

AN ANALYSIS OF BLOCKCHAIN TECHNOLOGY AND SMART CONTRACTS FOR BUILDING INFORMATION MODELING

SUBMITTED: April 2022
REVISED: September 2022
PUBLISHED: November 2022
EDITOR: Robert Amor
DOI: [10.36680/j.itcon.2022.047](https://doi.org/10.36680/j.itcon.2022.047)

*In Bae Chung, Ph.D. Student, corresponding author
Dept. of Civil, Architectural & Environmental Engineering, The University of Texas at Austin;
email: inbae908@utexas.edu*

*Carlos Caldas, Professor,
Dept. of Civil, Architectural & Environmental Engineering, The University of Texas at Austin;
email: caldas@mail.utexas.edu*

*Fernanda Leite, Associate Professor,
Dept. of Civil, Architectural & Environmental Engineering, The University of Texas at Austin;
email: fernanda.leite@austin.utexas.edu*

SUMMARY: Significant changes in the construction industry have been brought about by Building Information Modeling (BIM). While BIM has improved team collaboration and workflow efficiency, the model still faces multiple challenges. These are related primarily to the security, transparency, and reliability of the data shared in the model. A potential way to mitigate these problems, according to many studies, is blockchain technology. This paper reviews the recent literature on the integration of BIM and blockchain technology. Using a rigorous search-and-selection process, the authors conducted a systematic literature review by analyzing 70 studies relevant to BIM-blockchain integration. The state-of-the-art review explains how studies have implemented blockchain technology and provides an overview of different levels of adoption. Various application areas within the BIM process are explored to understand the ongoing research trend. The authors discuss limitations and offer recommendations on how best to implement future work in BIM-blockchain integration.

KEYWORDS: Blockchain Technology, Distributed Ledger Technology (DLT), Smart Contracts, Building Information Modeling (BIM)

REFERENCE: In Bae Chung, Carlos Caldas, Fernanda Leite (2022). An analysis systematic literature review of blockchain technology and smart contracts for Building Information Modeling. *Journal of Information Technology in Construction (ITcon)*, Vol. 27, pg. 972-990, DOI: [10.36680/j.itcon.2022.047](https://doi.org/10.36680/j.itcon.2022.047)

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1. INTRODUCTION

Over the past few decades, the architectural, engineering, and construction (AEC) industry has been significantly impacted by the advent of Building Information Modeling (BIM). BIM technology not only supports the design phase of a project but facilitates the entire project lifecycle by generating virtual models of the facility (Eastman *et al.*, 2011). According to Hartmann and colleagues (2008) and Mostafa and Leite (2018), the use of 3D/4D models can support construction management in multiple application areas. And over the past 10 years, practitioners have expanded their use of the 3D/4D model, addressing different challenges faced during the lifecycles of projects. It is evident that BIM enables the collaboration of the stakeholders through different disciplines (Leite, 2020). Using the accurate geometry and data contained in the model, BIM can accomplish various management tasks, thereby lowering costs, reducing project duration, and improving quality (Eastman *et al.*, 2011).

While its framework enables a collaborative approach among multidisciplinary teams, BIM still has several limitations (Nawari and Ravindran, 2019a). As information is exchanged among multiple parties, there is no guarantee regarding the transparency and reliability of the information (Zhong *et al.*, 2020). If the information exchanged through the BIM model cannot be trusted, it is difficult to identify the party that is liable for the input, which can lead to contractual claims and disputes (Eadie *et al.*, 2015). Another crucial component is the security of the BIM model, as it contains sensitive project information (Das *et al.*, 2021). Information can be easily leaked, lost, or corrupted by involved participants or, worse, by external criminal entities with malicious intent. Such cybersecurity threats can obviously have a negative impact on the BIM workflow and lead to financial loss (Nawari and Ravindran, 2019a).

Potential solutions to these challenges (as well as other changes to the practice of BIM) are offered by the emergent technology Blockchain. Blockchain, whose name became familiar to the general public with the rise of cryptocurrencies, is a Distributed Ledger Technology (DLT). Blockchain allows network members to digitally record and access transactions (Nakamoto, 2008). Users can interact directly through a peer-to-peer network, which removes the need for any central authority to manage every transaction (Yaga *et al.*, 2019). This coincides with the collaborative nature of BIM where stakeholders continually trade information throughout a project's lifecycle. In a blockchain network, information is recorded through blocks in a chronological order (Yaga *et al.*, 2019). Cryptographic hash functions generate a unique output of the previous data, which makes the blockchain tamper-resistant and append-only (Hassan *et al.*, 2019). Hence, blockchain is a linked list via hash pointers that is transparent and traceable to its users.

The use case of blockchain technology can be strengthened so as to be more practical by what are called smart contracts. Smart contracts can be defined as computerized transaction protocols that execute the terms of a contract (Buterin, 2014). Utilizing cryptographically signed transactions, these written lines of code can be deployed on the blockchain network (Swan, 2015). When the predefined conditions are met, smart contracts are automatically executed to process transactions across the blockchain network (Hassan *et al.*, 2019). Therefore, the use of smart contracts can automate transactions, which could result in huge cost savings by minimizing the costs associated with third-party involvement (Swan, 2015). According to a report by Accenture, blockchain-based solutions can minimize intermediary costs and result in cost savings up to eight billion USD (Accenture, 2017; Osmani *et al.*, 2021). Also, Dakhli and colleagues (2019) predicted potential cost savings from the use of blockchain for a real estate company, which was 8.3% of the total cost of residential construction.

Many different sectors have looked into blockchain's potential applications, and the construction industry is not an exception. Several systematic literature reviews have been conducted to analyze the current state of blockchain technology adoption in the overall construction sector (Kiu *et al.*, 2020; Li and Kassem, 2021; Scott *et al.*, 2021). Current applications have been investigated in different themes such as supply-chain management, construction payment, information management, and so on. There have been minor differences in how researchers categorized the application areas, but studies took a similar approach in identifying what the potential use cases are in the built environment and construction industry. Among these various applications, studies have pointed out the possibilities that lie in the application of blockchain in the BIM workflow (Turk and Klinc, 2017; Wang *et al.*, 2017). More research has been conducted, rapidly evolving from theoretical insights into conceptual frameworks, proofs-of-concept, and case studies (Li and Kassem, 2021).

While previous studies have indicated the potential of blockchain technology integrated with BIM process, they have not focused on how to implement this technology or in what areas. Especially, with the various management tasks leveraging BIM, there is a need to analyze how specifically blockchain could impact the BIM process. Thus, this paper conducts a systematic literature review to investigate the recent trends of BIM and blockchain technology integration. Based on the findings from the literature review, this study addresses the current status in the adoption of blockchain technology in BIM processes. It identifies BIM-specific application areas and blockchain integration studies. Finally, we discuss the limitations of BIM-blockchain integration along with possible lines for future work.

