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Investigating the barriers to the adoption of blockchain technology in sustainable construction projects

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ABSTRACT

Blockchain technology (BT) can execute transactions verifiable and permanently, which can help foster the idea of embracing sustainability pillars within industries. Therefore, BT holds considerable promise for the industrial and service sectors; however, its implementation during the procurement stage in a sustainable construction project (SCP) is a bottleneck because of inherent and unknown barriers. Though some attempts on the identification of these barriers have been carried out, the literature lacks a thorough investigation into the relationships and inner dependencies among the related barriers within the realm of SCP. Thus, a novel combination of fuzzy decision-making trial and evaluation laboratory (fuzzy DEMATEL) and social network analysis (FDSNA) is proposed in this paper to fill this gap; FDSNA uncovers causal relationships among leading barriers that impede the adoption of BT within an SCP, and it determines the most critical barriers by modeling their complex interrelationships in related intricate environments. The obtained results suggest "inadequacies in implementing block chain-based policies" and "unawareness and resistance to BT among customers" as the most significant barriers, and "technology immaturity," "market uncertainty and competition," and "technology accessibility" are identified as the most critical. These results present managers and governmental bodies with an inclusive picture regarding the major obstructions to the successful implementation of BT, and it is expected to open avenues to accrue benefits from such leading-edge technologies at a greater pace.

1. Introduction

The high consumption rate of natural resources in the construction industry has significantly impacted the environment (Sheng et al., 2020); for example, 2–3 billion tons of construction waste are generated yearly. Further, in most countries, the construction industry contributes 5–7% of the total gross domestic product and employs at least 7% of its workforce (Shojaei et al., 2021). The construction industry thus has both economic and social dimensions; therefore, it is closely linked to the three main pillars of sustainability: society, economy, and environment (Bartocci et al., 2017; Beatriz et al., 2018).

Thus far, sustainability has been extensively studied from diverse perspectives regarding the construction industry (Piccarozzi et al., 2022). However, there are several challenges with creating sustainable building projects: managing a substantial amount of data; coordinating projects from various disciplines, such as architecture, structural engineering, and mechanical engineering; and ensuring effective communication between several different professionals (Gupta et al., 2021; Yuan et al., 2021). Distributed ledger technology (DLT) is a reasonable approach to overcoming such challenges.

The construction industry contributes over 10% of the national revenue and plays a pivotal role in economic development; therefore, there is a need for this industry to adapt innovative concepts and techniques (Queiroz et al., 2022). However, recent technological innovations and trends pose challenges to the construction industry because they decrease efficiency, effectiveness, and productivity in the procurement process (Raj and Jeyaraj, 2022). Past studies have explored the potential of Industry 4.0 technologies, such as the Internet of Things, Big Data, and Artificial Intelligence, to enhance sustainability in various

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Nomenclature

BT	Blockchain technology
SCP	Sustainable construction project
F-DSNA	Fuzzy DEMATEL social network analysis
DLT	Distributed ledger technology
BPM	Blockchain-based procurement management
CP	Construction procurement
CPM	Construction procurement management
BCP	Blockchain in construction procurement
FDEMATEL	Fuzzy decision-making trial and evaluation laboratory
SNA	Social network analysis
BIM	Building information modeling
IPD	Integrated project delivery system

industries (Abdul et al., 2023; Beatriz et al., 2018; Yavuz et al., 2023). Research has shown that these technologies can improve resource efficiency, reduce waste and emissions, and support the transition to a circular economy (El Baz et al., 2022; Yavuz et al., 2023). However, there is also a need for caution, as some studies have raised concerns about the potential negative impacts of these technologies, such as the creation of e-waste and the unequal distribution of benefits (Bai et al., 2020; Bildirici, 2023). Overall, it is essential to consider both the opportunities and challenges of Industry 4.0 technologies for sustainability to ensure that they are deployed responsibly and equitably (El Baz et al., 2022; L. Yang et al., 2023).

Blockchain technology (BT) has surpassed transmission control protocol/Internet protocol and the Internet as a disruptive innovation. This technology is sometimes referred to as DLT, which uses distributed digital ledgers (Su et al., 2023). Satoshi Nakamoto, an anonymous individual, or group of people, introduced Bitcoin, the first decentralized digital currency in the world, in 2008 (Kochupillai et al., 2021). Since the start of 2022, users have mined almost 16,911,700 blockchains, having completed an average of 154,167 transactions daily; the market capitalization is estimated to be US$ 326.525 billion (Dey and Shekhawat, 2021). However, cryptocurrencies are among the many areas where blockchains can be used; the other areas include the e-government sector, online business (Expedia), e-commerce (Ever ledger), shipping (Maersk), connected transportation (Cyberczar), and auditable supply chains (Johnsonville and Maple Leaf Foods) (Zeyu Wang et al., 2023). Previously, SAP Labs released a blockchain-as-a-service offering for enterprises that would enable business applications on the blockchain (Muzumdar et al., 2022).

