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Integrating Blockchain with Building Information Modelling (BIM):A Systematic Review Based on a Sociotechnical System Perspective

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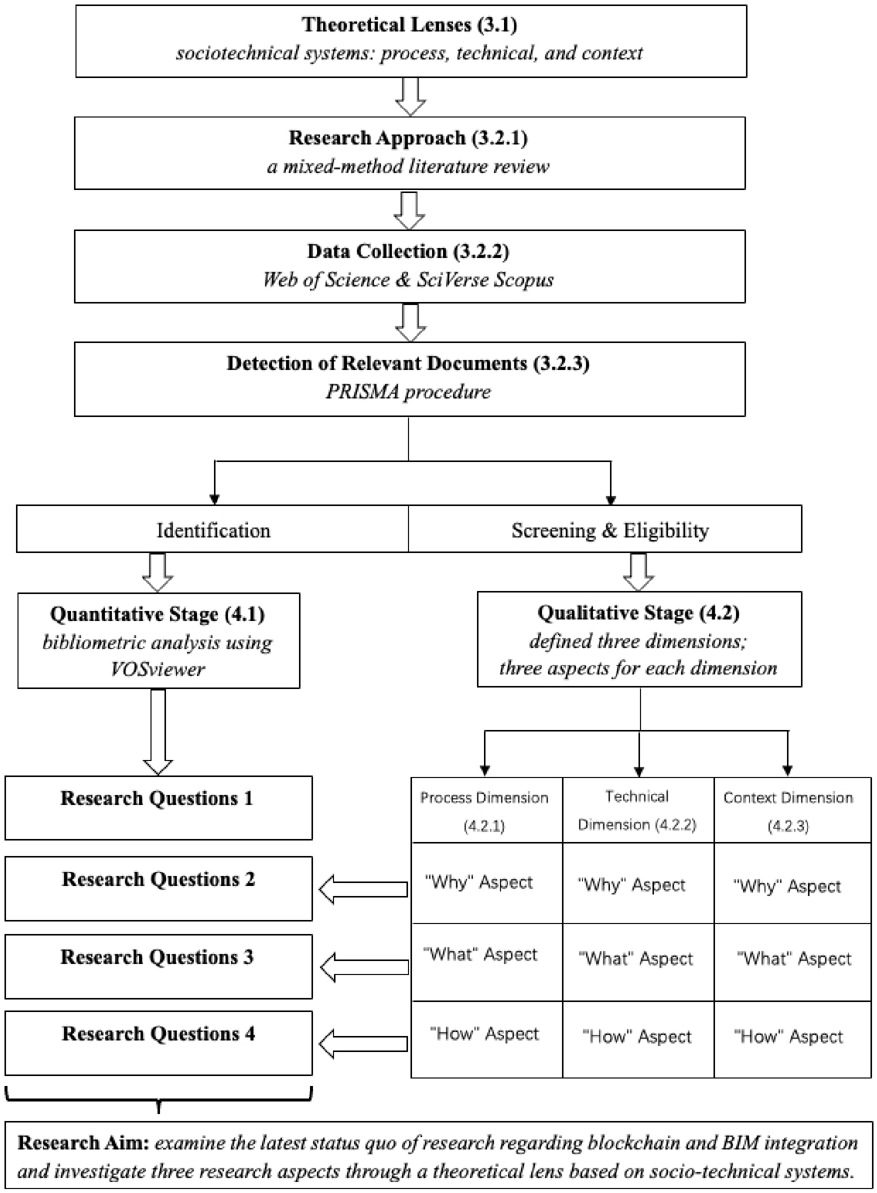

Figure 1

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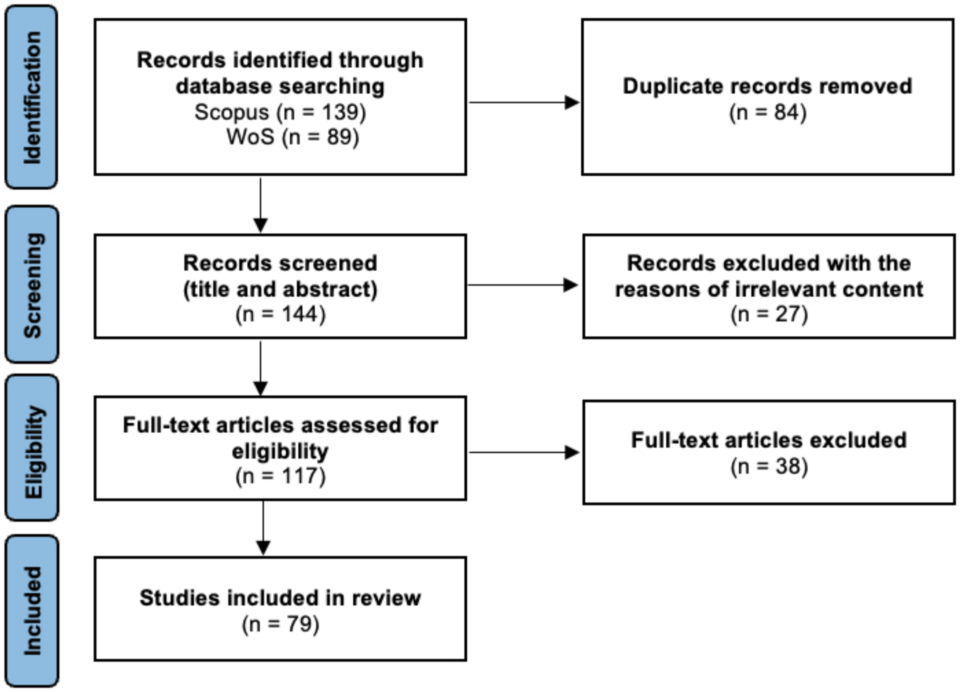

Figure 2

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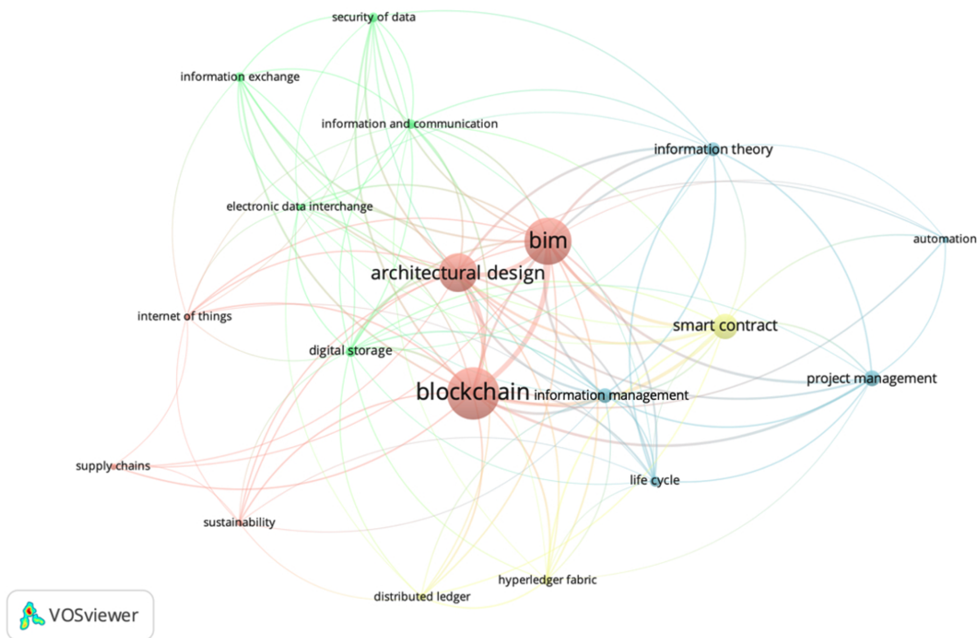

Figure 3

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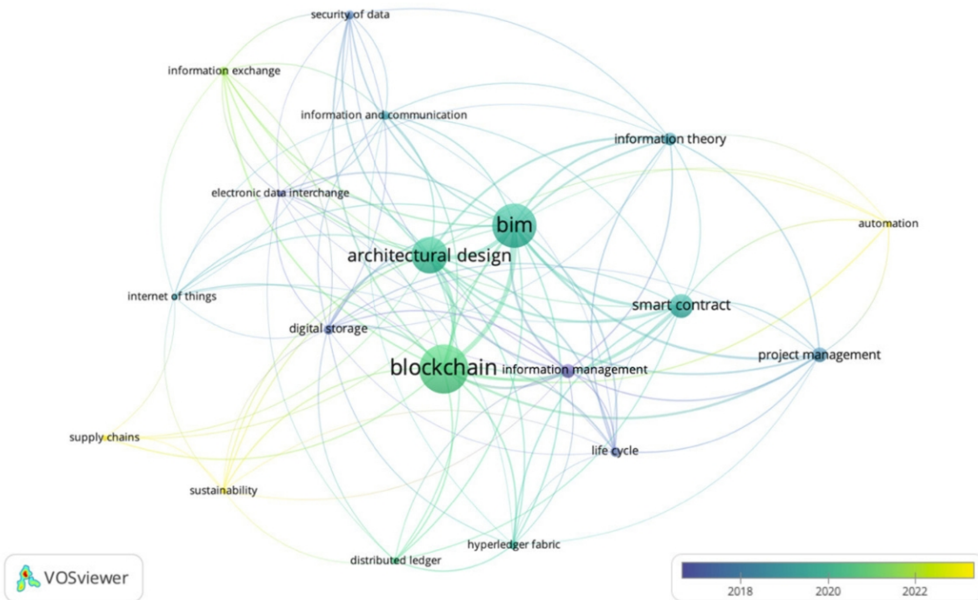

Figure 4

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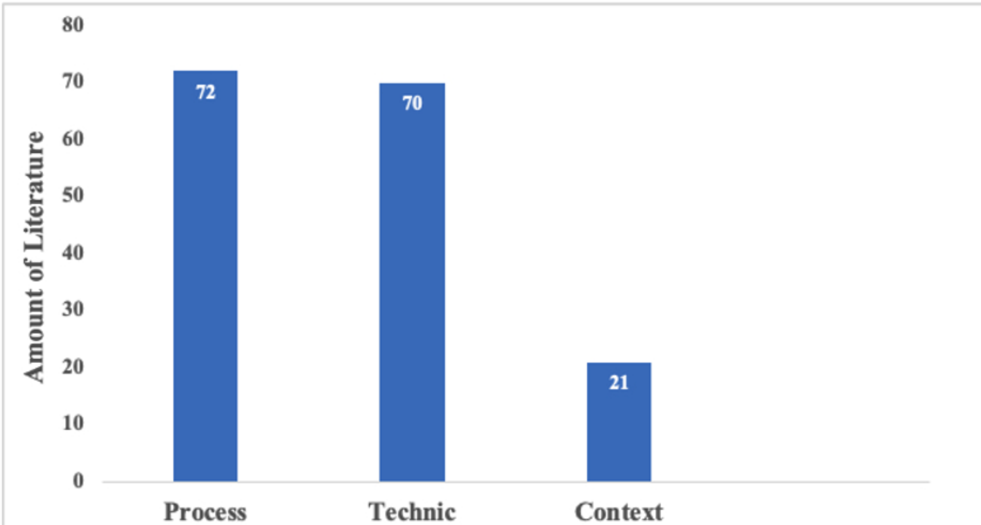

Figure 5

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Appendix A - results of the qualitative systematic review

Author(s) & Summary of Key Points	Dimension		
******Abbreviation*: ***PR*** *– Process,* ***TE*** *– Technical,* ***CO*** *– Context,* ***BC*** *– Blockchain,* ***AT*** *– Assistive Technologies,* ***SC*** *– Smart Contract.* ●*: Primary subject* ○*: Secondary subject*	PR	TE	CO
Aleksandrova et al. (2019) - Scrutinised integration of digital technology and recommended a "BC + BIM + AT" ecosystem for complete lifecycle management.	●	○	○
Amaludin and Taharin (2018) - Delineated the possibilities of blockchain in the construction industry and recommended the integration of blockchain and BIM to facilitate enhanced real-time management of projects.	●	○	
Bachtobji et al. (2022) - Proposed a "BIM + BC + IoT + edge computing" architecture for building management systems.		●	
Brandín and Abrishami (2021) - Discussed "BC + SC + BIM + AT" into an information traceability platform to support data lifecycle management of assets in offsite manufacturing.	●	○	
Bukunova and Bukunov (2019) - Demonstrated the necessities, approaches, and challenges of integrating blockchain with BIM.	●	●	
Calvetti et al. (2020) - Investigated lawful and personnel readiness to adapt the integration of blockchain and BIM.	○		●
Casillo et al. (2022) - Suggested the usage of NFTs to manage the ownership of digital assets, address BIM families' authentication and copyright management.		●	
Celik et al. (2023) - Designed a BC-based BIM data provenance model for the purpose of managing BIM data during construction and tested the solution in real project scenarios.	●	●	
Chong and Diamantopoulos (2020) - Investigated an actual case and designed a "BC + BIM + IoT" system for automatic payment in the building stage.	●	○	
Cocco et al. (2022) - Proposed a Self-Sovereign Identity-based system using "public BC + BIM + AT" to manage the flow of building-related information.	○	●	
Copeland and Bilec (2020) - Designed a "BC + BIM + AT" framework to implement circular economy.	●	○	
Darabseh and Martins (2020) - Reviewed the possibilities of blockchain applications in the construction industry (including, but not restricted to BIM), identified risks and prospects for integration with BIM.	●	●	
Das et al. (2021) - Reviewed and acknowledged the security levels of BIM and suggested utilising blockchain to enhance security.	○	●	
Dounas et al. (2019) - Designed a platform based on ETH and IPFS to integrate BIM and implement smart contracts to improve collaboration and competition in distributed design.	●	●	
Dounas, Jabi, et al. (2020) - Designed a decentralised BIM framework based on ETH and IPFS to enhance the design process.	○	●	
Dounas et al. (2021) - Designed a decentralised design framework of "ETH + SC + BIM" to enhance the design process.	●	●	