2. RESEARCH METHODOLOGY

To perform a comprehensive and structured literature search on the research topic, the authors adopted the systematic literature review process developed by Tranfield *et al.* (2003). Fig. 1 illustrates the review process in four phases. Phase 1 is to discover the literature through multiple data sources using keyword searches. Phase 2 narrows the literature through the inclusion and exclusion criteria. In Phase 3, the selected papers are then classified by different levels of adoption and BIM-application areas. Finally, in Phase 4, we explain the descriptive analysis of the selected papers and discuss the review's limitations and suggest future work for integrating blockchain technology with BIM.

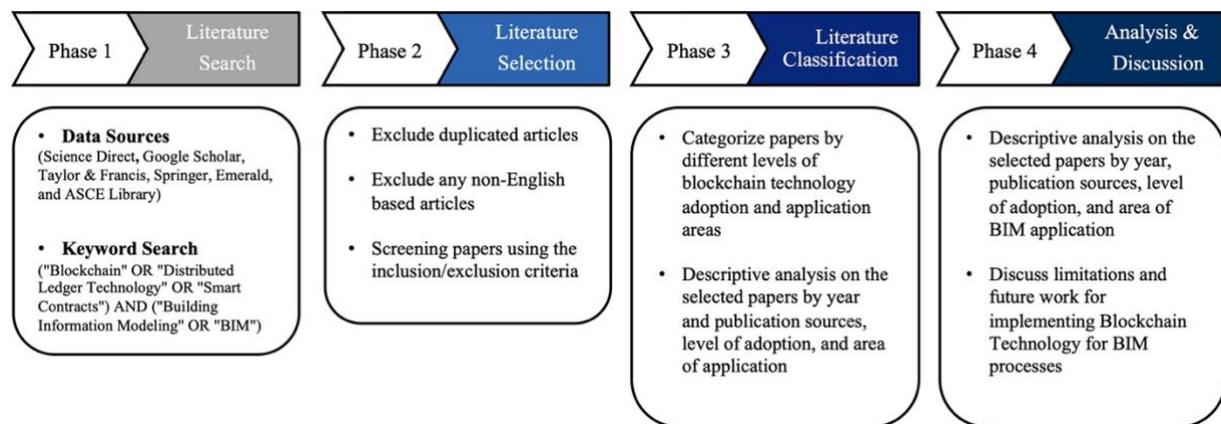


FIG. 1: Systematic Review Process

2.1 Search Strategy

To discover the current understanding of how blockchain technology can benefit the BIM process, the research team conducted a systematic literature review. The search covered the papers that had been published by December of 2021 or papers that had been accepted by that date and already given access. As data sources, the research team selected the research databases Science Direct, Google Scholar, Taylor & Francis, Springer, and Emerald. In addition, to discover publications in related conference proceedings, researchers carried out the same keyword search on the ASCE Library. Fig. 2 illustrates the overall search-and-selection process.

To select papers from numerous publications that fit the research objective, the keyword search was formulated into two filters. The first was used to evaluate whether the selected paper was relevant to blockchain technology. As keywords, researchers used the following terms: "Blockchain," "Distributed Ledger Technology," "Smart Contracts." The second filter screened out papers unrelated to BIM, i.e., "Building Information Modeling," and "BIM." Hence, the search keyword was set up as follows: ("Blockchain" OR "Distributed Ledger Technology" OR "Smart Contracts") AND ("Building Information Modeling" OR "BIM").

2.2 Selection Process

After the initial keyword search discovered a significant number of publications, another selection process was implemented that narrowed down the selected papers for review. In this process, papers found from different data sources were merged and duplicated articles were removed. The research team excluded non-English articles as well as articles that were not accessible on the web, leaving 343 papers.

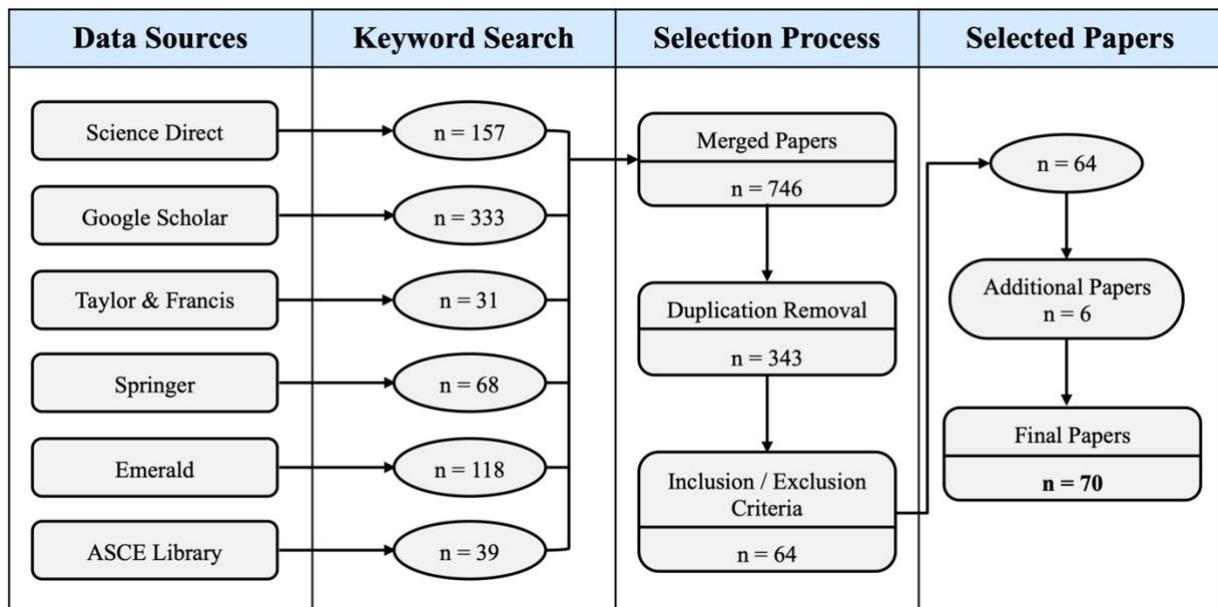


FIG. 2: Paper Search and Selection Process

To specify the studies that should be included in the literature review, the research team established inclusion and exclusion criteria. First, the type of publication had to be articles from either peer-reviewed journals or conference proceedings, excluding other types of manuscripts such as editorial notes or book reviews. Second, the publication had to be in the field of Construction, Architecture, and Engineering domains. Papers that were published in irrelevant domains were excluded. Third, the main content of the paper had to be the implementation of blockchain technology. Thus, any paper that briefly mentioned the use of blockchain for future work was not considered. Lastly, the study had to focus on how the adoption of blockchain technology was going to specifically impact the BIM process. Following these criteria narrowed down the number of papers to 64. Through a snowball search of cited papers, six additional papers were found that met the criteria. Therefore, for data extraction and content analysis, the researchers selected a total of 70 papers (listed in the Appendix).

2.3 Literature Classification

After completing the paper-selection process, the research team needed to extract the data and carry out a qualitative synthesis to present a tabulation of key characteristics and results (Tranfield *et al.*, 2003). In order to investigate the current status of blockchain technology in BIM processes, we categorized papers based on different levels of blockchain technology adoption. The four categories are the following: providing direction for future research, establishing a conceptual framework, prototype development, and simulated project scenarios. These categories are not mutually exclusive since a single research can fall into all four categories at the same time. A similar approach was taken by Yang *et al.* (2020) and Li and Kassem (2021), where the review revealed the trend of blockchain adoption in the field of construction.