As a future database technology, blockchain is open, digital, and peer-to-peer in that every node maintains the integrity and authenticity of the ledger; this makes BT ideal for auditing and accounting operations (Abdelmegid et al., 2020). Further, BT has been applied in many other fields, such as the Internet of Things, transportation, and supply chain management, where it has displayed great potential (Vadgama and Tasca, 2021). In an enterprise, internal control includes all plans, procedures, and methods required to implement restrictions and adjustments within the unit to ensure effective operation, obtain and utilize resources efficiently, and achieve the established management goal (Kouhizadeh et al., 2021). In BT, transactions are recorded and maintained in an unaltered publicly shared ledger (J. Li et al., 2019); each connected node stores a copy of the records/transactions whenever records/transactions are executed on the concerned system (Parn and Edwards, 2019). Therefore, no single stakeholder owns the system, and all activities executed within the system are auditable (Perera et al., 2020). Such a system can guarantee trust in today's business. These algorithms allow for the complete validation and authorization of transactions in a blockchain-based network (Hu et al., 2021). In addition to the proof of work, practical Byzantine fault tolerance, proof of stake, and proof of capacity, there are also algorithms for the proof of elapsed time (Maslin et al., 2019). There is a continuous improvement to BT given the aggressive research; therefore, it is worth studying if it can be applied to enterprise internal controls.

According to the literature, a construction organization is not more sustainable than procurement. Across industries, sustainability performance outcomes are influenced by agents in procurement, such as suppliers and subcontractors (Ershadi et al., 2021). In construction procurement (CP), every decision that involves parties can impact the achievement of the sustainability objectives (Y. Wang et al., 2021). Thus, sustainability can be achieved via effective cooperation and a mutual understanding of sustainability principles (Bartocci et al., 2017; Piccarozzi et al., 2022).

Blockchain-based procurement management (BPM) integrates the fundamentals of corporate social responsibility into procurement decisions for construction projects to achieve this objective (Ershadi et al., 2021). As part of BPM, organizations generate value for their businesses and the entire industry by efficiently supplying their requirements (Loosemore et al., 2021). Thus, businesses can boost operational productivity, decrease costs, comply with sustainability regulations, minimize waste, and align core business activities with sustainability objectives by implementing BPM (Dwivedi and Carvalho, 2022; Umbenhauer and Younger, 2018). Private and public sectors have different values and considerations, although BPM principles are universal and can be applied to all sectors, resulting in differences between their sustainable procurement approaches (R. Yang et al., 2020).

Further, blockchain-based systems can eliminate the need for intermediaries between public and private institutions, which can significantly reduce transaction costs by a significant margin (Tezel et al., 2020). Players on blockchain-based systems must trust each other's computer codes that are full proof (Kim et al., 2020). In CP, blockchain enables traceability, whereas smart contracts facilitate construction businesses smoothly (Zhaojing Wang et al., 2020). In addition, the blockchain-based system promotes sustainability in the procurement process by tracking conformance for each activity (Hultgren and Pajala, 2018). Although BT can significantly reform CP, its implementation remains in its infancy.

Most earlier literature discussed the drivers, enablers, critical success factors, and practices of blockchain implementation (Xu et al., 2021). Although blockchain has numerous benefits, its implementation in procurement operations remains challenging; several barriers restrict its implementation. Therefore, blockchain in construction procurement (BCP) adoption must be analyzed to identify the significant obstructions (Sheng et al., 2020). Most previous studies emphasized the barriers to BCP adoption, but they did not examine how they affect adoption in emerging economies (Shojaei et al., 2021); only a few articles have evaluated BCP barriers. Thus, there exists a sufficient gap in the research about the BCP barriers. The process of identifying and ranking suitable measures for a BCP can be utilized for BCP adoption. The construction industry increasingly focuses on BT in technology-driven sectors to meet its growing demands and needs. Therefore, it is necessary to identify existing barriers to facilitate further adoption. Given this context, the following research questions are addressed in this study:

RQ1: What is the cause-and-effect relationship among the identified barriers?

RQ2: How can the complex interrelationships existing among the identified barriers be uncovered?

In an effort to address the research questions put forward, a novel hybrid methodological approach based on the integration of fuzzy decision-making trial and evaluation laboratory (FDEMATEL) technique and social network analysis (SNA) (FDSNA, hereinafter) is proposed in this paper. An exhaustive list of relevant barriers is compiled through a comprehensive literature review in concert with interviews with experts. An inclusive causal relationship among the identified barriers is obtained, and the most critical barriers to such an implementation are identified using the proposed DSNA. The comprehensive picture attained in this study can assist the government, relevant policy-making bodies, organizations, and CP stakeholders in preparing a suitable strategy to adopt BT within a sustainable construction project (SCP).

The rest of this paper is organized as follows. A review of the relevant literature is presented in Section 2. Section 3 discusses the data collection methods. The analysis and findings are presented in Section 4, and the managerial implications are discussed in Section 5. Finally, conclusions are provided in Section 6, in addition to the future research directions.

2. Contextual background

2.1. Overview of blockchain applications in construction

In the construction industry, BT has been explored as a recent academic area of research. To this end, a systematic review was conducted on the intersection between BT and CP. An electronic search in the Scopus, Web of Science, and Pro-quest databases was conducted using search keywords, which led to the compilation of 99 publications. After reading the titles and abstracts of the papers, 30 articles were found to be directly relevant to blockchain adoption for CP. Most prominent blockchain applications include building information modeling (BIM) security, construction management, contract management, real estate, payment automation, and smart cities (Figueiredo et al., 2022a). However, these applications use BT not to achieve smart and sustainable cities but to coordinate and control urban services. As mentioned in Figueiredo et al.(2022a), six main areas under a built environment have hitherto benefitted from the utilization of BT: BIM security, construction management, contract management, real estate, payment automation, and smart city.