Elghaish et al. (2020) - Designed and tested a "BC + SC + BIM" system for automated financials throughout the lifecycle of IPD projects.	●	●	
Fitriawijaya and Hsin-Hsuan (2019) - Designed a framework utilising blockchain and smart contracts to improve management of supply chain in a BIM-enabled environment.	●	●	
Ganter and Lützkendorf (2019) - Suggested blockchain for improvement of information management of BIM throughout the whole lifecycle of projects.	●	○	○
Guo et al. (2022) - Proposed a BC and SC-based system for uploading BIM model copyrights.		●	
Hamledari and Fischer (2021) - Designed and tested an automated payment system based on the ETH platform, field data, BIM, and AI.	●	●	○
Hargaden et al. (2019) - Presented the prospects of blockchain in the construction industry, examined the possibility and resolution of integrating with BIM.	●	●	
Hammi et al. (2022) - Designed an information system using SC based on HLF and Odoo PLM/ERP framework with integrated BIM software so as to address collaboration issues in BIM workflows.	●	●	
Hijazi et al. (2022) - Designed a BIM single source of truth prototype based on HLF for supply chain data delivery.	●	●	
Honcharenko et al. (2021) - Introduced a BIM platform consisting of IoT, BC, and AT in order to manage the lifecycle of construction objects.	●	○	○
Huang et al. (2022) - Envisioned the use of BIM and BC to document urban development in the Metaverse.	●	○	
Jiang et al. (2022) - Designed a BC-Enabled BIM system framework based on Fabric consortium chain, storing BIM model data and key data in IPFS.		●	
Kasten (2020) - Reviewed the prospective applications of blockchain (including, but not restricted to BIM), taking note of the challenges and the significance of background for the integration.	●		○
Kifokeris and Koch (2020) - Proposed a blockchain-based digital business model (including BIM and other technologies) for construction logistics consultants through literature review and empirical study.	●		●
Kiu et al. (2020) - Reviewed the prospective applications for blockchain in the building industry (including, but not restricted to BIM) and discussed the significance and challenges of the integration of blockchain and BIM.	●		○
Le (2021) - Developed an ETH-based "BC + BIM" application so as to resolve model copyright issues.	○	●	
Lee et al. (2021) - Designed and tested a "BC + BIM + IoT" framework for digital twins.	●	●	
Lemeš and Lemeš (2019) - Demonstrated the possible and present limitations of the integration of blockchain and BIM.	●		○
Li et al. (2022) - Designed a BC-Enabled IoT-BIM platform for Data-Information-Knowledge drove supply chain management based on the open BIM standard extended from IFC, and performed case study experiments.	●	●	
Li, Chen, et al. (2021) - Designed a "BC + BIM + IoT+ AT" platform for prefabricated construction supply chain management, and corroborated it in an	●	●	

actual case.			
Li, Duan, et al. (2021) - Designed and tested a "BC + BIM + AI" platform for project management.	●	●	
Li, Greenwood, et al. (2019) - Investigated seven application areas of blockchain in the construction industry (including, but not limited to BIM), showcased a conceptual model and evaluated the applicability of the integration of blockchain and BIM.	●	●	●
Li, Kassem, et al. (2019) - Designed a digital ecosystem of "BC + SC + BIM + IoT + AT" to improve processes and payments throughout the lifecycle of projects.	●	●	
Liu et al. (2019) - Designed a "BC + SC + BIM" framework to improve data management in design processes of sustainable buildings.	●	●	
Liu et al. (2021) - Investigated the utilisation of blockchain, BIM, and City Information Management (CIM) to enhance sustainability throughout the lifecycle of buildings.	●	○	
Lokshina et al. (2019) - Designed a "BC + BIM + IoT" structure to improve the smart building design process.	●	○	
Mason (2017) - Interviewed practitioners and presented the potential and existing limitations in the integration of smart contracts and BIM.	●	●	●
McNamara and Sepasgozar (2020) - Designed a TAM and discussed with practitioners about investigating industry inclination for blockchain, BIM, and smart contracts.	○		●
McNamara and Sepasgozar (2021) - Designed TAM and looked into potential smart contracts applications in the construction industry (including, but not limited to BIM).	○		●
Nawari (2020) - Proposed an "HLF + SC + BIM" framework to improve the design process and implement automated building code compliance checking.	○	●	
Nawari and Ravindran (2019a) - Summarised the characteristics of blockchain and suggested a framework to improve the design workflow of BIM.	●	●	
Nawari and Ravindran (2019b) - Reviewed the latent applications of blockchain in the construction industry (including, but not restricted to BIM) and demonstrated a "BC + SC + BIM" framework for disaster recovery process.	●	●	
Nawari and Ravindran (2019c) - Summarised the characteristics of blockchain and offered the possibilities of the integration of blockchain and BIM for improvement of process.	●	●	
Ng (2021) - Designed a framework using blockchain to connect BIM and Generative Adversarial Neural Networks (GANs) to enhance design crowdsourcing processes.	●	●	
Ni et al. (2021) - Proposed an integrated digital management platform of "BIM + BC + SC" and a management mechanism to improve the efficiency of the project.	●	○	
Parn and Edwards (2019) - Examined cybersecurity in BIM and CDE and suggested the possibilities of the integration of blockchain and BIM.		●	○
Pattini et al. (2020) - Suggested the utilisation of blockchain and smart contracts to improve BIM processes throughout the lifecycle of projects.	●	○	
Pellegrini et al. (2020) - Investigated and proposed the integration of blockchain	●		○

and BIM to improve waste management dependability.			
Pradeep et al. (2019) - Examined the challenges in BIM processes and the possibilities and limitations of blockchain applications.	●	○	
Pradeep et al. (2020) - Presented functional requirements for the integration of blockchain and BIM to enhance exchange of data, and examined a case study of BIMCHAIN.	●	○	○
Pradeep et al. (2021) - Designed and tested a "BC + BIM" model for design accountability control.	●	●	○
Prakash and Ambekar (2020) - Interviewed practitioners, and suggested a roadmap for the adoption of the integration of blockchain, smart contract, and BIM in the industry.	○		●
Raco et al. (2021) - Demonstrates the findings of the development of a "BC + BIM" application that implements a CDE and optimises lifecycle management.	○	●	○
Raslan et al. (2020) - Investigated the integration of blockchain, BIM, and Asset Information Modelling (AIM) to improve asset management processes.	●	○	
Sheng et al. (2020) - Designed and tested an "HLF + SC + BIM" framework to improve the management of quality information.	●	●	
Shojaei, Flood, et al. (2019) - Designed and tested an "HLF + SC + BIM" framework to manage projects and enable semi-automatic payments.	●	●	
Siountri et al. (2019) - Designed a "BC + BIM + IoT" framework to improve O&M process of smart building.	●	○	
Siountri et al. (2020) - Suggested the integration of blockchain, BIM, and IoT for whole lifecycle management of smart buildings and analysed a case of smart museum.	●	○	
Sonmez et al. (2022) - Developed a "BIM + SC" progress payment management system, simulated real-life cases and surveyed practitioner attitudes.	●	●	●
Suliyanti and Sari (2019) - Suggested a framework for utilising blockchain to enhance security of BIM.	○	●	
Suliyanti and Sari (2021) - Designed an "HLF + BIM" framework for the improvement of information exchange throughout the lifecycle of projects.	●	●	
Tao et al. (2022) - Designed confidentiality-minded framework for BC-based BIM design collaboration using IPFS model, developed access control model and new design coordination strategy.	○	●	
Turk and Klinc (2017) - Advised blockchain to improve management and showed the technical logic for incorporation with BIM.	○	●	
Wang, Hao, et al. (2022) - Proposed a BC system for privacy protection of BIM big data in smart buildings.		●	
Wang, Shen, et al. (2022) - Designed a multi-person collaborative design model, utilising the SDT approach, IPFS storage model, and a period division mechanism addressing synchronisation issues.	○	●	
Wu et al. (2022) - Designed a BC-enabled IoT-BIM platform on the basis of the SDT approach for off-site production management, solving the 'single point of failure' problem in IoT networks.	○	●	
Xue and Lu (2020) - Designed and tested a resolution to reduce redundancy of		●	

information in the integration of blockchain and BIM.				
Yang et al. (2020) - Examined two case studies based on two blockchain platforms and indicated the advantages and disadvantages of the integration of blockchain and BIM.		●	●	○
Ye and König (2020) - Designed a "BC + SC + BIM" framework for automated payments.		●	●	
Ye et al. (2018) - Suggested a Cup-of-Water theory of the integration of blockchain, BIM and IoT.		●	○	
Ye et al. (2020) - Designed a "BC + SC + BIM" framework for automated payments.		●	●	
Ye et al. (2022) - Designed a "SC + BIM" framework to realise, record, and visualise the automation delivery, acceptance, and payment process.		○	●	
Zheng, Jiang, et al. (2019) - Designed and evaluated a model integrating BIM, cloud computing, big data, and blockchain to improve security of information in the design and construction stage.		●	●	
Zheng, Zhu, et al. (2019) - Designed and tested a context-aware access control model for cloud BIM amalgamated with blockchain.		●	●	
Total Count	**79**	**72**	**70**	**21**

Appendix B - literature classified into different lifecycle phases or application fields (process dimension)

	Lifecycle Phases		
	Pre-construction	**Construction**	**Post-construction**
Author(s)	Amaludin and Taharin (2018), Casillo et al. (2022), Dounas et al. (2019), Dounas et al. (2021), Dounas, Jabi, et al. (2020), Guo et al. (2022), Jiang et al. (2022), Le (2021), Liu et al. (2019), Lokshina et al. (2019), Nawari (2020), Nawari and Ravindran (2019a), Nawari and Ravindran (2019b), Ng (2021), Pradeep et al. (2020), Pradeep et al. (2021), Tao et al. (2022), Wang, Shen, et al. (2022), Zheng, Jiang, et al. (2019).	Amaludin and Taharin (2018), Brandín and Abrishami (2021), Celik et al. (2023), Chong and Diamantopoulos (2020), Hamledari and Fischer (2021), Li, Duan, et al. (2021), Pradeep et al. (2020), Sheng et al. (2020), Shojaei, Flood, et al. (2019), Sonmez et al. (2022), Wu et al. (2022), Ye and König (2020), Ye et al. (2020), Zheng, Jiang, et al. (2019).	Bachtobji et al. (2022), Hijazi et al. (2022), Raslan et al. (2020), Siountri et al. (2019), Ye et al. (2022). **Full Lifecycle** Aleksandrova et al. (2019), Cocco et al. (2022), Elghaish et al. (2020), Ganter and Lützkendorf (2019), Hammi et al. (2022), Honcharenko et al. (2021), Li, Kassem, et al. (2019), Liu et al. (2021), Ni et al. (2021), Pattini et al. (2020), Raco et al. (2021), Siountri et al. (2020), Suliyanti and Sari (2021), Ye et al. (2018), Zheng, Zhu, et al. (2019).
	Application Fields		
	Smart Building / Digital Twin	**Supply Chain Management**	**Sustainability / Circular Economy**
Author(s)	Lee et al. (2021), Lokshina et al. (2019), Siountri et al. (2019), Wang, Hao, et al. (2022).	Fitriawijaya and Hsin-Hsuan (2019), Hamledari and Fischer (2021), Hijazi et al. (2022), Kifokeris and Koch (2020), Li, Chen, et al. (2021), Li et al. (2022).	Copeland and Bilec (2020), Liu et al. (2019), Liu et al. (2021), Pellegrini et al. (2020), Sheng et al. (2020).

Integrating Blockchain with Building Information Modelling (BIM) - A Systematic Review Based on a Sociotechnical System Perspective

Abstract

Purpose:

The purpose of this paper is to analyse the current state of research on the integration of blockchain and Building Information Modelling (BIM) in the Architecture, Engineering, Construction, and Operations (AECO) industry as a means of identifying gaps between the existing paradigm and practical applications for determining future research directions and improving the industry. The study aims to provide clear guidance on areas that need attention for further research and funding and to draw academic attention to factors beyond the technical dimension.

Design/Methodology/Approach:

A mixed-method systematic review is employed, considering multiple literature types, and using a sociotechnical perspective-based framework that covers three dimensions (technic, process, and context) and three research elements (why, what, and how). Data are retrieved and analysed from the Web of Science and Scopus databases for the 2017-2023 period.

Findings:

While blockchain has the potential to address security, traceability, and transparency and complement the system by integrating supporting applications, significant gaps still exist between these potentials and widespread industry adoption. Current limitations and further research needs are identified, including designing fully integrated prototypes, empirical research to identify operational processes, testing and analysing operational-level models or applications, and developing and applying a technology acceptance model for the integration paradigm. Previous research lacks contextual settings, real-world tests, or empirical investigations and is primarily conceptual.

Originality:

This paper provides a comprehensive, critical systematic review of the integration of blockchain with BIM in the construction industry, using a sociotechnical perspective-based framework which can be applied in future reviews. The study provides insight into the current state and future opportunities for policymakers and practitioners in the AECO industry to prepare for the transition in this disruptive paradigm. It also provides a phased plan along with a clear direction for the transition to more advanced applications.

Keywords

Blockchain; Building Information Modelling (BIM); Systematic review

1. Introduction

The architecture, engineering, construction, and operation (AECO) industry is increasingly adopting new technologies and methodologies that will shape its future sustainable development. However, over the last few decades, the construction industry's productivity has consistently lagged behind other industries as manufacturing and finance. Moreover, the sector has been criticised for having difficulty in embracing digitisation, as it surpasses only agriculture, which is the least digitised (Rodrigo *et al.*, 2020). Numerous studies have pointed out several interrelated factors that contribute to the failures and underperformance of the construction industry. These factors include poor communication and collaborative information sharing (Mitkus and Mitkus, 2014), lack of transparency and accountability (Prakash and Ambekar, 2020), payment problems and poor contract management (Li *et al.*, 2019a).

Despite the slow progress of digitisation, it can be observed that the construction industry has been applying Information and Communications Technology (ICT) to enhance the flow of information and collaboration on projects and connect its productivity and performance gap compared to other sectors. With the wave of Construction 4.0, digitalisation and automation have become relatively prevalent in the industry, involving Building Information Modelling (BIM), the Internet of Things (IoT), Augmented Reality (AR), Virtual Reality (VR), big data, Artificial Intelligence (AI), blockchain, 3D printing, and the application of Modern Methods of Construction (MMC) (Bolpagni *et al.*, 2022; McNamara and Sepasgozar, 2021).

The digital revolution has facilitated the integration of the physical environment with digital ecosystems (Sepasgozar, 2021). BIM has been the foundation for the development of several technologies and methodologies that have been created throughout time to manage a range of jobs and activities during various construction and operating phases in the AECO industry (Wang *et al.*, 2020a). As a revolutionary form of methodology, it outlines concepts and principles for information management as presented in the ISO 19650 series: building information modelling (ISO 19650-1:2018). Therefore, BIM also includes interactive policy, working methods, and processes for coordinating multiple participants and multidisciplinary teams in a collaborative manner, allowing the integration of information, data, and management flow within the same ecosystem (Zheng *et al.*, 2019a).