The earliest papers addressing both blockchain and BIM commenced by providing a direction for future research (Belle, 2017; Mathews *et al.*, 2017; Turk and Klinc, 2017; Wang *et al.*, 2017). These papers analyzed the current state of research in BIM and proposed blockchain technology as the solution to challenges. The next level of papers established conceptual frameworks to illustrate how blockchain technology could be implemented for BIM processes (Das *et al.*, 2021; Liu *et al.*, 2019; Nawari and Ravindran, 2019a; Singh and Ashuri, 2019). Based on the conceptual frameworks, some studies took a step further to develop a working blockchain as a part of their research scope (Pradeep *et al.*, 2021; Zhong *et al.*, 2020). The highest level of blockchain-technology adoption examined the use of the developed prototype by using simulated project scenarios (Hamledari and Fischer, 2021a, 2021b; Hunhevizc *et al.*, 2022; Tao *et al.*, 2021). Some of the studies in this category even utilized actual project data to properly validate the blockchain prototype.

Another standard for classifying the selected papers were different BIM application areas. Application areas indicate the specific BIM-related uses within the entire life cycle of a building. The study done by (Meng *et al.*,

2020) summarized the current applications of BIM along with the integration of related technologies. Throughout a building's life cycle, researchers defined a total of 24 application areas. To present a better overview on how blockchain technology impacts BIM processes, this study categorized the studies into 13 application areas. This categorization process was applied to the studies that at least established a conceptual framework for blockchain adoption. This is because papers providing direction for future research tend to provide a relatively wide range of potential applications, making the categorization unnecessary. The BIM-blockchain application areas are listed in Fig. 3, and the Appendix provides the BIM areas that have been proposed by each selected paper.

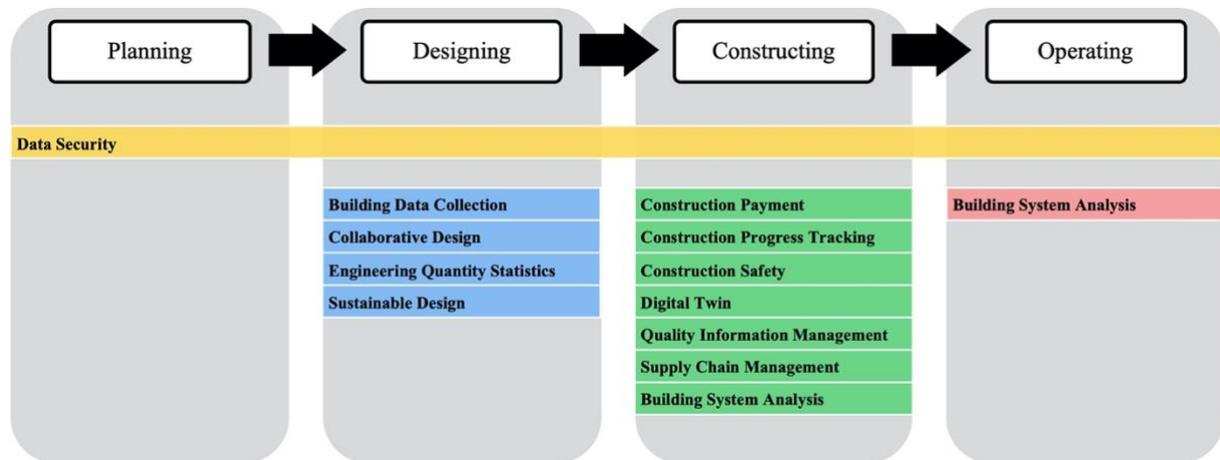


FIG. 3: BIM-blockchain Application Area throughout Project Lifecycle (Modified from (Meng et al., 2020))

3. STATE-OF-THE-ART PRACTICES OF BIM-BLOCKCHAIN INTEGRATION

This section provides a descriptive analysis based on the data extraction from our search of the literature. The selected papers were analyzed by year, publication sources, level of blockchain adoption, and area of BIM application. To illustrate the graphical representation of word frequency, a word cloud was generated using the titles and abstracts of the selected papers (see Fig. 4). The words have been visually weighted by size, which were determined by frequency of appearance in the titles and abstracts.

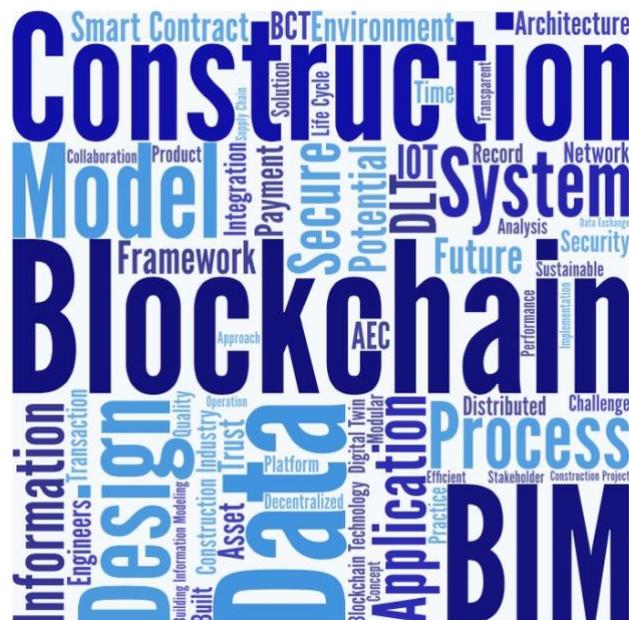


FIG. 4: Word Cloud Generated from the Selected Papers

3.1 Publication Trends by Year

Fig. 5 presents a chronological overview of the papers that have been selected for the review. The concept of Bitcoin was introduced by Satoshi Nakamoto, so the earliest papers talking about blockchain and BIM were published in 2017. The graph shows that except for year 2018, there has been, until recently, a gradual increase in the number of studies published. The search focused on papers that were accessible through the data sources through December of 2021. There were five papers that were found through the search but had a planned publication date in 2022. These papers were considered to be part of year 2021 to avoid confusion. It is evident from this publication trend that interest in and awareness of the integration of BIM and blockchain is growing. We may expect more papers to continue addressing this topic in the future.