One of the most recent studies worth reviewing was reported by Ciotta et al.(2021), and it focused on BT in the construction industry. Hunhevicz and Hall (2020) studied blockchain's potential use in real estate, smart cities, and smart energy applications and other aspects of the architecture, engineering, and construction sectors. A total of 27 relevant publications and book chapters were identified in (Espinoza Pérez et al.(2022) study from authors in 12 countries. These publications and book chapters are categorized using intensive analysis based on two criteria: integration with other digital technologies and digitization of work processes. One review study listed 13 papers that discuss BT and BIM technologies integrated under topics most widely discussed in the construction domain. Further, there is research on blockchain integration with IoT, radiofrequency identification, and sensors (eight publications) (Qi et al., 2023). In addition, digital technologies such as data management, supply chain management, smart contracts, and cryptocurrencies (economics). According to (Hamledari and Fischer (2021a), the building process includes automatic payments, contract execution (for instance, tendering), procurement of construction materials from the supply chain, data management, intellectual property rights, land registration during design, performance recordkeeping, land registration, and information management throughout the process. The researchers have a wide range of options, and it is possible to add more work processes to this existing list. Yet, Pattini et al. (2020) reported that most papers presented only initiations of such processes, with only a few presenting proofs of concepts dealing with cryptocurrencies. Nakamoto first applied BT to cryptocurrencies in 2008, which is not surprising.

Recently, Durdyev et al. (2022) and Apichart Boonpheng *et al.*(2020) addressed the issue of information management. In the early days of the blockchain, Pattini et al. (2020) suggested using technology for archiving operations and editing BIM models. Companies such as Bluebeam are currently implementing their approach (available at https://www.bluebeam.com/) to enhance traceback processes for identifying intellectual property rights and responsibilities during the development phases. Wang et al.(2019) argued that blockchains are useful for developing notarization-related applications that allow faster document authentications. BT can store documents in a distributed ledger where documents can be created, deleted, and updated; further, their traceability, immutability, and transparency can help ensure their authenticity (Dal Mas et al., 2022). The contribution of Wang's team, in this case, involves outlining the potential benefits associated with a blockchain-based document management approach; none of the potential applications are discussed, and neither are the implications or channels for integrating BIM-based information management.

Werner et al. (2021) discuss a method based on blockchains to manage information quality during the construction phase; providing reliable and secure information is a key part of their aim to identify the party responsible for meeting the standards. Although this team offers a solution based on the hyper-ledger fabric architecture (Stanley Benjamin Smith, 2015), the construction is still in its infancy with the implementation of BT. They have been unable to guarantee that fraudulent data will not be uploaded, which means they must find a way to overcome two fundamental assumptions: users will accept blockchains for managing information quality, and that data on the chain cannot be altered or manipulated. Shojaei et al.(2020) demonstrated that BT, BIM, the Internet of Things, and smart contracts could be integrated to provide improvements. Further, researchers are exploring methods to integrate BT with the IoT and smart contracts in other fields; for example, Hamledari and Fischer (2021b) investigate how smart contracts can improve shipment management efficiency. Moreover, researchers are investigating how blockchain can be integrated into IoT access control and authentication ((Kumar et al., 2021) (Elghaish et al., 2021). Harichandran et al. (2021) developed a framework to implement economic management in an integrated project delivery system (IPD). This framework allows IPD contracts to be integrated into core components of project teams for automating all financial transactions (or automatic payments) associated with IPD projects (i.e., reimbursements, profit, and cost savings). Another study was conducted to investigate the interoperability of the proposed framework using 5D BIM. Nawari and Ravindran (2019b) argued that BT could be incorporated into BIM-based construction projects to automate the bidding and payment processes.

Construction supply chain applications based on BT are still in their infancy (Vadgama and Tasca, 2021); live solutions can still offer little business value compared with other supply chains. According to Kouhizadeh et al. (2021), BT can be used to improve supply chain traceability and information sharing in precast-construction supply chains. These fundamental steps in the supply chain for precast construction elements can be replaced with smart contracts (referred to as the chain code in the hyper ledger fabric). Unfortunately, this solution is not integrated with economic flows or implementation.

BT and additive manufacturing are now used in a completely new manner. Das et al. (2021) described additive manufacturing in the cloud and used game theory models to establish the price of 3D-printed components. These systems generate estimates based on IoT sensors, which collect, update, and record information about the printing process based on on-chain data.

2.2. Past studies conducted on blockchain applications in CPM

Contracts are an essential part of construction, and digitalization's role in construction is increasingly emphasized; further, changing how construction work is contracted out has now become a necessity (Badi et al., 2021). The construction industry can take advantage of digitalized contracts or automated contracts from other industries; such contracts are called smart contracts in the blockchain. In construction contracts, blockchain can help eliminate trust issues, especially in payments (Hamledari and Fischer, 2021c).

Blockchain applications automate laws within construction contracts (Pattini et al., 2020). Sigalov et al. (2021) describe how contract automation works as an event trigger, which allows digitalized contracts to be governed by a distributed ledger and programmed to process payments automatically based on predefined conditions and secure payment credentials (Anticona, 2020). The decentralized consensus in this tamper-proof smart contract system enforces the self-enforcing nature of digital contracts (Ciotta et al., 2021).