Considering the enormous potential and benefits of BIM, governments and institutions worldwide have been focusing on it, with several BIM standards and policies being developed (e.g., in the UK, Italy, Spain, Finland, Germany and Singapore). BIM has also become the most extensively analysed digital approach in various types of research. It can also provide the technological foundation as a "central intersection" that connects with various complementary technologies, alongside an essential foundation for green and low-carbon building (Li *et al.*, 2012) and the circular economy, smart building, and the digital twin (Wang *et al.*, 2020a).

Nevertheless, the acceptance and penetration of BIM are thought to have remained slow (Ahmad *et al.*, 2018). Apart from the challenges from process-based and people-based factors, various studies have identified the issues and challenges with the BIM methodology. These issues and challenges include interoperability, security, reliability, and traceability of data in storage, exchange, and revision processes (Aleksandrova *et al.*, 2019; Kiu *et al.*, 2020; Pradeep *et al.*, 2021). Considerably, they are interfering with the collaboration and trust environment of the participants (Shelbourn *et al.*, 2007).

The emergence of blockchain technology has piqued the interest of the AECO industry. Aste *et al.* (2017) described it as the fourth industrial revolution poised to disrupt the industry. A theme of blockchain application in the industry that is incredibly prominent is the integration of blockchain and BIM (Li *et al.*, 2019a). Due to its decentralised nature of high security and immutability, it manifests the potential to address specific issues on data storage, security, and sharing, thereby enhancing the aspects of privacy, transparency, and trust (Lee *et al.*, 2021). Therefore, blockchain is seen as having the potential to overcome some of BIM's inherent challenges and enhanced benefits; this potential is widely proposed for improving data security and transparency issues relating to information exchange and accountability in different BIM workflow scenarios throughout a project lifecycle, thereby creating an environment of trust and effective collaboration (e.g., Lamb, 2018; Plevris *et al.*, 2022).

Due to the novelty of the technology, several growing and maturing research have been dispersed in this field, for example, integrating blockchain and BIM to improve data security (Lokshina *et al.*, 2019) and information management (Lee *et al.*, 2021) and facilitating smart contracts (Nawari and Ravindran, 2019a). The understanding of the link between BIM and blockchain can help the industry to investigate further areas of investment to solve current issues that BIM implementation is facing, accelerating adoption. Highlighting the gaps in existing research can help facilitate the potential identification of ways of improving integration while also suggesting future research directions. Therefore, it is necessary to conduct a systematic literature review on the integration of blockchain and BIM.

However, the current reviews have primarily focused on blockchain in the entire AECO industry. Li *et al.* (2019a) and Plevris *et al.* (2022) performed a rigorous examination of blockchain applications in the construction sector, summarising several current application categories. Similarly, Scott *et al.* (2021) reviewed the usage of blockchain in the construction industry; Li and Kassem (2021) examined blockchain-enabled smart contracts in construction. These works, however, mainly concerned potential application scenarios and they do not cover a more detailed discussion of options as well as models for BIM and blockchain integration that can benefit both academia and industry.

There is a very limited number of reviews specifically emphasising blockchain and BIM integration as found in various mainstream academic databases such as Web of Science and SciVerse Scopus. Although the title of Nawari and Ravindran's research (2019c) pertains to a review of the integration of blockchain and BIM, the said paper focuses on the description of blockchain and fails to mention the detailed content from the BIM side. In the same way, Tan *et al*. (2022) completed a review of BIM and blockchain; even though the paper discusses BIM and blockchain separately, the review of integration entirely emphasises the investigation of the potential of various application scenarios and overlooks the technical dimensions and the factors when implementing. Chung *et al*. (2022) examined the technical and application scenario dimensions but failed to investigate industry readiness or contextual factors.

In addition, Das *et al*. (2021) carried out a review that specifically concentrated on the usage of blockchain to enhance BIM security; however, this review only paid attention to the applicability of blockchain as a cybersecurity-enabling technology to BIM security, neglecting other applications scenarios and implementation processes. Similarly, reviews by Hijazi *et al*. (2021) and Nawari and Ravindran (2019b) focused only on data delivery and disaster recovery.

Furthermore, blockchain technology is a rapidly evolving field and although the studies contained the technical dimension, over time, many integrated solution designs and wider applications have developed in the years since the completion of these studies, such as some emerging models for the supply chain management (e.g., Hijazi *et al*., 2022; Li *et al*., 2022).

Overall, these reviews lack a more detailed discussion about the technical options for integration and the contextual factors, which makes it difficult to identify pertinent challenges and barriers. With increasing claims that blockchain is nothing more than a hyped technology, its actual usefulness in the construction industry is being questioned (Perera *et al*., 2020). Therefore, a theoretical perspective of sociotechnical systems is utilised in this paper. In addition, a review framework is constructed that more comprehensively integrates the three dimensions of process, technic, and context, while also setting out the "Why", "What", and "How" aspects under each of the three dimensions as a means of identifying the need for integration, application potential and the effort that is required to advance the field.

This study aims to analyse the current state of research on blockchain and BIM integration from a sociotechnical systems perspective and identify future research directions that can advance development and implementation. To achieve this, the study has established four research questions (RQs):

RQ1: *What is the current state of research and trends regarding BIM and blockchain integration?*

RQ2: *What problem-solving or performance improvements can blockchain provide to BIM in terms of process, technical and contextual dimensions?*

RQ3. *What solutions or applications have been proposed or implemented for this integration in terms of process, technical and contextual dimensions?*

RQ4. *What are the gaps or challenges of existing research and what should the future directions be in terms of process, technical and contextual dimensions?*

In the following section, this research reviews the background concept and the current state of research on BIM and blockchain, followed by rendering a theoretical lens and designing a research approach. A quantitative method applying bibliometrics and a qualitative review through the proposed framework was performed with the discussion of outcomes. Finally, this research provides a summary of findings and presentation of the conclusions discussing the innovative contribution as well as limitations.

2. Literature Review

2.1 Background of BIM

BIM integrates multidimensional data from organisations, programmes and projects and can represent them in a parametric and visual form (Copeland and Bilec, 2020). Information models can contain information about buildings and infrastructure, including geometric descriptions (e.g., material, weight, and dimensions of the components) and alphanumeric (e.g., function, behaviour, and price of the components) (Xue and Lu, 2020). Ye *et al*. (2018) indicated that by providing semantically rich and object-oriented digital building models for each process throughout a construction project's lifecycle, the efficiency of information management in a project could improve.

According to Rao (2006), information is probably the most important "building material", while Winch (2012, p. 16) describes construction projects as a matter of information management. BIM-based processes are in line with the industry's collaborative nature (Ye *et al*., 2018) and are claimed to streamline various management processes within the industry (Babalola *et al*., 2021) and significantly improve the communication and relationships among the involved parties (Kähkönen and Rannisto, 2015). As Kifokeris and Koch (2020) have indicated, BIM has become an essential paradigm for integrated collaboration. From an organisational management perspective, Siountri *et al*. (2019), Woodhead *et al*. (2018) and Zhou *et al.* (2017) refer to BIM as a critical direction for the future of information management in the industry.

They further note that BIM has resulted in various new business models, including "Buildings-as-a-Service".

Moreover, various technologies such as IoT sensors and smart devices have been utilised with BIM to enhance data-driven asset management and monitor system operational performance (Lemeš and Lemeš, 2019; Pasini *et al*., 2016). In addition, during the design and construction phases, BIM-based processes apply a range of digital technologies, which have been extensively explored to facilitate process efficiency. These technologies consist of integrating laser scanning and photogrammetry, VR and AR, and wearables (Siountri *et al*., 2019; Volk *et al*., 2014; Yin *et al*., 2019). Furthermore, Charef and Emmitt (2021) have discussed applying BIM with assistive technologies to facilitate waste management in a circular economy, while Lee *et al*. (2021) focused on BIM with integrated sensors creating a digital twin.

2.2 Challenges to Implementing BIM

Despite being praised as an end-all solution, Holzer (2011) identifies seven prevailing problems of BIM from a practical standpoint; the issues of technocentric and process change continue to impede practice today (Arrotéia *et al*., 2022). Jamal *et al*. (2019) argued that in addition to human-based challenges (e.g., learning curves and resistance to change), these problems arise from process challenges; for example, platforms in the BIM process are not effective in ensuring role-based access to information, and there is a disconnect at the data level at various stages of the lifecycle (Suliyanti and Sari, 2021). Tan *et al*.'s review (2022) summarised several weaknesses in the BIM process, including trust, asset ownership, and data reliability issues. BIM implementation would benefit from unified BIM standards and libraries to improve data exchange and interoperability (Babalola *et al*., 2021), as well as a method and mechanism to allow trusted, transparent, and traceable information handling as a fully collaborative and integrated approach (Dounas *et al*., 2019).

In addition, the transmission of information containers has raised the issue of data security. The conceptual principles of BIM platform security – confidentiality, integrity, and availability – have been presented by Singh *et al*. (2011). Originating from three sources, data corruption, loss, and manipulation are the three main risks to BIM workflow security. Boyes (2013) and Pradeep *et al*. (2021) have warned of threats from external sources, in which data theft and malicious attacks carried out by cybercriminals can represent various threats to data and are even sensitive physical building assets. Furthermore, Das *et al*. (2021) indicated that malicious or human errors from within the project might result in data leakage, misuse, and loss of property, trust, and reputation. Moreover, Nawari and Ravindran (2019b) detected system failures, indicating the risks of data corruption or leakage during transmission. As Pradeep *et al*. (2021) emphasised, third-party software or cloud providers that violate pertinent guidelines or use stored data for machine learning have raised privacy issues. Numerous studies have also examined the various legal and contractual issues associated with BIM applications. For example, Winfield has introduced Legal BIM all around the world and is the author of several articles on BIM legal issues, digitalisation and innovation in the construction industry and the author of the Society of Construction Law's award-winning article, "Building Information Modelling: The Legal Frontier-overcoming Legal and Contractual Obstacle" (Winfield, 2015; Winfield and Rock, 2018). Although more comprehensive guidelines have been continually defined, Turk and Klinc (2017) hold that it is challenging to rely on various legal tools from the paper world to resolve the issues in the digital environment.

2.3 Background of Blockchain in the Construction Industry

In the context of the AECO industry, several researchers have reviewed the current blockchain applications and their potential application scenarios. For example, Hunhevicz and Hall (2020) suggested a decision framework for designing various blockchain applications in the industry. Relative to this, a taxonomic analysis has been conducted, and a technical framework has been developed by Yang *et al*. (2020). Specifically, the functionality enabled by several essential components of the blockchain is believed to offer irreplaceable value to the AECO industry.

Firstly, transfers are realised through a peer-to-peer network without a central server, where encrypted and authenticated data are chronologically stored in a decentralised ledger, with each node having a complete historical ledger (Dakhli *et al*., 2019). Direct payments between stakeholders can replace the transfer of funds through intermediaries such as banks, and smart contracts in a decentralised environment can be automatically enforced when certain conditions are met. This has resulted in blockchain and smart contracts being regarded as promising means for improving late payments and payment risks in the industry (Peters *et al*., 2019). Regarding the facilitation of reliable information sharing, blockchain is a decentralised database that can effectively break down "data island", thereby improving the information flow and collaborative environment between stakeholders throughout a project lifecycle (Wu *et al*., 2022a).

In addition, data is stored in blocks, while each updated block includes the transaction data and timestamp of the previous block, hence producing a growing chain linked by a cryptographic hash (Kim *et al*., 2020). The consideration that transaction records may only be added to and not modified prevents malicious modifications and deletions (Pradeep *et al*., 2020). This secure, immutable and traceable property enables the achievement of data security and fraud prevention (Lee *et al*., 2021). For example, it ensures data privacy, reduces hacking opportunities and provides stable preservation of data that is generated from built assets (Parn and Edwards, 2019). In areas such as design, quality management and supply chain process management, blockchain provides more transparent evidence that it can improve issues, including intellectual property and liability ambiguity and has the potential to provide data evidence tracking throughout a project lifecycle (Zhong *et al*., 2023).

2.4 Current State of Research on the Integration of Blockchain and BIM

A review of blockchain in the construction industry conducted by Li *et al*. (2019a) indicates that more focus relies on integrating BIM. Not surprisingly, BIM, which is considered the central junction of various emerging technologies, will pair up with blockchain to help unleash even more tremendous potential.

More specifically, existing research is in agreement that blockchain can improve several aspects of BIM workflow while also providing greater benefits throughout a project lifecycle. The data security features blockchain provides can improve the problems of data leakage, loss or attack on collaborative BIM platforms (Pradeep *et al*., 2020). The blockchain features of fraud prevention, authentication and increased trust in transaction data have been proposed for improving transparency issues and the accountability of information exchange in BIM (Ye *et al*., 2022). For example, during the design phase, blockchain enables the recording of modification history as a means of determining how ownership and responsibility for the model are divided and assigning the access rights of participants (Guo *et al*., 2022). When models are updated, the models of participants can also be automatically updated in real-time, which creates an environment of trust and facilitates effective collaborative design (Wang *et al*., 2022b). In the construction and operation phases, the integrated solutions of blockchain, smart contracts, BIM and other assistive technologies are widely proposed for quality accountability and tracking, improving the traceability of asset maintenance records and automated maintenance operations (Lee *et al*., 2021; Ye *et al*., 2022).

However, research outside the construction domain has further indicated potential limitations and security issues of blockchain technology. These issues and limitations include the inability to ensure full reliability and privacy of data authentication, the limitation of bandwidth, and the lack of connectivity in platform and application designs (Hughes *et al*., 2019). Although relevant research is scarce from built environments, there are still some existing states to the limitations of such research. For instance, the integration of blockchain with BIM has been criticised by Ghaffarianhoseini *et al*. (2017), claiming that blockchain is presently only suitable as a tool for automated document and transaction data processing.

The commercial software BIMCHAIN is considered to increase trust in BIM data exchange through blockchain and was evaluated by Pradeep *et al*. (2020). However, the legal validity of the software functionality has not yet been tested, which is a key issue in the implementation of blockchain and BIM integration, i.e. the lack of legal precedents and regulations (Winfield, 2018). The level of digitisation of the industry and its acceptance of change is also seen as implementation barriers. Due to the slow digitisation progress in the AECO industry, the potential benefits of blockchain require a more interconnected and networked approach for collaborative BIM work (Li *et al.*, 2019a).

Li *et al*. (2019a) also indicated that much of the work currently visible in this field is focused on considering the technical dimension. As identified by Plevris *et al*. (2022) as a major barrier to BIM implementation, technocentrism has resulted in viewing BIM as a tool rather than considering process and people factors. Pradeep *et al*. (2021) further discussed that the human aspect should be more fundamental than the technical element and that process-related changes and macro-environmental support should also be considered. As demonstrated by the arduous road to BIM adoption, the construction industry has been very conservative in adopting new technologies (Sheng *et al*., 2020); indeed, it is not difficult to surmise that integrating blockchain with BIM can be even more daunting. Research on how these various aspects are balanced can help drive the field from conceptual to practical application. Hence, a theoretical lens is introduced in the 3.1 section to review the development and the limitations of the current research from an integrated perspective.

