data, limitation of data storage, interoperability
72	Erri Pradeep et al. [118]	2019	Conference	General description	BIM + blockchain	Accuracy and scalability of information
73	Hunhevicz and Hall [119]	2019	Conference	General description	Management process automation, SCM	Lack of awareness, skills, resistance to change
74	Hill [61]	2020	Conference	General description	IoT + blockchain	
75	Rodrigo et al. [120]	2020	Journal	Expert interview	Construction Supply Chain	
76	Turk and Klinc [30]	2017	Journal	General description	Information management	The impact of availability is uncertain
77	Tezel et al. [121]	2019	Conference	Expert interview	Information management	Security, scalability, human resources, governance mechanisms, laws, incentives
78	Tezel et al. [74]	2020	Journal	General description	Construction supply chain	Security, scalability, human resources, governance mechanisms, laws, incentives, wait and see
79	Amaludin and Bin Taharin [32]	2018	Journal	General description	Identity verification and notarization, project governance, BIM + blockchain	
80	Yang et al. [11]	2020	Journal	Case study	Business process management, SCM, information management	Business change, identity, cost, security, complexity of adoption, scalability
81	Sun and Wang [23]	2020	Conference	AHP	Construction supply chain	
82	Abrishami and Elghaish [122]	2019	Conference	Framework description	Stakeholder management	
83	Darabseh and Martins [123]	2020	Journal	Literature review	File ownership, smart contracts, SCM, BIM, facility management, sustainability	Culture
84	Hamledari and Fischer [75]	2021	Journal	General description	Automatic payment	Security
85	Das et al. [8]	2020	Journal	Framework description	Interim payment for construction projects	
86	Qian and Papadonikolaki [6]	2020	Journal	General description	SCM	Cost, social awareness, cost, talent, transformation,

Table A1. *Cont.*

No	Authors	Year	Publication Type	Methods	Findings	
					Benefits	Threats
87	Faraji [124]	2019	Conference	Questionnaire	Optimization of engineering contracts	
88	Mason and Escott [40]	2018	Conference	Questionnaire	Stakeholder management	Automatically respond to abnormal situations and human attitudes
89	Cardeira [63]	2015	Conference	General description	Automate construction payments	Societal acceptance, technology problem
90	Dounas et al. [62]	2020	Conference	General description	BIM + blockchain	
91	Ahmadisheykhsarmast and Sonmez [125]	2018	Conference	General description	Automatic payment	Lack of training, price fluctuations, industry acceptance, legal
92	Nanayakkara et al. [38]	2019	Conference	Expert interview	Stakeholder management	Changes in technology, people, organization, and construction environment
93	Badi et al. [126]	2021	Journal	Questionnaire	Stakeholder management	Observability, legal
94	Di Giuda et al. [64]	2020	Journal	General description	BIM + blockchain	
95	Sharma and Kumar [79]	2020	Journal	Interpretive structural modelling	SCM	Governance, supervision, skills
96	Dakhli et al. [13]	2019	Journal	General description	Potential cost savings, construction process	Security, slow speed, regulations, immature technology, privacy, audit requirements, data quality
97	San et al. [14]	2019	Conference	Literature review	Contract management, BIM, EDM, property management, SCM, fund management	Regulatory approach, slow adoption of construction technology
98	Hargaden et al. [66]	2019	Conference	General description	Information management, contract management	
99	Belle [127]	2017	Conference	Theoretical concept	Protection of intellectual property rights, building reputation, contract management	The capabilities of the industry to cooperate and organise work processes
100	Cardeira [128]	2017	Conference	General description	BIM + blockchain	
101	Li et al. [65]	2021	Journal	General description	AI + BIM + blockchain	
102	Qian and Papadonikolaki [129]	2019	Conference	General description	SCM	Social acceptance, cost
103	Shou et al. [12]	2017	Journal	Expert interview	Contract management, SCM, equipment leasing process	Technical limitations, construction industry inertia, initial cost, lack of awareness
104	Zhang et al. [22]	2020	Journal	Framework description	Prefabricated component quality traceability system	unwillingness to accept, information sharing, trust, cost, one-off, technical limitations

Table A1. *Cont.*

No	Authors	Year	Publication Type	Methods	Findings	
					Benefits	Threats
105	Heiskanen [67]	2017	Journal	General description	IoT + blockchain	
106	Dounas et al. [69]	2019	Conference	General description	BIM + IoT + blockchain	
107	Siountri et al. [68]	2019	Conference	General description	BIM + blockchain	Interoperability
108	Li et al. [130]	2021	Journal	Framework description	Off-site modular housing production supervision	
109	Chaveesuk et al. [39]	2020	Conference	General description	Stakeholder management	Coding of smart contracts
110	Sinenko and Doroshin [131]	2020	Conference	General description	Contract management	
111	Shi et al. [37]	2020	Conference	General description	Efficiency, transparency, productivity, network security	
112	Jo et al. [33]	2018	Journal	General description	IoT + blockchain	Security
113	Lee et al. [70]	2021	Journal	Framework description	IoT + BIM + blockchain	Security
114	Das et al. [71]	2021	Journal	Literature review	BIM + blockchain	
115	Parn and Edwards [72]	2019	Journal	Case study	BIM + blockchain	Application development and testing
116	Gurgun and Koc [132]	2021	Journal	AHP	Contract management	Stakeholder resistance

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