In the construction industry, the clients, contractors, subcontractors, and material suppliers are familiar with the construction payment issues. A subcontractor is the most vulnerable among all listed construction stakeholders. The construction industry can eliminate issues associated with non-payments and late payments by adopting smart contracts, which can help reduce payment disputes between contractors and subcontractors. Further, smaller contractors can benefit from smart contracts based on immutable distributed ledgers, which can help improve their payment security and build trust among them (Sheng et al., 2020). As an alternative to smart contracts, appointment contracts can also be used to establish an appointment contract between a client and a project consultant (designer, cost engineer, or project manager); this can profoundly change the nature of legal contracts, and litigation can be replaced by prevention (Anticona, 2020).

Although smart contracts provide many new opportunities for completing legal contracts in construction (S. Wang et al., 2019), public blockchains are incompatible with legal construction contract platforms. This is because data privacy can be better protected from public disclosure with permissioned-blockchains, which allow developers to explicitly permit participants (Stanley Benjamin Smith, 2015). Despite the adoption of smart contracts in the construction industry, there are still many challenges. For example, the construction industry does not currently accept cryptocurrencies for payments. With further developments in BT, it will not be necessary to use cryptocurrencies for blockchain applications in construction contracts in the future.

Traditional standard contract conditions must be simplified and compatible with smart contract coding demands to adopt smart contracts in the construction industry (Leng et al., 2019). This process involves interpreting and simplifying complex contract terms such as time extensions, payment claims, and retained damages; it can also involve simplifying clauses in contracts. Although smart contracts are used, they should ideally be combined with the standard contract form for binding contracts (Amoozad Mahdiraji et al., 2023). Construction disputes can be settled more efficiently in the case of smart contracts, and they are expected to serve as evidence for construction disputes. However, smart contracts are not a complete replacement for traditional construction contracts; they are an effective document enforcement system that reminds construction participants of their legal obligations (Leduc et al., 2021). With smart contracts, construction stakeholders can achieve time and cost efficiency and minimize the need to engage professional lawyers to resolve disputes. Thus, blockchain applications in construction contracts can significantly increase the level of trust between the contracting parties.

Smart contracts that automatically execute multiparty contracts on the blockchain can be used to implement tamper-proof purchasing contracts. In smart contracts, payments are released to the proper entity once they are assessed and executed. Multiple parties can be involved in a smart contract with fully incorporated end-to-end value and terms. Using programming logic, smart contracts can enable the disposition and execution of contractual agreements in the design and implementation of the blockchain (Haque et al., 2021). Further, smart contracts are most commonly used in Ethereum, which is a decentralized platform. Smart contracts brought about the blockchain 2.0 era when automated computerized processes could execute contracts on the blockchain. As part of computerized transaction protocols, Anticona (2020) suggested that contractual terms should be incorporated into the software. Thus, contract clauses can be automatically executed using smart contracts, which can help save time and money without the assistance of trusted intermediaries such as lawyers or banks (Hellwig et al., 2020). In combination with blockchain capabilities, smart contracts facilitate automated and synchronized business processes.

Users specify data structures, functions, and parameters to deploy their contracts on the blockchain. The contracts can be connected between stakeholders using Ethereum addresses and APIs (W. Li et al., 2021). Diakiv (2021) proposed a blockchain-based digital certificate. A smart electronic contract was developed to trace supply chain products by Das et al.(2021). Hunhevicz et al. (2022) proposed a smart contract with escrow-based payments for digital products to address buyer and supplier transaction issues. Balci and Surucu-Balci (2021) described a system of electronic payments for vaccine deliveries when cash is paid as part of an efficient vaccine shipment management system. According to Ciotta et al. (2021), smart contracts are designed to pay for construction contracts. The contract payments are made after construction is completed. Das et al. (2021) proposed tracking construction projects with drones and paying for them based on their completion. As a solution for vendor-managed inventory, (Hamledari and Fischer (2021b) proposed two payment options based on smart contracts. To the best of our knowledge, the literature reviewing barriers to implementing BCP did not address this issue.

Thus, there is an urgent need to investigate barriers hampering such BT implementation to promote the adoption of BT during the procurement stage within the respective sectors. Once such barriers have been studied, the potential implementation of such leading-edge technologies is expected to become feasible. There is a lack of research that focuses on these issues.

2.3. Point of departure

Researchers have conceptually discussed the potential uses of BT within the SCP; however, no systematic effort has been invested in analyzing the significance of the relevant barriers by unravelling their intricate relationships. Hence, the research gaps addressed in this study together with the corresponding objectives are elaborated as below:

(1) The causal relationships among the identified barriers have not yet been touched on in the literature. To tackle this, this study employs the FDEMATEL technique using the perspectives of qualified experts.
(2) The inherent interrelationships in such a complex environment hitherto have not received attention in the body of relevant literature; thus, SNA is used to determine critical barriers for improving decision-making in the concerned area.

3. Research method

The overall research methodology takes place in three phases, explained in detail in Fig. 1 in the following sections.