3. Research Method

Figure 1 summarises the framework and the different layers of this study, which will be explained in this section.

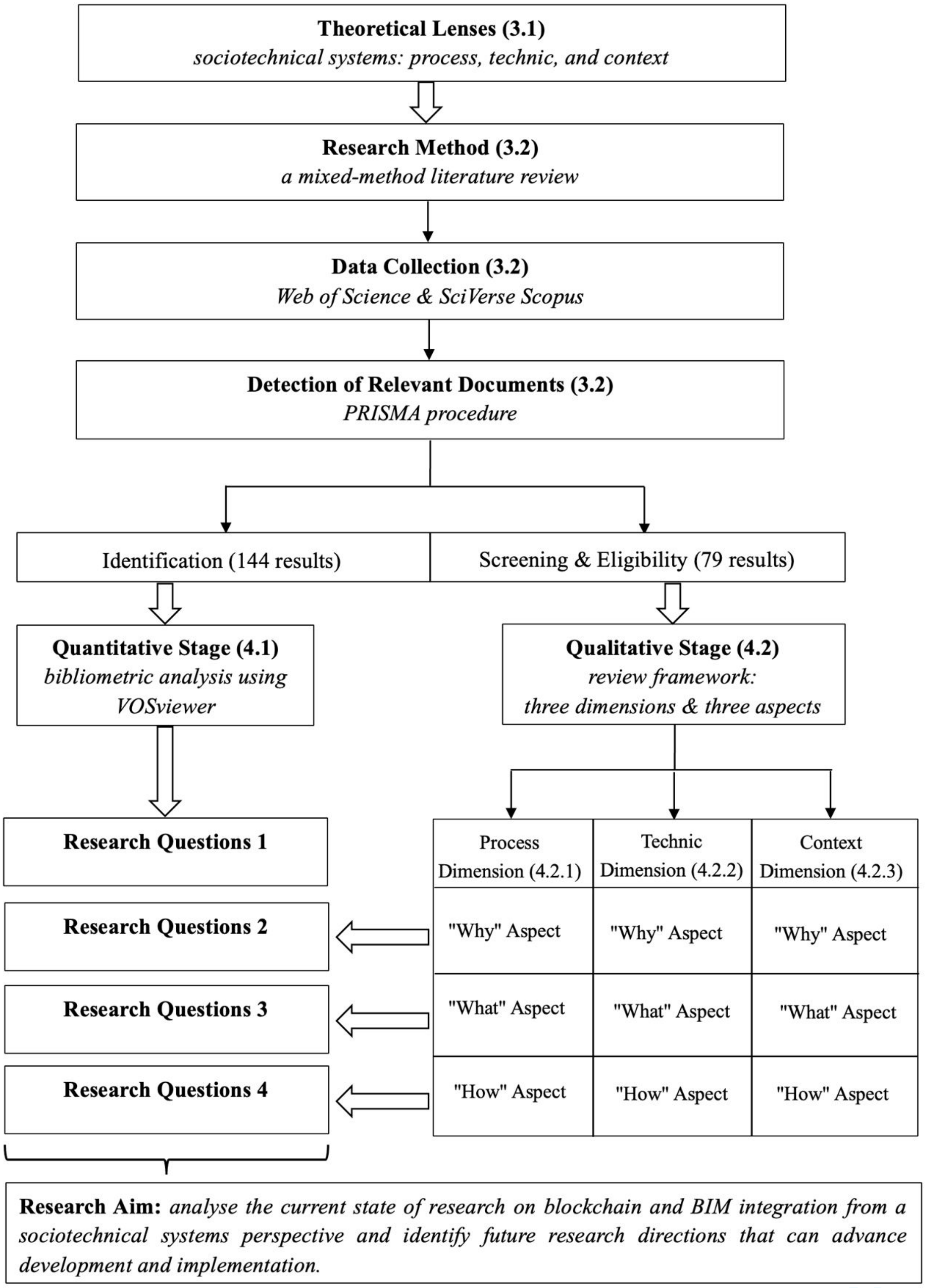

Figure 1 - research design

3.1 Theoretical Lenses of Research

The sociotechnical systems theory was initially developed by Trist and Bamforth (1951), stressing the connection between technology and society in the industry. For the digital system of blockchain and BIM integration, particular attention must be paid to meeting the needs for application in the workflow and the contextual background of the industry. Thus, in this research, three dimensions of consideration from the theory of sociotechnical systems are presented: process, technic, and context.

The process dimension considers the application of technology in various scenarios and at each lifecycle stage, examining the improvement or performance optimisation of the proposed integration on the workflow. The literature will be categorised and mapped to different phases or application scenarios within the project lifecycle. Different applications of the proposed integrations in the study and their development maturity will be investigated. In addition, challenges relating to integration in process applications will be identified so future directions for research in process applications could be suggested that transition to more advanced applications or facilitate industry implementations.

The technical dimension covers the technical environment and infrastructure, examining the inherent technical shortcomings in BIM that blockchain will address, in addition to the different technical options and their difficulties during the integration process. The technical dimension will also investigate how the technical drawbacks of blockchain can be mitigated in the integration paradigm by identifying solutions and the technical foundation that is required on the BIM side to meet blockchain accessions.

The contextual dimension includes the acceptance and adoption of technology by individuals and organisations, as well as pertinent rules and regulations. The ultimate aim of this integration is the improvement of underperformance in the BIM and the AECO industries. Therefore, the contribution blockchain will make to the acceptance and penetration of BIM will be identified first. Industry readiness for the adoption of this integration will also be reviewed, and any change-related challenges, regulations and legislative readiness will be identified as a means of determining the research efforts that are required to facilitate implementation.

Overall, this research emphasises that the three characteristics are not arranged hierarchically but are rather side-by-side and that the ideal scenario is for all of these aspects to grow in a balanced manner.

3.2 Research Design

Once the theoretical lenses used for the study were identified, the research methodology was developed.

This study follows a pragmatic mindset. Its aim is analysing the current state of research and identifying future research directions that can advance development and implementation. Therefore, the practical application value of this study is emphasised. In addition, the study intends to gain in-depth and comprehensive insight, and the theoretical lenses that are used include multiple dimensions where complex relationships must be addressed. A flexible combination of multiple methods will compensate for the shortcomings of a single method, enabling more reliable results to be obtained and allowing the research questions to be effectively addressed.

A mixed-method systematic literature review is considered to be the best option that can meet the aim of this study. This method obtains and analyses both quantitative and qualitative data in a single evaluation. It also compensates for the defects of utilising one method alone, thus ensuring the validity and reliability of the outcomes by complementing them with an in-depth and comprehensive review (Liu *et al*., 2020). This allows the study to identify themes, trends, and gaps more effectively (Sajovic *et al*., 2018).

During the data collection process, relevant literature must be located, filtered, assessed and analysed through a systematic and structured set of criteria to ensure the scientific validity and rigour of the study (Obrecht *et al*., 2020). This study followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) procedure to conduct document identification, screening, and inclusion; the procedure is the recognised standard for reporting evidence in systematic reviews (PRISMA, 2020).

Figure 2 summarises this study's procedural sequence. The data used for analysis were obtained by searching from two databases: the Web of Science (WoS) and SciVerse Scopus (Scopus). These two commonly used databases are thought to capture a wide variety of target search words and provide reliable search results (Charef *et al*., 2018). Based on the research questions, the following word string was used in the advanced search through Scopus: "TITLE-ABS-KEY (blockchain OR "smart contract*") AND TITLE-ABS-KEY ("building information model*" OR "building information management")"; eventually, 139 papers were retrieved for the 2017–2023 period. In the Web of Science Core Collection, the following word string was applied: "TOPIC= (blockchain OR "smart contract*") AND TOPIC= ("building information model*" OR "building information management")"; eventually, 89 papers were retrieved for the 2017–2023 period. No time or language restrictions have been set when searching. Search results were updated to early March 2023.

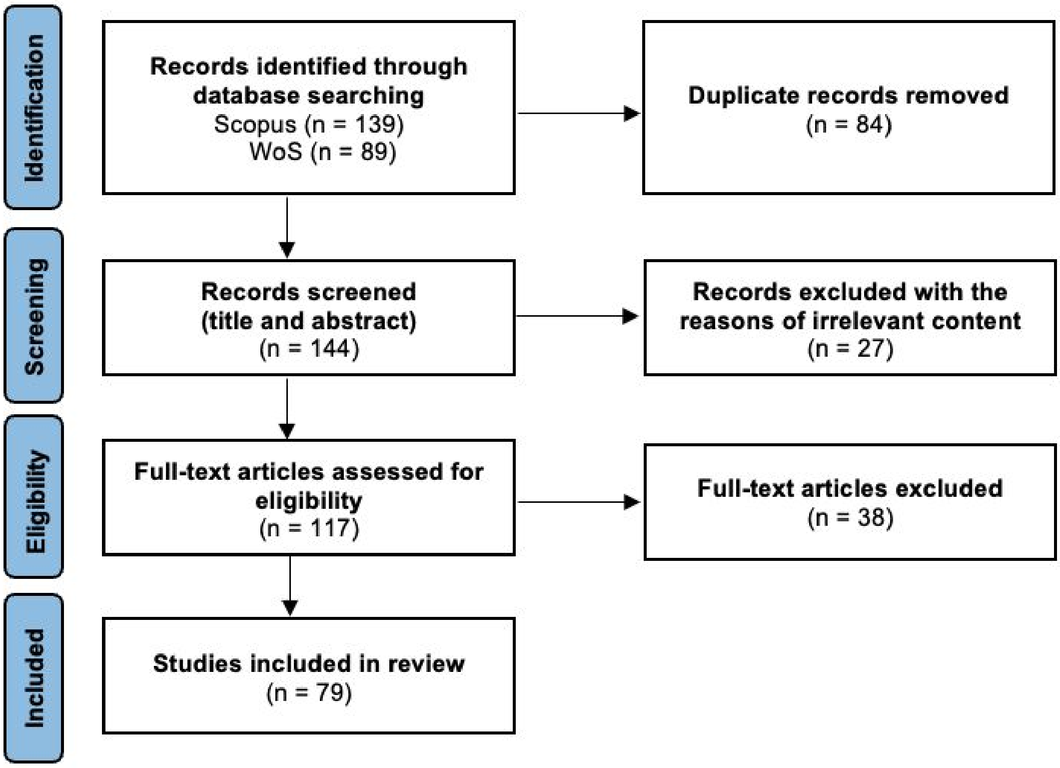

Figure 2 - flow diagram of the systematic review process (adapted from PRISMA, 2020)

Book chapters, conference proceedings, and unpublished research were not prohibited document categories because this would provide insight into the new technologies and identify the differences or gaps in traditional academic literature and other sources of information (Kasten, 2020). It is also worth discussing that search results from all fields are kept owing to the multidisciplinary nature of the research. Identical results between the two databases (84 articles), eventually yielding 144 results for quantitative review.

The relevancy of the search results was then determined based on each paper's title and abstract; from the "screening" process, 27 of the results were excluded because they were primarily concerned with the engineering or manufacturing field and did not include any BIM-related topic. The remaining 117 articles were then examined for full text during the "eligibility" stage, where 38 articles were excluded because they did not include any BIM-related topic, or blockchain was only seen as a minor variable. Therefore, 79 articles were eventually selected for qualitative review.

During the data analysis process, 144 results were used for quantitative analysis and bibliometric analysis was conducted as a means of addressing RQ1: *what is the current state of research and trends regarding BIM and blockchain integration?* Using scientific mapping algorithms and techniques to visualise the visible aspects of similarities and differences in compiled data, the knowledge structure, research trends, and current research progress on the combination of BIM and blockchain can be determined (Babalola *et al.*, 2021). Specifically, VOSviewer Version 1.6.16 was selected as the scientific mapping tool in this paper.

In the qualitative analysis process, the 79 articles that resulted from the data screening were used for content analysis. In order to answer RQ1-RQ3, the theoretical lens established was further developed as a framework for the qualitative analysis, with three research aspects set up under each of the three dimensions. This will be discussed within each of the three dimensions.

The three aspects are as follows:

The "Why" aspect: the need for integration and the benefits this provides. Analysing this aspect will answer RQ2: *what problem-solving or performance improvements can blockchain provide to BIM in terms of process, technical and contextual dimensions?*

The "What" aspect: integration applications and the level of adoption of current research. Analysing this aspect will answer RQ3: *what solutions or applications have been proposed or implemented for this integration in terms of process, technical and contextual dimensions?*

The "How" aspect: the issues that integration must address to progress or be wider implemented within the industry. Analysing this aspect will answer RQ4: *what are the gaps or challenges of existing research and what should the future directions be in terms of process, technical and contextual dimensions?*

In this way, this study constructed a framework as a common language for qualitative coding, which is visually explained in the table that is presented in the lower right part of Figure 1. A thorough content review of 79 articles was performed based on this pre-established framework, and all authors engaged in group discussions until they reached a consensus. Based on the affinity of each article to the three dimensions (process, technic, context), the research team categorised articles and mapped them to the relevant dimension. During this process, some articles were found to cover more than one dimension and were mapped to all the relevant dimensions. The articles from each of the three dimensions were then analysed and discussed in terms of the three aspects (why, what, how).

4. Results

4.1 Quantitative Phase

Keyword co-occurrence analysis can explore the research hotspots in the field and predict the research trends and frontiers (Zhao, 2017). The following criteria were established in VOSviewer: the co-occurrence threshold was set to at least seven times; the synonyms were merged, and the irrelevant keywords were deselected. Finally, 19 keywords were considered the most meaningful and visualised as nodes, with 113 links and four clusters.

Through network visualisation (Figure 3), keywords with close affinity were grouped into the same cluster. "Blockchain", "BIM", and "architectural design" were centrally located and had a high affinity, categorised as the red cluster, with associated keywords "IoT", "supply chain", and "sustainability". This most active cluster reflects the current research focusing on these application aspects of blockchain and BIM integration and confirms the findings in Section 2 that the development of BIM is in conjunction with IoT in the supply chain and sustainability field, as well as the challenges in the design process.