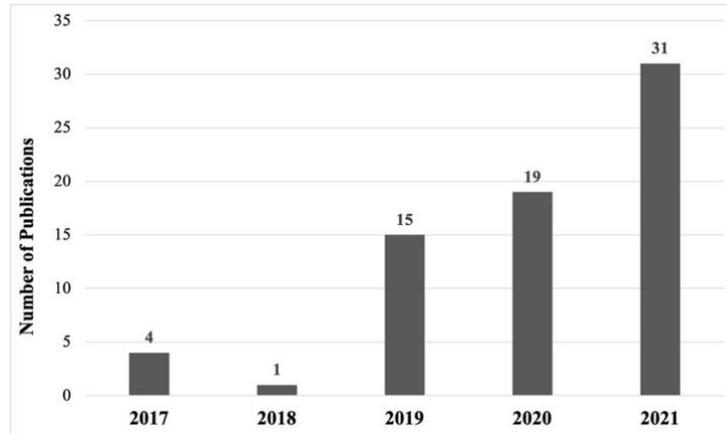


FIG. 5: Publication Trend by Year

3.2 Publication Sources

Based on the data extracted, the review discovered that 54 articles were published in journals and 16 articles were conference papers. Having published 18 studies, as shown in Table 1, *Automation in Construction* was the leading journal that addressed both BIM and blockchain. After that, *Buildings* and *Computers in Industry* each had four studies that talked about this topic. Four other journals published two studies each, while the rest only had one article each. As for conference proceedings, most of them had either one or two studies that were relevant. This result shows that the research around BIM-blockchain integration is still in its early stages with most sources just starting to publish papers on this topic (aside from *Automation in Construction*).

Table 1. Publication Sources of Selected Papers

	Publication Source	Count
Journals	Automation in Construction	18
	Buildings	4
	Computers in Industry	4
	Built Environment Project and Asset Management	2
	Frontiers of Engineering Management	2
	Journal of Building Engineering	2
	Journal of Construction Engineering and Management	2
	CIB W78 – Information Technology for Construction	2
Conferences	International Conference on Computing in Civil Engineering (i3CE)	2
	International Symposium on Automation and Robotics in Construction (ISARC)	2
	International Symposium on Advancement of Construction Management and Real Estate	2

3.3 Level of Adoption

As explained earlier in Section 2.3, studies have been classified into four levels of adoption, as shown in Fig. 6. Out of 70 studies, 37 of them identified how blockchain technology can be used to overcome current challenges in BIM and suggested directions for future research. Many of them provided an overview of blockchain technology and recommended areas for potential applications. For instance, Turk and Klinc (2017) identified the barriers such as legal issues and model ownership management and proposed a system architecture that uses blockchain for BIM transactions. Wang and colleagues (2017) investigated the potential of applying blockchain technology in the construction domain and mentions how blockchain can be useful in managing and recording changes to the BIM model throughout the design and construction phases. Parn and Edwards (2019) specifically addressed the cybersecurity threats in the built environment and recommended the use of blockchain technology as a potential mitigation measure. A good portion of studies started to shed light on the possibility of BIM integration, paving the way for further research in this area.

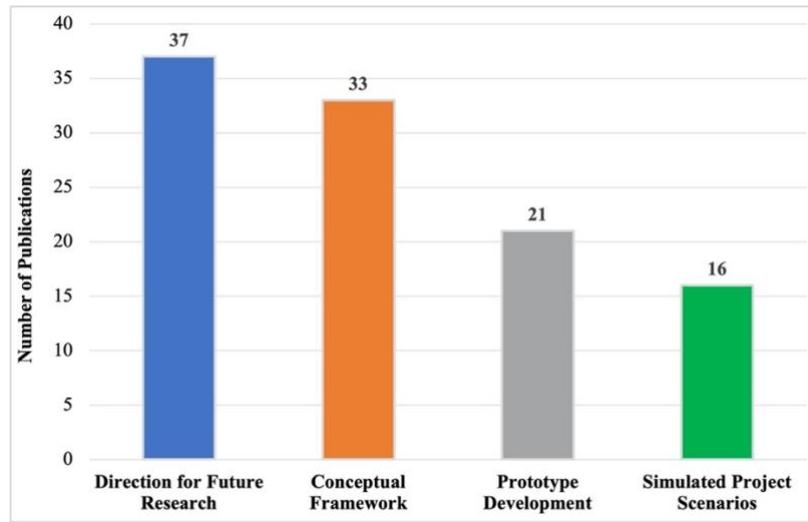


FIG. 6: Distribution of Papers by Level of Blockchain Technology Adoption

Another research method that was taken by many studies to provide direction for future research was to conduct a systematic literature review. The study by Li *et al.* (2019) was one of the first systematic review papers that investigated the current state of DLT in the built environment and the construction sector. Along with the literature review, the authors proposed a socio-technical framework, which provides a knowledge foundation for analyzing challenges and opportunities of DLT applications. Further research was then conducted, which added 142 sources and categorized them into construction-specific themes (Li and Kassem, 2021). Other studies also took a similar approach. Kiu and colleagues (2020), for instance, identified six potential areas in which blockchain technology could drive changes in the construction industry. Scott *et al.* (2021) investigated a total of 121 documents to organize them into seven subject areas. Hijazi *et al.* (2021) looked closer into challenges in supply-chain data delivery to propose the integration of BIM and blockchain technology. While there were differences in how they categorized the blockchain-related studies into different construction applications, they all identified BIM as a major area where blockchain technology could be a game changer.

Several studies took different approaches to promote the use of blockchain technology for BIM. Hunhevicz and Hall (2020) developed a decision framework for deciding what type of blockchain was suitable for various applications. McNamara and Sepasgozar (2020) interviewed industry experts to establish a theoretical technology acceptance model, which evaluates the readiness of blockchain-based construction contracts. Other studies discovered how blockchains can be used together with specific technologies such as Internet of Things (IoT) or artificial intelligence (Elghaish *et al.*, 2021; Pan and Zhang, 2021).

More research has been conducted afterwards, providing more detail on how blockchain technology can deal with the challenges facing BIM. A number of studies have established a conceptual framework that provides a more step-by-step process on how blockchain technology is going to improve the BIM workflow. Liu and colleagues (2019), for instance, proposed architecture for information management of sustainable-building-design processes.

The architecture illustrates the connection between the BIM user and the transaction recorded on the blockchain. Nawari and Ravindran (2019a) suggested a permissioned blockchain framework, where protected data exchanges can happen between a group of permissioned entities. Similarly, Singh and Ashuri (2019) created a conceptual framework that can track and register design commands from the BIM model into a blockchain platform. Also, (Das *et al.*, 2021) proposed two different frameworks for facilitating secure storage of BIM and recording its changes in a tamper-resistant ledger. All these conceptual models are aligned with different parts of the BIM workflow and emphasizes the vital role that blockchain technology can play in improving BIM.

Based on the detailed conceptual models, studies have started developing blockchain prototypes to demonstrate the use of this novel technology. Depending on the use of the blockchain, different platforms have been employed to develop prototypes. Ethereum is one of the most commonly used platforms, which provides public and permissionless blockchains for different applications (Buterin, 2014). Pradeep and colleagues (2021) developed a prototype blockchain on Ethereum due to its stronger security for recording sensitive information. The blockchain was able to track individual design inputs so that a trustable record of transactions could prevent any design-liability issues. Another widely used platform is Hyperledger Fabric, which targets private, permissioned blockchains (Androulaki *et al.*, 2018). In the Hyperledger Fabric network, users must be granted access to connect to the blockchain, which is suitable for multiple organizations operating on a network without public access. Zhong and colleagues (2020) presented the use case of a Hyperledger Fabric-based blockchain, where the system supports construction-quality management. Much work has been and continues to be done to develop functioning blockchains for use in actual projects.