3.1. Phase 1: identification of barriers

As shown in Fig. 1, the study included a systematic literature review and structured interviews with experienced connoisseurs. An extensive literature review is imperative for determining the barriers to blockchain adoption in sustainable construction projects. According to Mohandes, Karasan et al. (Mohandes et al., 2022), a comprehensive literature review was conducted. A comprehensive combination of relevant keywords was outlined and subsequently used to search prominent databases. Afterward, the relevant papers were refined based on exclusion criteria. Following that, Tariq et al. (2021)utilized the snowballing technique to increase the relevance of the papers. To identify the relative barriers, each relevant, comprehensive paper was meticulously reviewed. A total of twenty-two barriers were identified at this phase, grouped into four major clusters. In a semi-structured interview with professionals and academics in the construction industry, 10 barriers are determined that should be included in the questionnaire. According to Kouhizadeh et al. (2021), the interviews

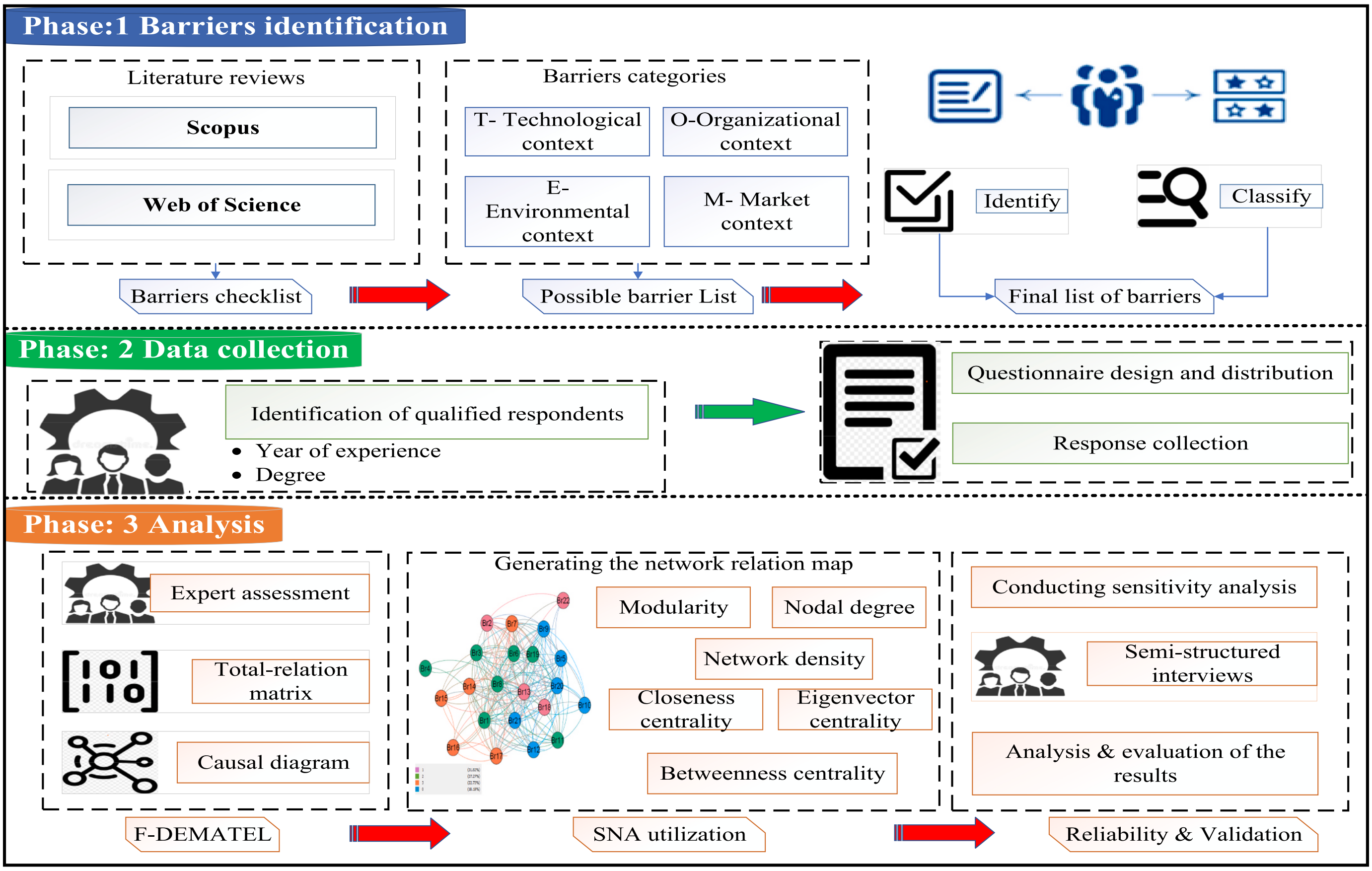

Fig. 1. Research methodology.

were conducted to contextualize the findings from the literature and determine whether the barriers in the literature are relevant to India. Table 1 shows the 22 barriers identified in Phase 1 as applicable to India".

3.2. Phase 2: data collection

The selection of qualified experts to collect data is essential to applying the proposed framework. To this end, experts are shortlisted using the following two criteria (Mohandes et al., 2022): 1) Experience ≥3 years, and 2) undergraduate degree related to building and construction (e.g., civil engineering, project management, construction management, facility management, procurement management, building services engineering). A threshold is established to select the most qualified experts to minimize bias. The experts are graded based on their profiles using the Likert Scale (from one to five, where one denotes very low and 5, very high), and the corresponding scores are assigned. Once the weights for all experts are calculated, they are normalized within the range of 0–1 to determine the expert deemed the most knowledgeable. An expert is deemed qualified and included in the study if his/her weight exceeds 0.75. Experts with weights less than the specified threshold (0.75) are eliminated from the list. Table 2 illustrates the demographic information of the ten experts selected for the discussion.