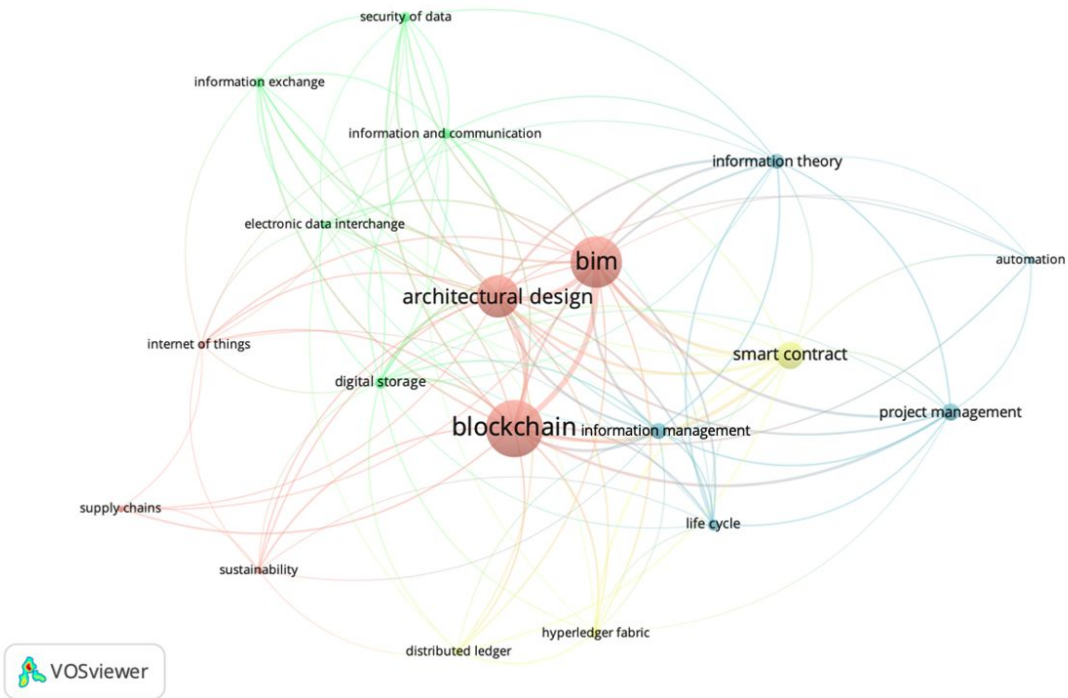

Figure 3 - network visualisation

The green cluster contains the terms associated with information exchange, implying that the research emphasises the role of blockchain in improving the "data and information flow" aspect of BIM. The blue cluster relates to the management of the processes in projects and stresses the role of blockchain in improving the "management flow" aspect of BIM. The yellow cluster relates to blockchain architecture and functionality, focusing on the technical aspects of integrating blockchain and BIM.

Figure 4 presents the distribution of research hotspots in terms of chronology. The research trend has gradually evolved from the management and storage of design and information in various projects to the architecture of blockchain and the application of smart contracts, while the latest research has transitioned toward automation, supply chain, and sustainability aspects. Arguably, research in the field has been improving in terms of dimensionality and depth, translating from initial exploratory studies like blockchain improving information exchange to the architectural aspects of blockchain and expanding to more novel and broader application dimensions.

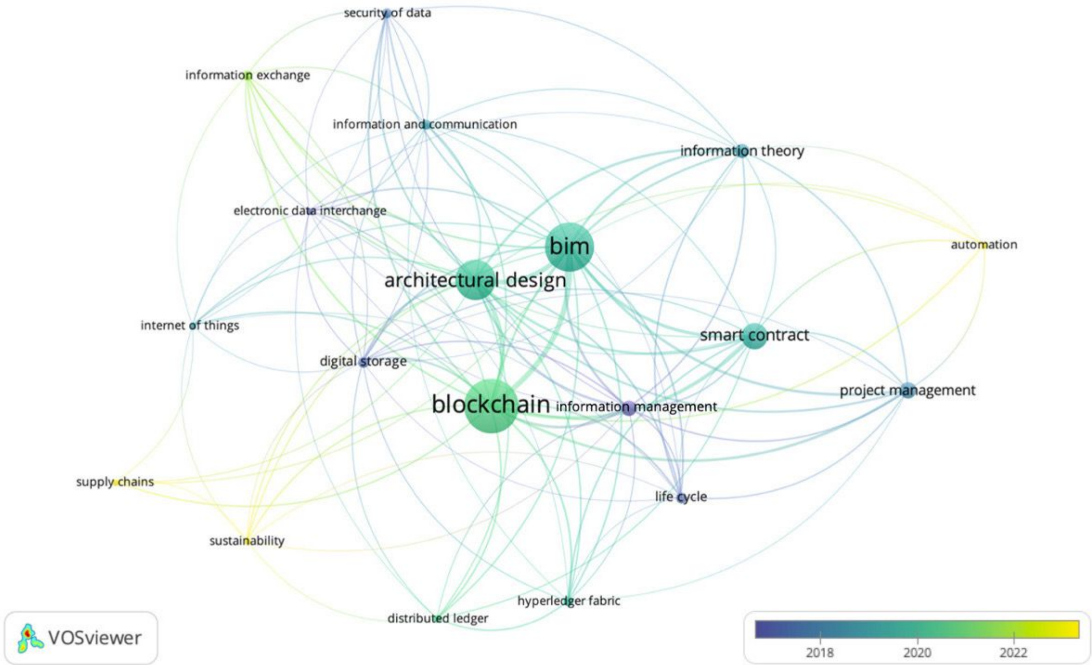

Figure 4 - overlay visualisation

An overall analysis reveals that, despite the little amount of research, the field is in a constant state of development and moving towards mature applications. Combining the time series of reviewed articles, the first two studies in this domain were from 2017—the conference paper of Turk and Klinc (2017) and the article of Mason (2017). 2017 was deemed the year of the blockchain (Amaludin and Taharin, 2018), and both papers meant that the "tipping" of blockchain technology had brought the construction industry into focus. Since 2019, there has been an explosion of growth; it is not difficult to surmise that as blockchain technology has entered a period of proliferation, alongside the continued maturation of BIM platforms and peripheral tools, and standards, in-depth research in this field has been facilitated.

In addition, most of the outermost nodes are associated with functional application areas and are mostly relatively new research. In contrast, keywords related to data exchange and information management primarily focus on the middle layer, emphasising addressing some shortcomings from the security aspects of BIM through integration. It can be surmised that research on the integration concepts and technical architectures has been recognised; impliedly, as research on the need and feasibility of integrating blockchain and BIM matures, the technical barriers are gradually being addressed, and this technology base enables emerging research to turn its focus to broader application scenarios.

4.2 Qualitative Phase

The qualitative review reveals the consideration of the three different dimensions in the literature. Appendix A summarises the central arguments of the reviewed articles and the dimension(s) they cover. Some articles covered multiple dimensions; however, much of the existing research was technical (with a focus on problem-solving) and either simplified or avoided the discussion of organisational, human, and macro contexts.

Figure 5 visualises the current research hotspots based on the number of articles in the three different dimensions in Appendix A. The figure shows the unbalanced state of the three dimensions (some of the reviewed articles may cover multiple dimensions). The process and technical dimensions are discussed more frequently (72 articles and 70 articles), while the contextual dimension is minimal (21 articles). Most of the conference papers proposed technical dimensions and lacked validated models. Some of the articles used real-world examples to validate the technical models, and only a few focused on the attitudes of practitioners.

In this section, the "Why", "What", and "How" aspects of each of the three dimensions are determined and discussed, with the suggested future research directions.

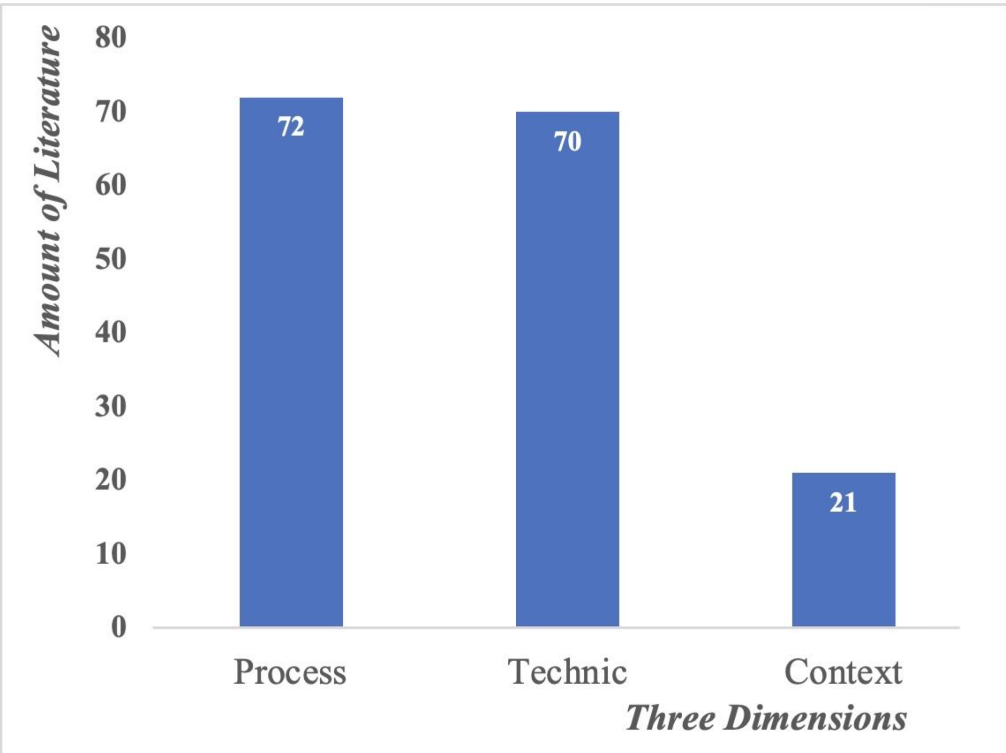

Figure 5 - unbalanced research status

4.2.1 Process Dimension

The process dimension considers the application of technology in different scenarios and each lifecycle stage.

The "Why" Aspect

The literature review section has identified the challenges of BIM and the potential for blockchain applications in the AECO industry; this section focuses on how the potential of blockchain is matched to address the challenges of BIM. Firstly, the integration focuses on the lack of transparency, traceability, and immutability in data transactions and information-sharing processes of BIM. Thus, Turk and Klinc (2017) suggested the role of blockchain in document management and protection. In addition, reliable information sharing can help improve adversarial practices in the industry. Calvetti *et al*. (2020) discussed that the emergence of blockchain would transform emotion-based trust into a system-based one. Pradeep *et al*. (2020) contended that new processes of competition and innovation could ultimately emerge, and improved collaborative processes would terminate hostile attitudes.

For payment issues in the BIM process, this integration would reduce manipulation or human errors and intermediary costs (Siountri *et al*., 2020), as well as the transaction longevity challenge of relatively long-term contracts (Li *et al*., 2019a). Further, the emergence of cryptocurrencies such as #AECoin (a cryptocurrency coin created explicitly for design and construction transactions) might impact the construction industry's future payments (Nawari, 2020).

The "What" Aspect

Existing research has proposed various applications of the integration paradigm in various lifecycle stages or scenarios. Appendix B categorises various literature into different stages or scenarios.

From a general perspective, the paradigm of integrating blockchain and BIM is applied to improve the information model and document management and assign access to information retrieval by the project participants and external observers through smart contracts (e.g., Guo *et al*., 2022; Wang *et al*., 2022a). In this manner, governance processes become streamlined (Dounas *et al*., 2021); moreover, numerous intermediaries can be removed as greater control and transparency are provided to the client (Darabseh and Martins, 2020). Therefore, Yang *et al*. (2020) indicated that this integration is especially suitable for public projects. Li *et al*. (2019a) and Shojaei *et al*. (2019) speculated that this would establish leaner procurement systems and contractual arrangements; specifically, for the recent growth in demand for the IPD method, Elghaish *et al*. (2020) designed an automated payment system to handle shared risks or rewards and incentivise value maximisation.

By always including BIM information within each lifecycle phase and with the blockchain providing security, the vision of various application areas can be facilitated, for example, digital twin (Lee *et al*., 2021), sustainable coordination (Liu *et al*., 2019), waste management (Pellegrini *et al*., 2020), off-site prefabricated supply chain (Li *et al*., 2022; Li *et al*., 2021a; Wang *et al*., 2020b; Wu *et al*., 2022b).

Specifically, several frameworks and models have been proposed to improve the design process. Although these approaches to integration vary, they are all committed to improving the tracking of the design changes and identifying responsibility (e.g., Dounas *et al*., 2021; Tao *et al*., 2022; Zheng *et al*., 2019a), thus ensuring the consistency of models and the notification of drawing updates (Pradeep *et al*., 2021; Wang *et al*., 2022b). The creation of Non-Fungible Tokens (NFTs - unique cryptographic tokens that exist on a blockchain and cannot be replicated) utilising blockchain technology was suggested by Casillo *et al*. (2022) to address the issues of authentication and copyright management of object libraries. Besides, Pradeep *et al*. (2019) investigated a commercialised application, BIMCHAIN, an integrated public blockchain-based solution that creates digital proofs for different transaction scenarios in the BIM workflow, thus attempting to address these challenges in the design process.

For the construction phase, Ye *et al*. (2018) proposed a Cup-of-Water theory that integrated BIM, IoT, and blockchain: real-time data from the IoT sensors were provided to the BIM model, while blockchain was applied to enhance information reliability. Some frameworks could support real-time construction event management or automatically verify the compliance of real progress and the BIM plan in conjunction with the construction site data (e.g., Lee *et al*., 2021; Li *et al*., 2021b; Zheng *et al*., 2019a). Moreover, Yang *et al*. (2020) investigated a real-world project application in which certified work status data could trigger automatic payments using a smart contract.

In the post-construction phase, the project information model (PIM) can be used as a basis for facilities management; in this phase, blockchain is proposed to provide security for sensor data and operations & maintenance (O&M) log files (Pradeep *et al*., 2019), and facilitate the assessment of construction performance (Liu *et al*., 2021), real estate transactions (Ganter and Lützkendorf, 2019), and demolition of buildings (Suliyanti and Sari, 2021). However, operational-level models or applications in this phase have not been seen in the literature.

The "How" Aspect

From the review of the process dimensions, BIM arguably provides the information and records of assets and components, while blockchain provides a secure platform for all parties to meet the storage, access, and execution needs; therefore, the two are considered complementary. Their integration can potentially address the fragmented and inadequate accountability in the construction industry. At the same time, the IoT provides the prerequisites for the correctness of data, which, combined with complementary technologies like big data and AI, can drive digital transformation. A BIM and blockchain-based digital ecosystem can be generated in the future, and conventional business processes are highly likely to be disrupted.