While prototypes have been useful in demonstrating the blockchain use and smart contract algorithms, in the end, they are still prototypes. Further validation is necessary to see the true value of the technology in a capital project where BIM is being implemented. Thus, studies have started to create simulated project scenarios to verify the use of blockchains. (Tao and colleagues (2021) did so with a proposed framework that was evaluated based on real-world project scenarios. The authors created three illustrative scenarios to validate the performance of the blockchain. Studies have also validated their technical architecture by testing their prototype on data from a real-world building or projects that have been implemented (Hamledari and Fischer, 2021a, 2021b; Hunhevcz *et al.*, 2022). So far, project scenarios have been an essential part of research to validate the prototype and prove the main contributions of the paper. More publications that explain the use of a simulated project scenario can be found in the Appendix.

3.4 Application Area

This section illustrates how blockchain has been implemented in different application areas within the BIM process. Fig. 3 illustrates the various application areas of BIM-blockchain integration studies, and Fig. 7 shows the number of publications for each application area.

One major application area is data security. As sensitive project information may be stored and distributed through BIM models, if they end up being lost or stolen, it could result in financial loss (Das *et al.*, 2021). Thus, cybersecurity threats that may impact the digital built environment have been identified, and blockchain technology has been recommended as a potential solution (Parn and Edwards, 2019; Parn and de Soto, 2020). Studies have identified the information-security requirements of BIM platforms and proposed a conceptual framework that utilizes encryption algorithms to enable secure storage and distribution of BIM models (Das *et al.*, 2021). Additionally, since blockchains are inherently unsuitable for storing large-sized design files like BIM models, studies have come up with ways to protect BIM data integrity. One such way was to utilize the interplanetary file system (IPFS) for storing separately large BIM models (Tao *et al.*, 2021). IPFS is a novel protocol for storing and sharing files in a peer-to-peer fashion without a centralized server (Benet, 2014). Another study proposed using a semantic differential transaction (SDT) approach to minimize information redundancy (Xue and Lu 2020). Their approach is applicable to the standard Industry Foundation Classes (IFC), which is used across various BIM platforms and captures the model changes at the semantic level not the byte level (Xue and Lu, 2020). Thus, incremental changes to BIM semantics can be recorded instead of capturing every unnecessary data changes. Li and colleagues (2021) proposed a two-layer blockchain model that prevents any privacy leaks among the stakeholders. As can be seen from Fig. 7, data the most popular topic for BIM-blockchain integration revolved around security.

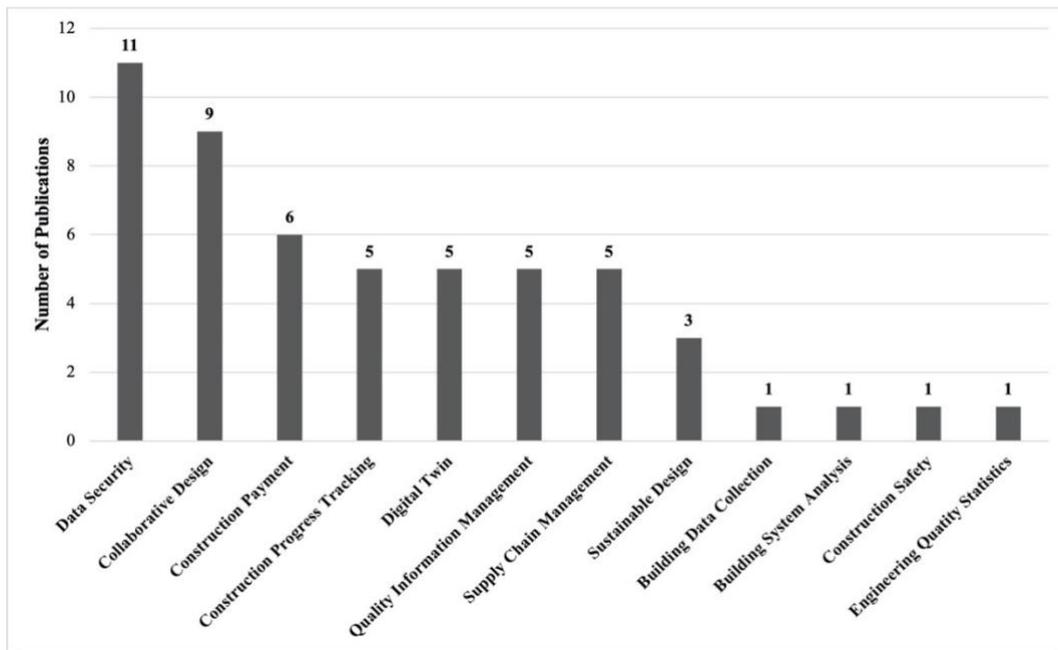


FIG. 7: Distribution of Papers by BIM-blockchain Application Area

The use of BIM is crucial for collaborative design where multiple stakeholders of different trades need to work together. This is where blockchain technology can be leveraged since stakeholders can reach a consensus by providing evidence of trust on a distributed decentralized ledger (Nawari and Ravindran 2019b). Blockchain technology has been identified as the enabler in the design-development phase that can track and input design changes in a secure, transparent, and collaborative manner (Singh and Ashuri, 2019). A conceptual architecture for blockchain-aided BIM has been proposed and validated for design coordination and collaboration during the building life cycle (Liu *et al.*, 2019). Moreover, in a collaborative design process lack of design liability in a 3D BIM model can lead to contractual disputes (Pradeep *et al.*, 2019). A commercial tool named BIMCHAIN has been developed to register proofs of data transactions in a BIM model that can be legally binding and traceable (Pradeep *et al.*, 2020). Any individual design inputs are recorded as snapshots on the blockchain to enable a trustable record of transactions, which could prevent design-liability issues in the BIM workflow (Pradeep *et al.*, 2021). Hence, BIM-blockchain integration has the potential to bring improved communication and transparency for collaborative design processes (Nawari and Ravindran, 2019a).

The use of blockchain technology with the BIM process can even contribute to solving payment delays. Payment delay is a prevalent issue in the construction industry, often resulting in cost overruns, delays, and further slowing down the processing of payments (Hamledari and Fischer, 2021b). Therefore, studies have started linking the payment-related data to the BIM-based data and incorporated blockchain technology to achieve an automated financial system (Ye *et al.*, 2020). The use of smart contracts has enabled automated payments without any third-party intervention (Elghaish *et al.*, 2020). Hamledari and Fischer (2021a) have gone one step further—automating progress payments based on integrating the physical and financial chain. In this particular use case, construction-progress data is generated on BIM, which in turn processes the payment using crypto assets. Based on the literature, automated payments through the integration of BIM and blockchain is a promising application area that could revolutionize the industry.