The experts belong to Tamil Nadu, which is one of the largest states located in South India (Venkatesh et al., 2017). The mild climate of Tamil Nadu makes it a suitable destination for people migrating to urban areas; this implies that there is a considerable need for housing construction. Tamil Nadu was selected as the case study because of the large number of construction projects and facilities reported in this state (Muthukrishnan et al., 2020). The designed questionnaire survey was administered to the experts using email or face-to-face. The designed questionnaire includes two main sections; the first section was concerned with the demographic information of the experts, while in the second section, they were asked to compare the barriers against each other by defining the impact of the one placed in the row as compared to the other one placed in the column using linguistic variables.

3.3. Phase 3: analysis

3.3.1. Fuzzy-DEMATEL

DEMATEL is the most practical instrument for identifying cause-and-effect relationships among the obstacles at hand when examining Byzantine decisions (Tabatabaee et al., 2022). According to graph theory, DEMATEL applies visualization to analyze and describe complex problems (Alam-tabriz et al., 2014); (Dou et al., 2014); (Feng and Ma, 2020). With DEMATEL, we can observe interrelationships among different barriers and the influence of each barrier. DEMATEL is employed in this study to explore the interdependencies among the identified barriers to BT adoption. Therefore, triangular fuzzy numbers are adopted instead of crisp values to counteract their disadvantages in the analysis (W. W. Wu, 2012). Steps for successfully implementing the D-SNA method are briefly discussed below.

Step 1. Develop a questionnaire. The questionnaire is designed using linguistic scales and fuzzy numbers, as indicated in Table 3. Each barrier is assessed in terms of its influence on other barriers.

Step 2. The questionnaires are distributed among experts. The total number of experts, *E,* fill out the questionnaires based on the language scales provided and return them. The experts have to express their opinion about merely direct influences to fill in the total $n \times (n-1)$ numbers of direct influences because the causes themselves have no direct influence on themselves. Cronbach's alpha (α) is calculated

Table 1
List of identified barriers.

Categories	Barriers	Code	Source
T- Technological context	Challenges in cybersecurity	Br1	(Sheng et al., 2020); (W. Li et al., 2021); (Haque et al., 2021); (Bag et al., 2021); (Balci and Surucu-Balci, 2021); and two academic experts
	Technology accessibility	Br2	(Haque et al., 2021); (W. W. Wu, 2012); (Kouhizadeh et al., 2021); (Galati, 2021); (Nawari and Ravindran, 2019a); (Badi et al., 2021); and two academic experts
	Negative perceptions of technology	Br3	(Kouhizadeh et al., 2021); (Kumar et al., 2021); (Badi et al., 2021); two academic experts; and three industry experts
	Blockchain immutability challenge	Br4	(Yaqoob et al., 2021); (Das et al., 2021); (Das et al., 2020); (Košťál et al., 2019); (Martino et al., 2020); two academic experts; and three industry experts
	Technology immaturity	Br5	(Tezel et al., 2020); (Sanka et al., 2021); (W. Li et al., 2021); (Haque et al., 2021) (Hamledari and Fischer, 2021b); one academic expert; and two industry experts
O-Organizational context	Limited financial resources	Br6	(Sanka et al., 2021); (Bag et al., 2021); (Balci and Surucu-Balci, 2021); (Vadgama and Tasca, 2021); two academic experts; and eight industry experts
	Inaction and lack of commitment by the management	Br7	(Bag et al., 2021); (Pinto Lopes et al., 2021); (Hamledari and Fischer, 2021b); two academic experts; and one industry expert
	Inadequacies in implementing blockchain-based policies	Br8	(Balci and Surucu-Balci, 2021); (J. Li et al., 2019); (Hughes et al., 2019); (Sheng et al., 2020); one academic expert; two industry experts
	Insufficient knowledge and expertise	Br9	(Bag et al., 2021); (Hellwig et al., 2020); (J. Li et al., 2019); (Hunhevicz and Hall, 2020); (Bag et al., 2021); two academic experts; and three industry experts
	Challenges in changing organizational culture	Br10	(Ciotta et al., 2021); (Sheng et al., 2020); (W. Li et al., 2021); (Haque et al., 2021); (Hamledari and Fischer, 2021b); two academic experts; and one industry experts
	Reluctance to adopt new systems	Br11	(R. Yang et al., 2020); (J. Li et al., 2019); (Espinoza Pérez et al., 2022); (Das et al., 2020); one academic expert; and two industry experts
	Absence of tools for CI implementation based on BT.	Br12	(Kouhizadeh et al., 2021); (Anticona, 2020); (R. Yang et al., 2020); (Mason, 2017); two academic experts and two industry experts
E– Environmental context (CI view)	Unawareness and resistance to BT among customers	Br13	(Parn and Edwards, 2019); (CHO et al., 2019); (Anticona, 2020); (Shojaei, 2019); (Kouhizadeh et al., 2021); (J. Li et al., 2019); two academic experts; and three industry experts
	Collaborating, communicating, and coordinating are problematic in CI.	Br14	(J. Li et al., 2019); (Hunhevicz and Hall, 2020); (Pattini et al., 2020); (Tezel et al., 2020); (Lee et al., 2021); (Tao et al., 2021); (Nawari and Ravindran, 2019b); and one industry expert
	CI partners face challenges in sharing information.	Br15	(Ciotta et al., 2021); (Sheng et al., 2020); (W. Li et al., 2021); (Hamledari and Fischer, 2021b); (R. Yang et al., 2020); (Park et al., 2020); two academic experts; and two industry experts
	Implementing BT and sustainable practices through CI	Br16	(Ciotta et al., 2021); (Y. Wang et al., 2021); (J. Li et al., 2019); (Hamledari and Fischer, 2021a); (Hunhevicz and Hall, 2020); (Sigalov et al., 2021); two academic experts; and three industry experts
	Differences between cultures of CI partners	Br17	*
M- Market Barriers	Inadequate government policy	Br18	(Ershadi et al., 2021); (Mishra and Maheshwari, 2021); (J. Li et al., 2019); (Hughes et al., 2019); and two industry experts
	Market uncertainty and competition	Br19	(Galati, 2021); (Uriarte et al., 2021); (Xu et al., 2021); (W. Li et al., 2021); (Espinoza Pérez et al., 2022); and three industry experts
	Lack of external stakeholder involvement	Br20	(W. Li et al., 2021); (Balci and Surucu-Balci, 2021); (Espinoza Pérez et al., 2022); (Lee et al., 2021); (Cheng et al., 2021); (Hijazi et al., 2021); and two academic experts
	Involvement of industry in blockchain adoption, ethics, and safety	Br21	(Elghaish et al., 2021); (Mackey et al., 2019); (Triana Casallas et al., 2020); (Tezel et al., 2021); (Ciotta et al., 2021); two academic editors; and four industry experts
	Lack of incentives and rewards	Br22	(Penzes, 2018); (Hughes et al., 2019); (