On the other hand, process barriers that have been identified thus far may arise from the following: the workload of smart contract coding (Elghaish *et al.*, 2020), the lack of a relatively collaborative structure of the contract (McNamara and Sepasgozar, 2021), and the need for member collaboration to establish the standards and identify who pays the premiums arising from the adoption (Ganter and Lützkendorf, 2019; Kiu *et al.*, 2020).

Besides tackling the known barriers highlighted above, the review result of research trends suggests some obvious future research challenges. The current scope of research covers a vast range of applications across the lifecycle, particularly in the design and construction phases, with the emergence of commercial applications like BIMCHAIN and the #AECoin cryptocurrency. However, the granularity of research into various niche areas has led to fragmented applications and inadequate holistic solutions; besides, most research is limited to conceptual frameworks or theoretical models (e.g., Dounas *et al.*, 2021; Lee *et al.*, 2021; Zheng *et al.*, 2019a). Despite a limited validation of effectiveness, well-controlled simulation environments have been limited due to a lack of empirical data. Examples may involve accuracy in actual data transactions and the applicability to non-critical transactions, as well as real-world cost-benefit analysis. As a result, even for practical applications, functionality and processes may not be generalisable to various project environments.

To improve the above-mentioned limitations of current research and overcome the challenges with feasible steps, recommendations for future research directions are offered for the process dimension to aid the industry in taking full advantage of this integration. Future research on the process dimension can consider the following:

a) designing fully integrated prototypes (horizontal expansion) or incorporating more functionality (vertical extensions) to the existing frameworks;

b) the adaptability and suitability of the integration paradigm to various project types and procurement methods; and,

c) empirical research to identify the operational processes necessary to accommodate the blockchain and its influence or benefits to the organisation.

4.2.2 Technical Dimension

The technical dimension concerns the technical environment and infrastructure.

<u>The "Why" Aspect</u>

BIM is the basis for digitising the entire lifecycle of an asset and is a prerequisite for linking technologies such as IoT and blockchain. However, as discussed in Section 2, security challenges are currently associated with sharing and storing data in a Common Data Environment (CDE). Nawari and Ravindran (2019c) argued that blockchains and smart contracts allow for notarising and authorising information and access, thus guaranteeing security and providing "evidence of trust" amongst the stakeholders. However, the integration process likewise faces several technical hurdles. The most fundamental concern is that blockchains are not designed to store and share massive amounts of data in real time (Bukunova and Bukunov, 2019); Xue and Lu (2020) stressed the challenge of information redundancy caused by frequent changes in information models. It considers the choice of type of blockchain and faces "the blockchain trilemma", as none of the various types can simultaneously and perfectly satisfy the properties of decentralisation, scalability, and security (Lee *et al*., 2021).

The "What" Aspect

Regarding selecting the blockchain type to integrate with BIM, this paper found that private blockchains are proposed more; the Hyperledger Fabric (HLF) platform is extensively used, such as in a real-world project investigated by Chong and Diamantopoulos (2020). Its permitted architecture benefits data privacy protection and unlimited nodes (Sheng *et al*., 2020; Suliyanti and Sari, 2021); however, since there are only a few trusted nodes, it lacks security (Lee *et al*., 2021). A public blockchain with more security is also considered in some relevant literature; Pradeep *et al*. (2020) indicated that a commercialised application, BIMCHAIN, has been using the public blockchain's Ethereum platform. However, despite supporting the fully decentralised BIM solution, public blockchain has been facing issues of data privacy and expensive storage (Dounas *et al*., 2020).

Furthermore, considering the limited storage capacity of blockchain, Li *et al*. (2021a) proposed that the information model, especially the geometrical representation, should be compressed and stored in the blockchain; in this way, it can also support the migration of geometrical representations to various mobile terminals. Cloud databases are also used by some frameworks (e.g., Lokshina *et al*., 2019; Zheng *et al*., 2019a); however, off-chain databases may face challenges in terms of access to information by unauthorised users (Pradeep *et al*., 2020). Zheng *et al*. (2019b) then designed an access control model to handle roles and permissions securely. Besides, Interplanetary File System (IPFS) technology, as a peer-to-peer distributed file system arrangement, is considered to be a subsidised technology for blockchain for storing and distributing large files; thus, as a more secure off-chain storage solution, it has been utilised widely in various integration frameworks (e.g., Dounas *et al*., 2019; Jiang *et al*., 2022; Hamledari and Fischer, 2021; Pradeep *et al*., 2020; Wang *et al*., 2022b). These frameworks store key data in IPFS, with their changes and hashes being stored on the chain.

The critical element in the integration process is interoperability, which must be supported by an Application Programming Interface (API) to access and use data (Fitriawijaya and Hsin-Hsuan, 2019). Meanwhile, the Industry Foundation Classes (IFC) format (e.g., ifcXML) plays an essential function in exporting data for storage, inspection, or translation. It can be converted to the scripting language used by the blockchain platform (e.g., Java or Go, used by HLF) (Nawari, 2020). However, the adoption of the IFC schema in commercial tools should be improved to facilitate interoperability (Xue and Lu, 2020).

The "How" Aspect

The review of the technical dimension has found the capacity of blockchain technology to complement BIM, thus compensating for certain deficiencies, including lack of security and traceability of data in BIM, and aiding the industry in transitioning toward deeper collaboration in BIM. However, the application of this integration is still in an early stage, and there are still technical barriers that need to be addressed.

For blockchain technology, it is still necessary to investigate better solutions to the blockchain trilemma: maximising security and decentralisation within the constraints of scalability. While existing research has proposed various solutions, including reducing redundancy and off-chain storage, these solutions involve exporting models and exchanging data formats (e.g., Cocco *et al.*, 2022; Xue and Lu, 2020; Zheng *et al.*, 2019a). However, none of the literature has validated the accuracy of the information model when recovering the IFC in a high level of detail or complex projects.

Ultimately, confidence in this integrated system comes from the future technology maturation phase, and complete development still requires much work. With the expansion of digitisation, such challenges may be temporary; the recent Ether merger, for instance, offers new opportunities. The identified technical obstacles may come from: the accurate coding of smart contracts (Elghaish *et al.*, 2020), the blockchain immutability making it challenging to revise or withdraw erroneous data (Pradeep *et al.*, 2019), the inability to guarantee complete security (e.g., 51% attacks or key leaks) (Darabseh and Martins, 2020), and "blockchain trilemma" (Lee *et al.*, 2021).

While waiting for blockchain technology to mature, emphasis should be placed on improving some of the shortcomings identified in the current research trends. Firstly, architectural models designed and run-in sandboxes or web pages cannot fully simulate performance, scalability, and compatibility in a complete network or real projects (e.g., Kasten, 2020; Pradeep *et al.*, 2021). The proprietary costs of blockchain implementation may further dissuade some businesses, yet no apparent concerns had been identified in the review. Moreover, human involvement in automated processes is perhaps more efficient; examples are the judgment of force majeure clauses in contracts or the quick determination of defects in building/infrastructure inspections by experienced staff rather than deploying several expensive sensors (Li *et al*., 2019b; Mason, 2017).

Therefore, short-term research can consider the following directions:

a) optimising the existing solutions and testing the system in more diverse projects;

b) conducting comparative studies to investigate all options thoroughly (e.g., choice of platform and storage methods); and,

c) investigating the most suitable integration options for various project types.

4.2.3 Contextual Dimension

The contextual dimension includes the acceptance and adoption of technology by individuals and organisations, as well as pertinent rules and regulations.

The "Why" Aspect

The legal and contextual aspects are provided in this section; although only a few studies have considered this aspect, it is nonetheless essential in facilitating adoption in the industry. Contractual and legal issues are significant obstacles when implementing BIM; disputes and litigation are often complicated to determine causation and responsible parties. Due to these perceived legal risks, flexible, loose, and vague contracts act as "the rules of engagement" (McNamara and Sepasgozar, 2020). The integration of blockchain has been claimed to provide digital evidence; for instance, BIMCHAIN functions as a tool for resolving legal issues (Darabseh and Martins, 2020). Apart from mitigating the cost of network and trust, the values created by reliable information become clearer in co-innovation and disintermediation (Kifokeris and Koch, 2020).

The "What" Aspect

The conservative attitude of the industry may generate scepticism and fear regarding the use of unknown technologies. Aside from time and cost considerations associated with process change and adaptation (McNamara and Sepasgozar, 2020), the interviews conducted by Chong and Diamantopoulos (2020) suggested that companies were more concerned about being deprived of bargaining power and declining profits. McNamara and Sepasgozar's review (2021), based on the technology acceptance model (TAM), suggested that apart from enhancing the system's usefulness and proving measurable value to the industry, people's trust also seemed to depend on the realisation of the business case.

Meanwhile, Yang *et al*. (2020) mentioned that the construction industry's limited understanding, knowledge, experience, and lack of personnel skills had produced barriers and have faced various learning curve challenges. For instance, generating and managing blockchain keys can be foreign to the construction industry. With the proliferation of digital technologies amidst Construction 4.0, cross-company collaboration, open innovation, learning culture, and professional standards for personnel training are urgently necessary (Hargaden *et al*., 2019).

The disruptive impact on various business models should also be considered. The shift from cognitive to systemic trust signifies a change in business relationships (Aleksandrova *et al*., 2019); automated decision-making processes may replace experience-based managers with smart contract mediators causing flatter organisational structures (Darabseh and Martins, 2020). Financing methods and cash flow management can also be revolutionised; some conventional intermediaries (e.g., main contractors) may observe their profitability decline or die out (Li *et al*., 2019a). Kifokeris and Koch (2020) contended that a successful adoption requires considering relatively long-term strategic objectives and overcoming legacy issues. Prakash and Ambekar (2020) then proposed a route that began with identifying suitable use cases and precedent projects, then designing and preparing an implementation strategy and eventually expanding into an industry-wide level.

What is significant is for governments to ensure that regulations and legislations are in place. Legal issues are currently remaining an element that hinders blockchain and smart contracts (Ye *et al*., 2020). Prakash and Ambekar's interview (2020) with some practitioners suggested that the flexibility of traditional contracts is still vital in some cases. On the other hand, in Sonmez *et al*.'s survey (2022) on the payment management system they designed, construction practitioners pointed out the lack of legal as well as accounting infrastructure to implement it. Furthermore, Pradeep *et al*. (2020) discussed that the legal environment for smart contracts in the construction industry had not been experimented with, that the proofs claimed by BIMCHAIN are not acceptable in court, and that the automated processes necessitate legally recognised entities to be held accountable (McNamara and Sepasgozar, 2021).

The "How" Aspect

The review of the contextual dimension revealed a lack of contextual readiness for integration. Discussion regarding this dimension was also minimal, with most of the results coming from interviews with practitioners. This might be related to the lack of adoption within the industry, considering the immaturity of existing applications and thus unable to determine the adaptations and attitudes of the participants during implementation (e.g., Li and Kassem, 2019; McNamara and Sepasgozar, 2020; Prakash and Ambekar, 2020; Sonmez *et al*., 2022). Furthermore, the sample size of the studies based on a phenomenological approach might be insufficient to reflect the truth (e.g., Prakash and Ambekar, 2020).

The lack of a behavioural science perspective yields an imbalance between theoretical foundations and actual implementations. Concept development may lack the consideration of the problems that must be resolved in practice; more seriously, no advanced system can be deployed without considering the implementation's benefits and value creation. For instance, some proposed automatic payment frameworks mainly depend on providing cash upfront for allowing subsequent automatic payment or requiring contractors to provide detailed pricing information during bidding (e.g., Sonmez *et al*., 2022; Ye *et al*., 2020). These frameworks may cause concern for clients and contractors due to impaired cash flow and information privacy. Indeed, consideration for the user of the technology is a prerequisite in any application.

Additionally, there is a lack of quantifiable investigation into the claimed productivity and efficiency gains; in this case, the required input and preparation of the organisations and how the model must be integrated into the business processes are not observed in the review. Practitioners and policymakers cannot gain insight into the paradigm from existing literature; considering a lack of insight into the "value delivered" and the "conditions required", this uncertainty further hinders the implementation in the industry (McNamara and Sepasgozar, 2020). Therefore, this paper argues that some operational-level applications must be tested in broader industry scenarios, focusing on capturing the dynamic changes throughout the processes, including participant attitudes and actions. It will help analyse the applicability and identify any unforeseen event or unconsidered issue to guide future research and relevant regulatory initiatives.

Therefore, contextual barriers in the short term may emerge from industry acceptance and regulatory uncertainties, while future challenges may arise from a lack of experience and governance. Application scenarios are hindered at this stage until the legal issues are clarified and the pertinent standards and regulations are in place. This is consistent with the findings of the structured interviews conducted by Papadonikolaki *et al*. (2022) on the blockchain innovation ecosystem in the construction industry, which found that policymakers need to encourage open innovation and the adoption of this technology through rules, regulations, and demonstration projects. Future research on this dimension can consider the following:

a) developing and applying a TAM for the integration paradigm and mapping out process roadmaps for various cases;

b) investigating feedback from various stakeholders and experts' perceptions of existing frameworks; and,

c) testing and analysing the operational-level models or applications in extensive industry scenarios.

5. Discussion

The findings from the bibliometric analysis in the quantitative section answered RQ1: *what is the current state of research and trends regarding BIM and blockchain* *integration?* Through keyword co-occurrence analysis, this paper reveals that the current state of research is primarily focused on the application areas of blockchain and BIM integration, with great attention to architectural design, IoT, supply chain, and sustainability. In terms of dynamic trends, since 2017, when blockchain has attracted substantial attention in a number of industries, research in the field has placed great emphasis on the concept of integrating this technology with BIM. Early investigations tended to focus more on aspects related to data exchange and information management, with an emphasis on the application to BIM security; as such, early research concentrated on the most obvious features of blockchain, notably security and fraud prevention features. After 2019, as blockchain technology flourishes and the BIM side continues to mature, the field gradually shifts to more in-depth research. This includes research on blockchain architecture and the usage of smart contracts, which consequently triggers research into broader areas such as automation, supply chain, and sustainability. This indicates that the technical basis is being progressively refined, allowing for exploring a wider range of application scenarios. Coupled with the cost reductions and network performance improvements brought on by the Ethereum (ETH) merging in 2023, as well as the broader adoption prospects implied by scalability upgrades (Ethereum.org, 2023), the research trend is expected to experience significant growth.

As a result, the field is transitioning from early concepts to mature applications. In other words, early research has pointed out that blockchain can solve problems, and early ideas are currently being tested and developed to implement conceptual frameworks and technical architectures for a variety of application scenarios. As blockchain technologies proliferate and are updated, it is expected that the research on architecture will advance, which will, in turn, propel the maturation of existing models and explore a wider range of application scenarios. The field will therefore evolve towards maturity, diversification, and industrialisation.