Some of the greatest features of blockchain technology is the transparency and traceability of transactions on the shared ledger, which are characteristics that can improve the information management in a BIM model. For example, several studies have proposed a blockchain system for governing a construction project, where a tamper-resistant record of project progress is maintained and tracked over time (Hamledari and Fischer, 2021c; Jiang *et al.*, 2021; Lee *et al.*, 2021; Li *et al.*, 2021; Shojaei, Flood, *et al.*, 2020). Smart contracts enable the automatic recording of each step in the BIM model, which can lead to significantly fewer disputes over construction progress. Another use of such features is a framework for managing construction-quality information (Ciotta *et al.*, 2021; Li *et al.*, 2021; Sheng *et al.*, 2020; Wu *et al.*, 2022; Zhong *et al.*, 2020). The project participants can access and

share the quality information stored on the blockchain and prevent any disputes over construction quality (Sheng *et al.*, 2020). Quality-compliance checking is a manual task that involves the assistance of a third party, often being a subjective and inefficient process. The smart contracts can be written using business logics that may contain specific quality constraints from building codes and regulations, which can run automatically. As quality information is uploaded into the system, compliance-checking outcomes generated from smart contracts are recorded and shared to all stakeholders, which assures that the quality of construction products meets the requirements (Zhong *et al.*, 2020). Accurate recording of quality information on the blockchain can not only improve the coordination of project stakeholders, but also reduce unnecessary disputes that result from nonconformances (Sheng *et al.*, 2020).

Supply chain management is another application area that can benefit from the information traceability of blockchain technology. Information sharing in supply chain management can be fragmented due to involvement of stakeholders through multiple stages (Li *et al.*, 2022). Thus, a framework that uses real-time digital ledgers for tracking the flow of materials from production to installation can improve the quality of the project (Brandín and Abrishami, 2021). The main contribution of these studies has been designing a system architecture that links the physical supply chain to the virtual layer to enable transparent and traceable management (Brandín and Abrishami, 2021; Hamledari and Fischer, 2021a; Li *et al.*, 2021, 2022; Wu *et al.*, 2022). A few studies have designed a blockchain prototype that is specifically for the supply chain management of off-site modular construction (Li *et al.*, 2021, 2022; Wu *et al.*, 2022). Furthermore, the study conducted by Hamledari and Fischer (2021a) demonstrated how physical and financial supply chains can be integrated by using blockchain-based crypto assets. This work demonstrated how the progress on the product flow can be linked to a BIM model, which in turn generates payment processing based on crypto assets. The systems developed from the studies have been validated using case studies and project scenarios based on actual commercial projects.

More recently, research has been conducted on how blockchain technology can be integrated with digital twins to achieve secure and traceable data communication among project participants (Lee *et al.*, 2021). Studies have found that some of the key factors enabling the integration between these two themes are providing immutable records for BIM data and sharing a trustable single-source BIM model on a distributed ledger (Teisserenc and Sepasgozar, 2021). A digital twin updates the BIM model using the real-time data from IoT sensors. Because of this, researchers have developed conceptual models with multiple layers to store the sensor data and create a digital twin, with blockchain technology being used at the core of the model (Jiang *et al.*, 2021; Lee *et al.*, 2021; Teisserenc and Sepasgozar, 2021). Götz and colleagues (2020) investigated how blockchain-based digital twins can be used for asset-lifecycle management. Hunhevicz and colleagues (2022) proposed a connection between digital twin and blockchain-based smart contracts that automates performance-based digital payments. These two hot topics—blockchain and digital twins—are sure to generate more studies exploring their integration.

Lastly, sustainable design using BIM is a growing area where the potential role of blockchain technology is being explored. Sustainability in construction is an issue that cannot be neglected, and recent studies have identified how BIM and blockchain technology make the sustainable design process more efficient (Copeland and Bilec, 2020; Liu *et al.*, 2019; Shojaei, Wang, *et al.*, 2020). One example is a BIM-blockchain approach for sustainable building design information management, which proposes a conceptual framework for ensuring the realization of sustainable design goals (Liu *et al.*, 2019). Blockchain technology can be used to improve built-asset sustainability as well, improving life-cycle-assessment methods to be much more inclusive and reliable (Shojaei, Wang, *et al.*, 2020). Another study proposed a framework wherein buildings use material banks in a circular economy (Copeland and Bilec, 2020). Information from radio-frequency identification (RFID) data tags are housed in a blockchain network to keep track of material information. The versatility of these studies shows that BIM and blockchain can be integrated in different ways to improve the sustainability of the construction industry.

4. DISCUSSION

In the past few years, interest has grown regarding how blockchain technology can be applied in the construction industry. One potential application is Building Information Modeling (BIM). As can be seen in Fig. 7, the literature review has highlighted studies that discuss a wide range of blockchain applications within the BIM process. The top three application areas are data security, collaborative design, and construction payment.

In its application with data security, blockchain technology operates a peer-to-peer network using asymmetric encryption and consensus algorithms, thus improving the security by recording data in a distributed manner (Das

et al., 2021). This main feature of the technology led to studies related to data security on the BIM platform, which out of all application areas had the highest number. The application area that had the second highest number of studies was collaborative design. One of the purposes of BIM is to enable multiple stakeholders to work together (Leite, 2020). The blockchain enables stakeholders to track model changes transparently, contributing to more studies being conducted related to design liability during the collaborative design process (Pradeep *et al.*, 2020). The third application area was construction payment, which tried to handle the common issue of payment delay in the industry (Hamledari and Fischer, 2021b). The fact that blockchain technology is mostly used for cryptocurrency seems to have affected studies to focus on smart-contract-administered payments via cryptocurrencies and tokens (Hamledari and Fischer, 2021a).

What is promising about BIM-blockchain integration is that over the years more and more contractors are adopting blockchain technology. Fig. 8 summarizes the yearly count of papers for different levels of adoption. The earliest papers that provided direction for future research began being published in 2017; papers continued to be published as more researchers found interest in how to apply blockchain technology to BIM processes. It was not until 2019 that studies started to create conceptual frameworks for blockchain implementation. Out of the 12 studies that created a conceptual framework, 9 of them developed a working prototype and 4 of them validated the prototype using project scenarios in 2020. The numbers increased in 2021, as 12 studies created conceptual frameworks, and 9 of them developed and validated the prototype through scenarios. This trend suggests that the number of papers testing the technology and validating them will increase so that in the future blockchain applications will be used for construction projects.