(continued on next page)

Table 1 (*continued*)

Categories	Barriers	Code	Source
			Kouhizadeh et al., 2021); (Hunhevicz et al., 2022); and four industry experts

Note: * denotes that the respective barrier was identified in the pilot study.

to test the validity of the responses, as reported by (Kouhizadeh et al., 2021); α > 0.7 ensures the reliability of the collected responses. Otherwise, the experts must refill the pertinent survey. The selected experts are provided with a fuzzy DMATEL-based survey.

Step 3. Construct a direct-relation matrix. The following matrix shows how each expert relates directly to each barrier.

$$D^{(e)}=\begin{bmatrix}0 & d_{12}^{(e)} & \cdots & d_{1n}^{(e)}\\ d_{21}^{(e)} & 0 & \cdots & d_{2n}^{(e)}\\ \vdots & \vdots & \vdots & \vdots\\ d_{n1}^{(e)} & d_{n2}^{(e)} & \cdots & 0\end{bmatrix} e=1,2,\cdots E \tag{1}$$

where $d_{ij}^{(e)}=(l_{i,j}^{(e)},m_{i,j}^{(e)},u_{ij}^{(e)})$ And d_{ij} represents the degree to which barrier *i* affects barrier *j*.

Step 4. Establish a normalized direct-relation matrix. A normalized direct-relation fuzzy matrix represents each expert in each group.

$$ND^{(e)}=\begin{bmatrix}nd_{11}^{(e)} & nd_{12}^{(e)} & \cdots & nd_{1n}^{(e)}\\ nd_{21}^{(e)} & nd_{22}^{(e)} & \cdots & nd_{2n}^{(e)}\\ \vdots & \vdots & \vdots & \vdots\\ nd_{n1}^{(e)} & nd_{n1}^{(e)} & \cdots & nd_{nn}^{(e)}\end{bmatrix} \tag{2}$$

where $nd_{ij}^{(e)} = \frac{d_{ij}^{e)}}{max(\cdot\sum_{j=1}^{n}u_{ij}^{(e)})1} \leq i \leq n.$

Step 5. Aggregate the normalized matrices. All experts' inputs are averaged to create a normalized direct-relation fuzzy matrix

$$A_{ND}=\begin{bmatrix}a_{11} & a_{12} & \cdots & a_{1n}\\ a_{21} & a_{22} & \cdots & a_{2n}\\ \vdots & \vdots & \vdots & \vdots\\ a_{n1} & a_{n2} & \cdots & a_{nn}\end{bmatrix} \tag{3}$$

where $a_{ij}=\left(\frac{(\sum_{e=1}^{E}nd_{ij}^{(e)}\times W_E)}{E}\right)$. Notably, W_E represent the weight assigned to the experts involved in the study.

Step 6. Calculate the total (direct–indirect) relationship matrix. Equation (4) calculates the total relationship matrix with all values being fuzzy. Microsoft Excel 2019 was used in this research to conduct all calculations using the functions "minverse" and "mmult."

$$T=\begin{bmatrix}t_{11} & t_{12} & \cdots & t_{1n}\\ t_{21} & t_{22} & \cdots & t_{2n}\\ \vdots & \vdots & \vdots & \vdots\\ t_{n1} & t_{n2} & \cdots & t_{nn}\end{bmatrix}=A_{nd}\times(I-A_{nd})^{-1} \tag{4}$$

where *I* denotes the identity matrix.