The content analysis in the qualitative section indicated that the process and technical dimensions were discussed more frequently in the three dimensions; only a few articles were concerned with the contextual dimension and investigated the attitudes of practitioners. The study answered RQ2-RQ4 by further discussing the "Why", "What", and "How" aspects within the three dimensions.

The discussion of the "Why" aspects in the three dimensions addressed RQ2: *what problem-solving or performance improvements can blockchain provide to BIM in terms of process, technical and contextual dimensions?* Blockchain can address the process challenges of BIM by improving transparency, traceability, and immutability of data transactions and information sharing, lowering intermediary costs, facilitating more effective project collaboration and management, and even driving future changes in payment methods in the industry. In the technical dimension, while blockchain plays a significant technical role in enhancing information sharing and storage security, more advanced industrial applications still need to make trade-offs between decentralisation, scalability, and security. In the contextual dimension, blockchain has the potential to provide digital evidence for the resolution of contractual and legal issues, providing choices for fostering an environment of trust and facilitating BIM penetration. However, there are still barriers potentially preventing blockchain adoption in the AECO industry. The benefits need to be realised through enhanced policy support and regulatory development, and increased integration with existing legal frameworks. Therefore, this study points out that these potentials and benefits of integration require a thorough comprehension of technical limitations as well as attention to synergies with contextual factors including laws and regulations and organisational culture.

The discussion of the "What" aspects in the three dimensions addresses RQ3: *what solutions or applications have been proposed or implemented for this integration in terms of process, technical and contextual dimensions?* Existing research has put forward a range of applications that cover the entire lifecycle from the start to the post-construction phase for the purpose of more efficient information management processes and collaboration processes, and to optimise collaboration between participants. Despite the fact that some of the solutions are limited to conceptual frameworks, there are already commercialised applications such as BIMCHAIN for improving the design process and several applications that have been implemented in real-world projects for automated payments. In the technical dimension, private blockchains are more common when integrated with BIM, with Hyperledger Fabric being the most widely utilised platform in the existing research. For the purpose of addressing the challenges of data privacy and storage costs, many integration frameworks have adopted IPFS. Regardless of the type of blockchain used for integration, there is consensus in existing research on the significance of interoperability: the necessity of API support and improved IFC schema adoption in commercial tools. The conservative attitude of the industry was evident through an examination of the contextual dimensions, which meant that the factors of system viability and influence on business models should become key considerations. In addition, the study found that policy support proposals and regulatory development are not yet in place. In conjunction with the quantitative section, which found that the field is in the transition from initial development to mature adoption, it is crucial at this stage to focus on the key role that organisations, individuals and governments play in facilitating integration in order to ensure large-scale adoption of this integration.

The discussion of the "How" aspects in the three dimensions addresses RQ4: *what are the gaps or challenges of existing research and what should the future directions be in terms of process, technical and contextual dimensions?* This study makes the argument that one of the noticeable gaps in the field is the neglect of the contextual dimension, which might result in an imbalance between the theoretical underpinnings and practical implementation. Some of the articles based on interviews with practitioners highlighted that the industry is not sufficiently prepared for integration; these interviews also failed to take a behavioural science perspective into account. Future studies should pay more attention to the development and application of TAM, as well as feedback from various stakeholders. On the other hand, due to the immaturity of existing models, as well as their limited ability to fully simulate real-world situations to demonstrate the full value of the integration, these models may make it less practical to conduct research on contextual dimensions. Hence, process and technical barriers must be addressed. Despite the complementary nature of BIM and blockchain, the current technology integration is still in its development, and the blockchain trilemma still requires the testing of different solutions; technological developments and changes in the industry environment may change the current findings. In addition, process application challenges such as the complexity of smart contract coding, the absence of collaborative contract structures, and additional costs still exist. Therefore, the need for future research to place emphasis on the design of fully integrated prototypes, the adaptability and practicality of integration paradigms across different project types, and empirical studies were highlighted.

Overall, the review finds current research on the recognition of blockchain in addressing issues such as security, traceability, and transparency, and complementing the system by integrating supporting applications. The ultimate vision can be a unified system where the information models are stored and operated on a fully decentralised distributed ledger, with smart contracts and assistive technologies for use in various scenarios throughout the lifecycle. However, significant gaps still exist between these potentials and widespread industry adoption.

Regarding future research on the process dimension, the aim should be to design fully integrated prototypes (horizontal expansion) or incorporate more functionality (vertical extensions) into the existing frameworks. The adaptability and suitability of the integration paradigm to various project types and procurement methods should also be studied. Empirical research to identify the operational processes necessary to accommodate the blockchain and its influence or benefits on the organisation is also essential. In terms of short-term technical dimension research, optimising existing solutions and testing the system in more diverse projects should be explored. Conducting comparative studies to investigate all options thoroughly, such as the choice of platform and storage methods, is also crucial. Investigating the most suitable integration options for various project types can also help in the short term. On the contextual dimension, developing and applying a TAM for the integration paradigm and mapping out process roadmaps for various cases should be prioritised. Investigating feedback from various stakeholders' and experts' perceptions of existing frameworks is crucial. Testing and analysing operational-level models or applications in the extensive industry can also provide valuable insights.

Ultimately, this study highlights the importance of interdisciplinary collaboration, industry acceptance, and empirical research to instil substantial development in blockchain and BIM integration. Balanced development of the process, technic, and context is necessary for this integrated system. More mature applications are still necessary to bridge the gap between the potential of this integration and widespread industry adoption. To facilitate more mature applications, technological developments are still necessary for the blockchain field to provide more reliable technologies for integration, emphasising the necessity to focus on the construction industry and interdisciplinary collaboration. For the construction industry, improved BIM readiness and IFC/other interoperable schemas implementation in applications are necessary. While waiting for the technology to mature, empirical research must be brought into focus to instil substantial development. In the short term, the research should focus more on industry acceptance and the development of regulatory and Standard Operating Procedure (SOP) guidelines. A phased approach like the BIM maturity definition may be feasible in the longer term, with public sector projects remaining a prospect for private sector adoption, while optimising systems and designing supporting governance structures are the new targets.

The novelty of this study lies in providing a framework based on a sociotechnical perspective. The proposed framework contains three dimensions (process, technic, and context), and three research elements were established to fulfil the study's aims: the "Why" aspect (necessities for integration), the "What" aspect (current applications or solutions), and the "How" aspect (considerations for moving the field forward). This framework enriches reviews by Tan *et al*. (2022) and Chung *et al*. (2022) by emphasising a balanced focus on the three dimensions and an integrated assessment of the three research aspects. This starting point draws academic attention to the factors beyond the technical dimension and is expected to be applied in other future reviews. In addition, the study provides policymakers and practitioners working in the AECO industry with insight into the current state and future opportunities to prepare for the transition in this disruptive paradigm.

6. Conclusion

In conclusion, this research paper presents a comprehensive systematic review of the current state and future opportunities for blockchain and BIM integration in the AECO industry. Using a mixed-method systematic review, the study considers various literature types and dimensions or life cycle stages, synthesising dispersed literature to identify current limitations and future research needs. It highlights the importance of interdisciplinary collaboration, industry acceptance, and empirical research to bridge the gap between the potential of blockchain and BIM integration and its widespread adoption in the industry and proposes future research directions on the process, technical, and contextual dimensions. Ultimately, the overall aim of this study was achieved, which is to analyse the current state of research and identify future research directions that can advance development and implementation.

This review provides policymakers and practitioners in the AECO industry with insights into the current state and future opportunities for blockchain and BIM integration, preparing them for the transition in this disruptive paradigm. The proposed sociotechnical framework provides a starting point for future reviews, considering multiple dimensions and aspects. Due to the multidisciplinary nature of the research topic, future reviews could consider additional databases and keyword combinations, as well as evidence from various fields, to provide a more comprehensive review.

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Appendices

Appendix A - Results of the Qualitative Systematic Review

Author(s) & Summary of Key Points	**Dimension**		
****Abbreviation*: ***PR*** *– Process,* ***TE*** *– Technical,* ***CO*** *– Contextual,* ***BC*** *– Blockchain,* ***AT*** *– Assistive Technologies,* ***SC*** *– Smart Contract.* ●*: Primary subject* ○*: Secondary subject*	**PR**	**TE**	**CO**
Aleksandrova *et al.* (2019) - Scrutinised integration of digital technology and recommended a "BC + BIM + AT" ecosystem for complete lifecycle management.	●	○	○
Amaludin and Taharin (2018) - Delineated the possibilities of blockchain in the construction industry and recommended the integration of blockchain and BIM to facilitate enhanced real-time management of projects.	●	○	
Bachtobji *et al.* (2022) - Proposed a "BIM + BC + IoT + edge computing" architecture for building management systems.		●	
Brandín and Abrishami (2021) - Discussed "BC + SC + BIM + AT" into an information traceability platform to support data lifecycle management of assets in offsite manufacturing.	●	○	
Bukunova and Bukunov (2019) - Demonstrated the necessities, approaches, and challenges of integrating blockchain with BIM.	●	●	
Calvetti *et al.* (2020) - Investigated lawful and personnel readiness to adapt the integration of blockchain and BIM.	○		●
Casillo *et al.* (2022) - Suggested the usage of NFTs to manage the ownership of digital assets, address BIM families' authentication and copyright management.		●	
Celik *et al.* (2023) - Designed a BC-based BIM data provenance model for the purpose of managing BIM data during construction and tested the solution in real project scenarios.	●	●	
Chong and Diamantopoulos (2020) - Investigated an actual case and designed a "BC + BIM + IoT" system for automatic payment in the building stage.	●	○	
Cocco *et al.* (2022) - Proposed a Self-Sovereign Identity-based system using "public BC + BIM + AT" to manage the flow of building-related information.	○	●	
Copeland and Bilec (2020) - Designed a "BC + BIM + AT" framework to implement circular economy.	●	○	
Darabseh and Martins (2020) - Reviewed the possibilities of blockchain applications in the construction industry (including, but not restricted to BIM), identified risks and prospects for integration with BIM.	●	●	
Das *et al.* (2021) - Reviewed and acknowledged the security levels of BIM and suggested utilising blockchain to enhance security.	○	●	
Dounas *et al.* (2019) - Designed a platform based on ETH and IPFS to integrate BIM and implement smart contracts to improve collaboration and competition in distributed design.	●	●	
Dounas *et al.* (2020) - Designed a decentralised BIM framework based on ETH and IPFS to enhance the design process.	○	●	
Dounas *et al.* (2021) - Designed a decentralised design framework of "ETH + SC + BIM" to enhance the design process.	●	●	

Elghaish *et al.* (2020) - Designed and tested a "BC + SC + BIM" system for automated financials throughout the lifecycle of IPD projects.	●	●	
Fitriawijaya and Hsin-Hsuan (2019) - Designed a framework utilising blockchain and smart contracts to improve management of supply chain in a BIM-enabled environment.	●	●	
Ganter and Lützkendorf (2019) - Suggested blockchain for improvement of information management of BIM throughout the whole lifecycle of projects.	●	○	○
Guo *et al.* (2022) - Proposed a BC and SC-based system for uploading BIM model copyrights.		●	
Hamledari and Fischer (2021) - Designed and tested an automated payment system based on the ETH platform, field data, BIM, and AI.	●	●	○
Hammi *et al.* (2022) - Designed an information system using SC based on HLF and Odoo PLM/ERP framework with integrated BIM software so as to address collaboration issues in BIM workflows.	●	●	
Hargaden *et al.* (2019) - Presented the prospects of blockchain in the construction industry, examined the possibility and resolution of integrating with BIM.	●	●	
Hijazi *et al.* (2022) - Designed a BIM single source of truth prototype based on HLF for supply chain data delivery.	●	●	
Honcharenko *et al.* (2021) - Introduced a BIM platform consisting of IoT, BC, and AT in order to manage the lifecycle of construction objects.	●	○	○
Huang *et al.* (2022) - Envisioned the use of BIM and BC to document urban development in the Metaverse.	●	○	
Jiang *et al.* (2022) - Designed a BC-Enabled BIM system framework based on Fabric consortium chain, storing BIM model data and key data in IPFS.		●	
Kasten (2020) - Reviewed the prospective applications of blockchain (including, but not restricted to BIM), taking note of the challenges and the significance of background for the integration.	●		○
Kifokeris and Koch (2020) - Proposed a blockchain-based digital business model (including BIM and other technologies) for construction logistics consultants through literature review and empirical study.	●		●
Kiu *et al.* (2020) - Reviewed the prospective applications for blockchain in the building industry (including, but not restricted to BIM) and discussed the significance and challenges of the integration of blockchain and BIM.	●		○
Le (2021) - Developed an ETH-based "BC + BIM" application so as to resolve model copyright issues.	○	●	
Lee *et al.* (2021) - Designed and tested a "BC + BIM + IoT" framework for digital twins.	●	●	
Lemeš and Lemeš (2019) - Demonstrated the possible and present limitations of the integration of blockchain and BIM.	●		○
Li *et al.* (2022) - Designed a BC-Enabled IoT-BIM platform for Data-Information-Knowledge drove supply chain management based on the open BIM standard extended from IFC and performed case study experiments.	●	●	
Li *et al.* (2021a) - Designed a "BC + BIM + IoT+ AT" platform for prefabricated construction supply chain management and corroborated it in an actual case.	●	●	