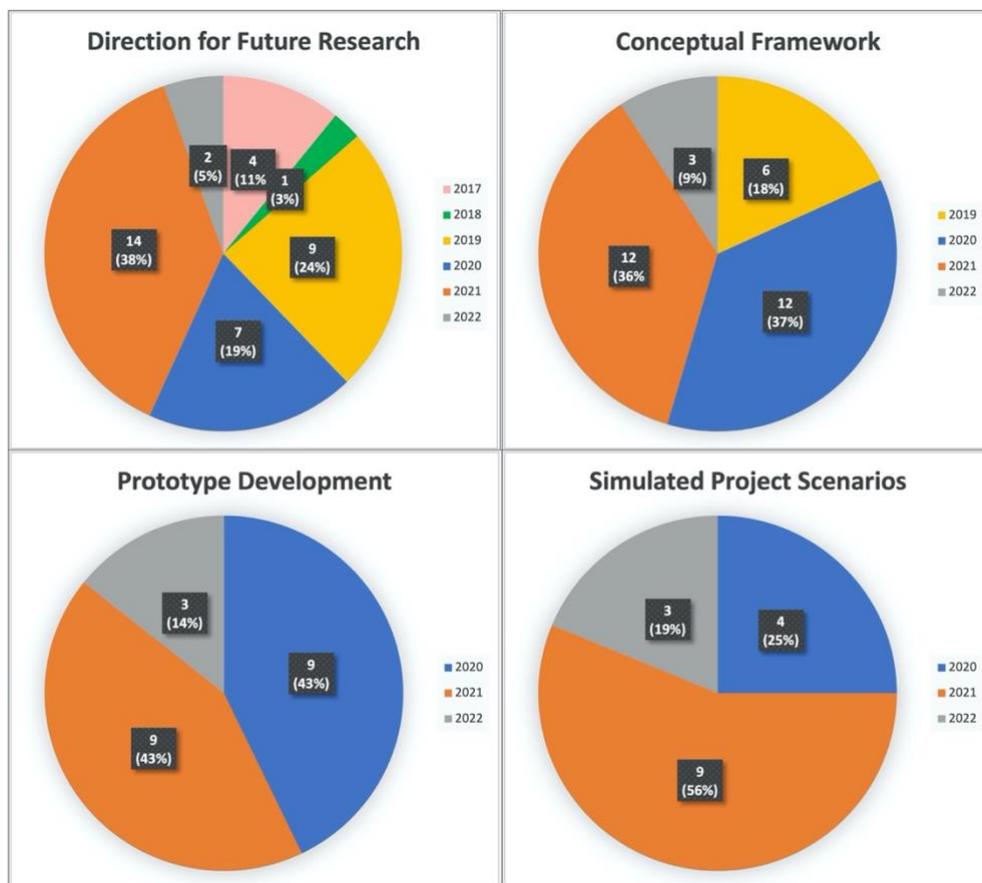


FIG. 8: Number of Papers per Year in Different Levels of Adoption

However, while different studies talk about how blockchain technology can be integrated with BIM, there has to be sufficient consideration given to whether a blockchain is really necessary for specific applications. Multiple studies have developed frameworks to decide if the application actually requires blockchain technology (Hunhevicz and Hall, 2020; Li *et al.*, 2019; Wust and Gervais, 2018). As it is for the application of any new

technology, an irrational adoption could result in an existing system being run on a blockchain architecture that fails to offer benefits for the overall process.

Studies have discovered the key drivers and functions of blockchain technology that should be required to address the challenges in the BIM process (Perera *et al.*, 2020; Pradeep *et al.*, 2020). Perera and colleagues (2020) identified the following drivers: security, anonymity, no single point of trust, fraud resistance, non-physicality, and financial incentives. Pradeep and colleagues (2020) provided the key functional requirements for the blockchain to be integrated with BIM. According to their study, blockchain should enable secure storage of data off-chain, assign and transfer asset ownership, and establish a transparent record of transactions that is tamper resistant. Furthermore, transactions should be made without additional third-party access, and incorporate functions such as multi-signature and time-stamped approvals. The use of blockchain should enable some type of evaluation of the data that is stored, and data recording from sensors and IoT devices should be made autonomously. Reflecting on the key drivers and functions of blockchain technology, future studies should review them thoroughly so that the proposed applications make use of the benefits of blockchain technology as much as possible.

5. FUTURE OUTLOOK

Out of different application areas identified in this study, the authors believe that the use case for blockchain can be stronger when the study falls into multiple areas at the same time. One promising area is automating construction payments. Since payment-related data is extremely sensitive for a project, it requires a transparent record of transactions and resistance to tampering. Payment processing can be integrated with construction-progress tracking. By using automated data-collection technologies and machine-learning algorithms, project managers can capture construction progress and analyze it to process payments to contractors (Hamledari and Fischer, 2021c).

Another great example of how blockchain technology can be applied to multiple BIM aspects is connecting digital twins with construction payments. When collecting data from IoT sensors into the virtual representation of the physical project, the data can be stored in a more secure and transparent way. Performance evaluation of a facility can be made with contract details embedded, and through smart contracts reward payments to stakeholders may be executed automatically (Hunhevicz *et al.*, 2022). This ensures the payment is made on time and based on a trustable source that is stored on the distributed ledger. As seen from these examples, blockchain technology can be utilized to close the gap between different BIM application areas. More studies should focus on how blockchain functions can be applied to multiple areas.

Also, future research should delve into incentive mechanisms and privacy-preserving mechanisms of blockchain technology. BIM is a collaborative process that involves different actors. It is crucial to understand the interests of each party to provide them with an award for making transactions on the blockchain network. While sharing information is important and beneficial for the users, some of the information in the model can be sensitive and should be kept confidential. Preserving confidentiality could be a key element that would allow BIM users to protect their sensitive data but utilize smart contracts to generate an output that can be shared in a transparent and trustable way (Chung and Caldas, 2022). As advanced algorithms for incentivizing users and preserving privacy are developed, researchers should continually assess whether they are things that can be applied to improve the BIM process.

Furthermore, the future outlook of BIM and blockchain-technology integration is dependent on the concepts being tested in real life. Studies involving prototype development and simulated project scenarios are increasing, but researchers should look into how developed systems can be used in practice for BIM to fully adopt the technology. Case studies of BIM-blockchain applications being implemented in real-world projects should be conducted and compared with previous systems. The benefits of integrating BIM and blockchain can be confirmed only after studies validate its use in actual projects.

6. CONCLUSION

For construction projects, BIM is a crucial process that has progressed over the past decades. Despite the advantages that it brings to construction, the BIM process still faces challenges related the transparency, reliability, and security of the data stored in the BIM model. Recent studies have suggested that blockchain technology could solve these problems and improve the current BIM process. Thus, this study conducted a systematic literature review by going through keyword searches on multiple data sources, screening papers based on inclusion and

exclusion criteria. As a result, a total of 70 papers were selected. Data was extracted from the papers to provide a descriptive analysis based on the year of publication, publication sources, level of blockchain adoption, and BIM application area. The papers were categorized into different levels of blockchain adoption and BIM application areas to illustrate the state-of-the-art of BIM-blockchain implementation.

The descriptive analysis and categorization have shown that the past few years have advanced blockchain research in BIM processes. Starting from suggesting potential research directions, studies have developed conceptual frameworks that implement blockchain technology. More recently, multiple studies have focused on developing prototypes and validating them through simulated project scenarios. We divided the BIM-blockchain implementations into 13 application areas. Having the highest number of publications was data security around the BIM model, followed by collaborative design and construction payment. Other popular topics included supply chain management, quality information management, digital twins, and construction-progress tracking.

This research was able to identify the recent trends of research in BIM-blockchain integration. While more studies exploring this topic may be a promising thing, the authors suggest that researchers carefully consider whether a blockchain is really necessary to their future BIM applications. Prior to making a technology selection, project managers should review decision frameworks and key functional requirements for adopting blockchain developed from previous studies. This in turn will elevate the quality of research and ultimately improve potential applications.

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APPENDIX

No.	References	Year	Publication Type	Method or Area of Application
1	(Belle, 2017)	2017	Conference	Overview and Potential Applications
2	(Mathews <i>et al.</i> , 2017)	2017	Conference	Overview and Potential Applications
3	(Wang <i>et al.</i> , 2017)	2017	Journal	Overview and Potential Applications
4	(Turk and Klinc, 2017)	2017	Conference	Overview and Potential Applications
5	(Ye <i>et al.</i> , 2018)	2018	Conference	Overview and Potential Applications
6	(Pradeep <i>et al.</i> , 2019)	2019	Conference	Overview and Potential Applications
7	(Li <i>et al.</i> , 2019)	2019	Journal	Systematic Literature Review Focus Group Discussion Decision Framework for Blockchain Use
8	(Lokshina <i>et al.</i> , 2019)	2019	Journal	Overview and Potential Applications
9	(Nawari and Ravindran, 2019b)	2019	Conference	Overview and Potential Applications
10	(Parn and Edwards, 2019)	2019	Journal	Overview and Potential Applications
11	(Safa <i>et al.</i> , 2019)	2019	Journal	Overview and Potential Applications
12	(San <i>et al.</i> , 2019)	2019	Conference	Overview and Potential Applications
13	(Darko <i>et al.</i> 2020)	2020	Journal	Overview and Potential Applications
14	(Hargaden <i>et al.</i> , 2019)	2019	Conference	Overview and Potential Applications
15	(Harty, 2019)	2019	Journal	Overview and Potential Applications
16	(Hunhevicz and Hall, 2020)	2020	Journal	Decision Framework for Blockchain Use
17	(Kiu <i>et al.</i> , 2020)	2020	Journal	Systematic Literature Review
18	(Lemeš and Lemeš, 2020)	2020	Journal	Overview and Potential Applications
19	(McNamara and Sepasgozar, 2020)	2020	Journal	Technology Acceptance Framework Expert Interview
20	(Parn and de Soto, 2020)	2020	Journal	Overview and Potential Applications
21	(Perera <i>et al.</i> , 2020)	2020	Journal	Systematic Literature Review
22	(Bu <i>et al.</i> , 2021)	2021	Conference	Overview and Potential Applications
23	(Çevikbaş and Işık, 2021)	2021	Journal	Systematic Literature Review

Direction for future research

Conceptual Framework	24	(Cheng <i>et al.</i> , 2021)	2021	Journal	Systematic Literature Review
	25	(Elghaish <i>et al.</i> , 2021)	2021	Journal	Systematic Literature Review
	26	(Hamledari and Fischer, 2021b)	2021	Journal	Case Study
	27	(Hijazi <i>et al.</i> , 2021)	2021	Journal	Systematic Literature Review Focus Group Discussion
	28	(Huang <i>et al.</i> , 2021)	2021	Journal	Systematic Literature Review
	29	(Li and Kassem, 2021)	2021	Journal	Systematic Literature Review
	30	(Liu <i>et al.</i> , 2021)	2021	Journal	Systematic Literature Review
	31	(Lou <i>et al.</i> , 2021)	2021	Conference	Overview and Potential Applications
	32	(Mohammed <i>et al.</i> , 2021)	2021	Journal	Systematic Literature Review
	33	(Pan and Zhang, 2021)	2021	Journal	Systematic Literature Review
	34	(Scott <i>et al.</i> , 2021)	2021	Journal	Systematic Literature Review
	35	(Zhao <i>et al.</i> , 2021)	2021	Conference	Overview and Potential Applications
	36	(Olawumi <i>et al.</i> , 2022)	2022	Journal	Systematic Literature Review
	37	(Xu <i>et al.</i> , 2022)	2022	Journal	Systematic Literature Review
	38	(Liu <i>et al.</i> , 2019)	2019	Journal	Collaborative Design Sustainable Design
	39	(Nawari and Ravindran, 2019a)	2019	Journal	Data Security Collaborative Design
	40	(Nawari and Ravindran, 2019c)	2019	Journal	Data Security Collaborative Design
	41	(Nawari and Ravindran, 2019d)	2019	Journal	Data Security Collaborative Design
	42	(Singh and Ashuri, 2019)	2019	Journal	Data Security Collaborative Design
	43	(Zheng <i>et al.</i> , 2019)	2019	Journal	Data Security
	44	(Chong and Diamantopoulos, 2020)	2020	Journal	Data Security Construction Payment
	45	(Copeland and Bilec, 2020)	2020	Journal	Sustainable Design
	46	(Götz <i>et al.</i> , 2020)	2020	Journal	Digital Twin

	47	(Darabseh <i>et al.</i> , 2021)	2021	Conference	Data Security
	48	(Das <i>et al.</i> , 2021)	2021	Journal	Data Security
	49	(Teisserenc and Sepasgozar, 2021)	2021	Journal	Digital Twin
Prototype Development	50	(Dounas <i>et al.</i> , 2020)	2020	Conference	Collaborative Design
	51	(Elghaish <i>et al.</i> , 2020)	2020	Journal	Construction Payment
	52	(Shojaei, Flood, <i>et al.</i> , 2020)	2020	Journal	Construction Progress Tracking
	53	(Ye <i>et al.</i> , 2020)	2020	Conference	Engineering Quantity Statistics Construction Payment
	54	(Zhong <i>et al.</i> , 2020)	2020	Journal	Quality Information Management
Simulated Project Scenarios	55	(Pradeep <i>et al.</i> , 2020)	2020	Conference	Collaborative Design
	56	(Sheng <i>et al.</i> , 2020)	2020	Journal	Quality Information Management
	57	(Shojaei, Wang, <i>et al.</i> , 2020)	2020	Journal	Sustainable Design
	58	(Xue and Lu, 2020)	2020	Journal	Data Security
	59	(Brandín and Abrishami, 2021)	2021	Journal	Supply Chain Management
	60	(Ciotta <i>et al.</i> , 2021)	2021	Journal	Construction Safety Quality Information Management
	61	(Pradeep <i>et al.</i> , 2021)	2021	Journal	Collaborative Design Data Security
	62	(Hamledari and Fischer, 2021c)	2021	Journal	Building Data Collection Construction Payment Construction Progress Tracking
	63	(Hamledari and Fischer, 2021a)	2021	Journal	Construction Payment Supply Chain Management
	64	(Jiang <i>et al.</i> , 2021)	2021	Journal	Construction Progress Tracking Digital Twin
	65	(Lee <i>et al.</i> , 2021)	2021	Journal	Construction Progress Tracking Digital Twin
	66	(Li <i>et al.</i> , 2021)	2021	Journal	Data Security Construction Progress Tracking Quality Information Management Supply Chain Management

67	(Tao <i>et al.</i> , 2021)	2021	Journal	Data Security Collaborative Design
68	(Hunhevicz <i>et al.</i> , 2022)	2022	Journal	Construction Payment Digital Twin Building System Analysis
69	(Li <i>et al.</i> , 2022)	2022	Journal	Supply Chain Management
70	(Wu <i>et al.</i> , 2022)	2022	Journal	Quality Information Management Supply Chain Management