Li *et al.* (2021b) - Designed and tested a "BC + BIM + AI" platform for project management.	●	●	
Li *et al.* (2019a) - Investigated seven application areas of blockchain in the construction industry (including, but not limited to BIM), showcased a conceptual model, and evaluated the applicability of the integration of blockchain and BIM.	●	●	●
Li *et al.* (2019b) - Designed a digital ecosystem of "BC + SC + BIM + IoT + AT" to improve processes and payments throughout the lifecycle of projects.	●	●	
Liu *et al.* (2019) - Designed a "BC + SC + BIM" framework to improve data management in design processes of sustainable buildings.	●	●	
Liu *et al.* (2021) - Investigated the utilisation of blockchain, BIM, and City Information Management (CIM) to enhance sustainability throughout the lifecycle of buildings.	●	○	
Lokshina *et al.* (2019) - Designed a "BC + BIM + IoT" structure to improve the smart building design process.	●	○	
Mason (2017) - Interviewed practitioners and presented the potential and existing limitations in the integration of smart contracts and BIM.	●	●	●
McNamara and Sepasgozar (2020) - Designed a TAM and discussed with practitioners about investigating industry inclination for blockchain, BIM, and smart contracts.	○		●
McNamara and Sepasgozar (2021) - Designed TAM and looked into potential smart contracts applications in the construction industry (including, but not limited to BIM).	○		●
Nawari (2020) - Proposed an "HLF + SC + BIM" framework to improve the design process and implement automated building code compliance checking.	○	●	
Nawari and Ravindran (2019a) - Summarised the characteristics of blockchain and suggested a framework to improve the design workflow of BIM.	●	●	
Nawari and Ravindran (2019b) - Reviewed the latent applications of blockchain in the construction industry (including, but not restricted to BIM) and demonstrated a "BC + SC + BIM" framework for disaster recovery process.	●	●	
Nawari and Ravindran (2019c) - Summarised the characteristics of blockchain and offered the possibilities of the integration of blockchain and BIM for improvement of process.	●	●	
Ng (2021) - Designed a framework using blockchain to connect BIM and Generative Adversarial Neural Networks (GANs) to enhance design crowdsourcing processes.	●	●	
Ni *et al.* (2021) - Proposed an integrated digital management platform of "BIM + BC + SC" and a management mechanism to improve the efficiency of the project.	●	○	
Parn and Edwards (2019) - Examined cybersecurity in BIM and CDE and suggested the possibilities of the integration of blockchain and BIM.		●	○
Pattini *et al.* (2020) - Suggested the utilisation of blockchain and smart contracts to improve BIM processes throughout the lifecycle of projects.	●	○	
Pellegrini *et al.* (2020) - Investigated and proposed the integration of blockchain and BIM to improve waste management dependability.	●		○
Pradeep *et al.* (2019) - Examined the challenges in BIM processes and the	●	○	

possibilities and limitations of blockchain applications.			
Pradeep *et al.* (2020) - Presented functional requirements for the integration of blockchain and BIM to enhance exchange of data and examined a case study of BIMCHAIN.	●	○	○
Pradeep *et al.* (2021) - Designed and tested a "BC + BIM" model for design accountability control.	●	●	○
Prakash and Ambekar (2020) - Interviewed practitioners and suggested a roadmap for the adoption of the integration of blockchain, smart contract, and BIM in the industry.	○		●
Raco *et al.* (2021) - Demonstrates the findings of the development of a "BC + BIM" application that implements a CDE and optimises lifecycle management.	○	●	○
Raslan *et al.* (2020) - Investigated the integration of blockchain, BIM, and Asset Information Modelling (AIM) to improve asset management processes.	●	○	
Sheng *et al.* (2020) - Designed and tested an "HLF + SC + BIM" framework to improve the management of quality information.	●	●	
Shojaei *et al.* (2019) - Designed and tested an "HLF + SC + BIM" framework to manage projects and enable semi-automatic payments.	●	●	
Siountri *et al.* (2019) - Designed a "BC + BIM + IoT" framework to improve O&M process of smart building.	●	○	
Siountri *et al.* (2020) - Suggested the integration of blockchain, BIM, and IoT for whole lifecycle management of smart buildings and analysed a case of smart museum.	●	○	
Sonmez *et al.* (2022) - Developed a "BIM + SC" progress payment management system, simulated real-life cases and surveyed practitioner attitudes.	●	●	●
Suliyanti and Sari (2019) - Suggested a framework for utilising blockchain to enhance security of BIM.	○	●	
Suliyanti and Sari (2021) - Designed an "HLF + BIM" framework for the improvement of information exchange throughout the lifecycle of projects.	●	●	
Tao *et al.* (2022) - Designed confidentiality-minded framework for BC-based BIM design collaboration using IPFS model, developed access control model and new design coordination strategy.	○	●	
Turk and Klinc (2017) - Advised blockchain to improve management and showed the technical logic for incorporation with BIM.	○	●	
Wang *et al.* (2022a) - Proposed a BC system for privacy protection of BIM big data in smart buildings.		●	
Wang *et al.* (2022b) - Designed a multi-person collaborative design model, utilising the SDT approach, IPFS storage model, and a period division mechanism addressing synchronisation issues.	○	●	
Wu *et al.* (2022b) - Designed a BC-enabled IoT-BIM platform on the basis of the SDT approach for off-site production management, solving the "single point of failure" problem in IoT networks.	○	●	
Xue and Lu (2020) - Designed and tested a resolution to reduce redundancy of information in the integration of blockchain and BIM.		●	
Yang *et al.* (2020) - Examined two case studies based on two blockchain platforms	●	●	○

and indicated the advantages and disadvantages of the integration of blockchain and BIM.				
Ye and König (2020) - Designed a "BC + SC + BIM" framework for automated payments.		●	●	
Ye *et al.* (2018) - Suggested a Cup-of-Water theory of the integration of blockchain, BIM and IoT.		●	○	
Ye *et al.* (2020) - Designed a "BC + SC + BIM" framework for automated payments.		●	●	
Ye *et al.* (2022) - Designed a "SC + BIM" framework to realise, record, and visualise the automation delivery, acceptance, and payment process.		○	●	
Zheng *et al.* (2019a) - Designed and evaluated a model integrating BIM, cloud computing, big data, and blockchain to improve security of information in the design and construction stage.		●	●	
Zheng *et al.* (2019b) - Designed and tested a context-aware access control model for cloud BIM amalgamated with blockchain.		●	●	
Total Count	**79**	**72**	**70**	**21**

Appendix B - Literature Classified into Different Lifecycle Phases or Application Fields (Process Dimension)

	Lifecycle Phases		
Author(s)	**Pre-construction**	**Construction**	**Post-construction**
	Amaludin and Taharin (2018), Casillo *et al*. (2022), Dounas *et al*. (2019), Dounas *et al*. (2021), Dounas *et al*. (2020), Guo *et al*. (2022), Jiang *et al*. (2022), Le (2021), Liu *et al*. (2019), Lokshina *et al*. (2019), Nawari (2020), Nawari and Ravindran (2019a), Nawari and Ravindran (2019b), Ng (2021), Pradeep *et al*. (2020), Pradeep *et al*. (2021), Tao *et al*. (2022), Wang *et al*. (2022b), Zheng *et al*. (2019a).	Amaludin and Taharin (2018), Brandín and Abrishami (2021), Celik *et al*. (2023), Chong and Diamantopoulos (2020), Hamledari and Fischer (2021), Li *et al*. (2021b), Pradeep *et al*. (2020), Sheng *et al*. (2020), Shojaei *et al*. (2019), Sonmez *et al*. (2022), Wu *et al*. (2022b), Ye and König (2020), Ye *et al*. (2020), Zheng *et al*. (2019a).	Bachtobji *et al*. (2022), Hijazi *et al*. (2022), Raslan *et al*. (2020), Siountri *et al*. (2019), Ye *et al*. (2022). **Full Lifecycle** Aleksandrova *et al*. (2019), Cocco *et al*. (2022), Elghaish *et al*. (2020), Ganter and Lützkendorf (2019), Hammi *et al*. (2022), Honcharenko *et al*. (2021), Li *et al*. (2019b), Liu *et al*. (2021), Ni *et al*. (2021), Pattini *et al*. (2020), Raco *et al*. (2021), Siountri *et al*. (2020), Suliyanti and Sari (2021), Ye *et al*. (2018), Zheng *et al*. (2019b).

	Application Fields		
Author(s)	**Smart Building / Digital Twin**	**Supply Chain Management**	**Sustainability / Circular Economy**
	Lee *et al*. (2021), Lokshina *et al*. (2019), Siountri *et al*. (2019), Wang *et al*. (2022a).	Fitriawijaya and Hsin-Hsuan (2019), Hamledari and Fischer (2021), Hijazi *et al*. (2022), Kifokeris and Koch (2020), Li *et al*. (2021a), Li *et al*. (2022).	Copeland and Bilec (2020), Liu *et al*. (2019), Liu *et al*. (2021), Pellegrini *et al*. (2020), Sheng *et al*. (2020).

Reviewers Comments to Author	Authors Response to Reviewers Comments
Reviewer 1	
1. Originality There are a few issues that must be resolved in the introduction. a) I would suggest that the introduction captures the actual problem that has merited this study to be undertaken. Why is there a need to integrate blockchain with BIM? b) The aim must be clearly stated in the introduction. c) The research questions or specific objectives must be clearly stated in the introduction.	Thank you for your comments. We have made modifications based on your comments. a) A discussion of the need to integrate blockchain with BIM has been added to the introduction section (Page 3 lines 3-21) b) The aim has been stated in the introduction section (Page 4 lines 35-38). c) Four research questions (RQs) have been added (Page 5 lines 1-8).
2. Relationship to Seminal Literature This section must be improved. Please consider the suggestions below. a) Under Section 2, it will be good to give the write-up from line 24 a sub-heading before section 2.1. b) Section 2.1 could be retitled as ‘Challenges to implementing BIM’. c) Page 5 line 13, I do not think the word ‘sins’ used is correct. Please replace it. d) Under Section 2.2, please check lines 9-29. I do not see how this directly relates to blockchain in the construction industry. I would recommend this section to be reworked to improve the content. e) The entire section 2.3 must also be reworked. The contents do not provide readers with information on the current state of research on the integration of blockchain and BIM. f) Section 2.4 must be collapsed and integrated as part of the introduction to make a strong case for the study. g) Page 8 lines 20-45 must be checked. The four points provided are not questions they are	This section has been improved. a) We have added a sub-heading ‘2.1: Background of BIM’ (Page 5 line 17). b) It has been retitled as ‘Challenges to implementing BIM’ (Page 6 line 11). c) It has been replaced with ‘prevailing problems’ (Page 6 lines 12-13). d) We have improved the content by discussing the relationship between blockchain functionality and the industry (Page 7 lines 15-37). e) We have added more information on the current state of research (Page 8 lines 5-38). f) It has been collapsed and integrated into the introduction section (Page 3 line 22 - Page 4 line 34). g) We have revised this and presented four research questions (Page 5 lines 1-8).

statements. Please frame and state the research questions well. I think those four points are specific objectives and must be stated as such.	
h) Please pay attention to the in-text references throughout the manuscript. There are several errors. A typical example is Li, Greenwood et al. (2019). Similar issues like this are found throughput the manuscript.	h) All in-text citations have been checked and revised throughout the paper.
3. Research Methodology This section must be improved. Figure 1 well summarizes the design. However, the write-ups on the various phases of the design were problematic. The various sections were not well titled and there were no interconnections between them. I would suggest to the authors to take their time to improve this section. In addition to other issues please see the comments below.	Section 3 has been restructured and contains two parts: 'Theoretical Lenses of Research' and 'Research Design'. Figure 1 has been amended accordingly.
a) The methodology must be well-titled. Is research design different from research method? I believe the research design is a subset of the research method. Therefore, section 3 must be given the broad section title 'Research Method'.	a) The title of section 3 has been changed to 'Research Method' (Page 9 line 15).
b) Section 3.1 must be checked again. The initial lines, i.e., 58-59 on page 9 and 4-16 on page 10 do not add any meanings to the section. Page 10 lines 18-30 must be the main focus of the section but it must be expanded to introduce readers to the theoretical lenses used for this study.	b) Section 3.1 has been revised to expand the elaboration of the three dimensions in the theoretical lens (Page 11 lines 2-29).
c) Under Section 3.2.1, there is no need to introduce readers to the research onion. Every good researcher is aware of this. Please go ahead and state and justify the philosophical stance of this study. Following this, the research approach chosen must be stated and justified as well.	c) The introduction to research onion has been removed. The philosophical stance and research approach have been further elaborated and justified (Page 11 line 34 - Page 12 line 13; Page 14 lines 20-29).
d) Figure 2 is not referenced under section 3.2.2	d) The location where this reference appears has been optimised (Page 12 line 20).
e) Furthermore, it will be good to indicate which research questions are addressed at each phase of the quantitative and the qualitative.	e) The RQs corresponding to the quantitative and qualitative sections have been indicated (Page 13 line 17 - Page 14 line19).

4. Results This section could still be improved. The results must clearly be presented under the specific objectives. The number of objectives set for this study must be recapped to enable the section to benefit from presenting the results under them. Some other issues worth considering include the following.	We have included a discussion section. In this section, we present the specific results for the four RQs and discuss the results.
a) Section 4.1 is only titled 'Quantitative phase'. Although some findings are presented, it is not clear which research objectives are addressed under this phase.	a) The findings of the quantitative part are used to answer RQ1, and the results for RQ1 have been summarised in the discussion section (Page 25 line 36 - Page 26 line27).
b) The horizontal axis of Figure 5 must be labelled.	b) Figure 5 has been modified and labelled with the horizontal axis (Page 17 line 20).
c) So many issues have been presented under the results and discussion section of the paper. However, what is not clear is whether the specific objectives stated have been achieved. I would rather before the conclusion, a section was created for how the various objectives were achieved and the key findings regarding those objectives. For instance, after this study 1) what is the current state of integrating blockchain and BIM in the construction industry? 2) What are the future opportunities for integrating blockchain and BIM in the construction industry?	c) A discussion section has been added to describe how the four research questions were addressed and to discuss the main findings (Page 25 line 36 - Page 28 line 16). The previous conclusion section has been partially split into the discussion section (Page 28 line 17 - Page 29 line 29).
d) Under section 5 lines 33-41, please try to tease out the answers to these questions well in the results and discussion section.	d) This paragraph has been rearranged into the discussion section (Page 29 lines 18-29).
e) The conclusion is lengthy. It must be clear and concise.	e) The conclusion section in the previous manuscript has been collapsed and partially integrated into the discussion section (Page 28 line 17 - Page 29 line 29).
5. Implications for research, practice and/or society This section seems to be enshrined in the conclusion. I would recommend a separate section to be created to clearly discuss the theoretical and practical implications of the findings of this study.	The content of this section has been arranged in the discussion section.

6. Quality of Communication I would recommend to the authors to thoroughly proof read this paper. There were too many grammatical issues that made reading very difficult. I really had to strain myself to make meaning into most of the issues presented.	We apologise for any inconvenience caused. The grammar of the entire manuscript has been proofread.
Reviewer 2	
The purpose in the abstract can be more precise as in the current version it seems to be similar to the method.	Thank you for your comments. We have made modifications based on your comments. The purpose of the abstract section has been revised (Page 1 lines 5-9).
How it is different from other frameworks of BIM and blockchain integration. Can authors discuss in the introduction what already has been done, the gaps and how the current study addresses/takes a different approach?	Section 2.4 in the previous manuscript has been integrated into the introduction section. We have included a discussion of other reviews and their gaps, highlighting the comprehensive and systematic nature of the framework of the paper (Page 3 line 22 - Page 4 line 34).
Also, can the authors consider including a discussion section towards the end of the paper? The authors could base the discussion based on the existing literature reviews on BIM and Blockchain and the current study. And discuss how novel is the current study.	We have included a discussion section. In this section, we present the specific results for the four research questions and discuss the results (Page 25 line 36 - Page 28 line 16), highlighting the novelty and contribution of this study (Page 29 lines 18-29).