Step 7. Defuzzify the total relation matrix. Use (5) and (6) to defuzzify the values of matrix T (Diabat and Govindan, 2011) to generate the total relation matrix with crisp values.

$$D_T=(d_{Tij})_{n\times n} \tag{5}$$

$$d_{Tij}=(l_{ijj}+4m_{ijj}+u_{ijj})/6 \tag{6}$$

Step 8. Eliminate minor effects based on the average values of the matrix DT. A threshold value * is set to isolate any negligible causal relationships (Wu et al., 2022b). After removing the minor influences, the correlation matrix (S) is expressed as

$$S=(s_{ij})_{n\times n} \tag{7}$$

$$(s_{ij})_{n\times n}=\begin{cases} d_{T_{ij}} \text{ if } d_{Tij}>\alpha\\ 0 if\, d_{Tij}\leq\alpha\end{cases} \tag{8}$$

Step 9: Develop causal diagrams. Create a causal diagram using

$$D_i=\sum_{j=1}^{n}s_{ij} \tag{9}$$

$$R_j=\sum_{i=1}^{n}s_{ij} \tag{10}$$

The D-R values indicate the magnitude of the effect of each barrier on the other. A higher "D + R" value indicates a closer relationship for each barrier.

Table 3
Expert semantic evaluation and the triangular fuzzy numbers.

Linguistics assessment	Corresponding score	Triangular fuzzy numbers
No influence	0	(0,0, 0.25)
Very low influence	1	(0, 0.25, 0.5)
Low influence	2	(0.25, 0.5, 0.75)
High influence	3	(0.5, 0.75, 1)
Very high influence	4	(0.75, 1, 1)

Table 2
Demographic information of experts.

Experts	Degree	Field of study	Occupation	Number of years of experience in construction projects	Number of years of experience in procurement
Exp 1	PhD	Construction management	Researcher	From 7 to 10	From 3 to 6
Exp 2	UG	Civil Engineering	Facility Manager	More than 15	From 7 to 10
Exp 3	PhD	Construction management	Researcher	From 7 to 10	From 3 to 6
Exp 4	UG	Civil Engineering	Facility Manager	From 7 to 10	From 3 to 6
Exp 5	PhD	Construction management	Researcher	From 7 to 10	From 3 to 6
Exp 6	PhD	Project management	Consultant	More than 15	From 7 to 10
Exp 7	UG	Project management	Consultant	From 11 to 14	From 7 to 10
Exp 8	PhD	Construction management	Researcher	From 7 to 10	From 3 to 6
Exp 9	UG	Civil Engineering	Facility Manager	More than 15	From 11 to 14
Exp 10	PG	Project management	Researcher	From 3 to 6	From 3 to 6

3.3.2. Social network analysis

The SNA uses network and graph theory to study several types of social networks (Badi et al., 2021), which have different effects on the actors within them. Winship et al. (1996) reported that social networks include nodes and edges with predefined content (nodes and edges). The relationship between actors can be characterized as "directed" or "undirected" based on the edges. The SNA exposes sophisticated relationships between nodes using several metrics. In this study, the SNA is used as follows:

Step 1: Generate the Network Relation Map (NRM). This diagram effectively presents an insight into a complex system and simplifies it into manageable segments. The NRM is constructed by setting a threshold to minimize complexity and isolate key barriers. Consequently, for the total-relation matrix, T, only negligible relationships larger than the threshold value need to be mapped to the graph. Either the average of all entries in the total relation matrix or expert opinions by Gölcük & Baykasoł;lu (2016) can be used to reach this threshold. All relationships between the main barriers were filtered when they were larger than the threshold. All barriers were imported into Gephi to examine and visualize the network along with their important links.

Step 2. Analysis: A number of metrics are used to explore the complex interrelationships among key barriers:

1) **Network density:** The network density is defined as the number of connections divided by the total number of connections. Density is measured in terms of the number of connections between key barriers, ranging from 0 (with no connections) to 1 (with all possible connections). Increasing the value of the motus results in a denser and more cohesive node network. Information flows more easily than when sparse if the network is dense.
2) **Modularity:** Modules are defined as groups, clusters, or communities with modularity as their measure of stability (Jalaei and Jrade, 2014). Community structures are detected using modularity to optimize the network methods. There is a high degree of complexity between internal components and dense connections among key barriers in clusters with high modularity. A dense connectivity persists among key barriers in a network with high modularity.
3) **Nodal weighted degree:** The degree of a barrier's size is determined by the number of connections (edges) it has with others in the network that comprise the 22 identified key barriers. The weighted degree of a barrier can be determined by adding all the weights of the edges. In nodal-weighted degrees, incoming edges are weighed more heavily than the outgoing edges (the total weight of the inward edges). The weighted in-degree score is subtracted from the weighted out-degree score for calculating the net weighted degree. The weighted edges indicate the influence a barrier has on its neighbor; a barrier with a greater weight has the greatest impact compared to a barrier influenced by another barrier.
4) **Betweenness centrality:** The betweenness centrality of a barrier is defined as the number of times it appears on the shortest path among the barriers. This indicator suggests which barriers function as "bridges" among the 22 key barriers in the network. As more information passes through a barrier with high betweenness centrality (assuming that information transfer follows the shortest path), it has greater network control.
5) **Closeness centrality:** The closeness centrality measures the relationship between barriers and the rest of the network. The average path length between all barriers in the entire network can be calculated using this measure. A central barrier is likely to be closer to all other barriers, and barriers with strong closeness centrality can quickly influence and communicate without going through various intermediaries.
6) **Eigenvector centrality:** The eigenvector centrality of a barrier is determined by calculating the number of connections it has to other barriers within the network. In the eigen centrality analysis, barriers that interact with high-scoring barriers are assigned higher scores than barriers that do not interact with high-scoring barriers.

4. Results

4.1. Results of analyses

Pairwise comparisons of the influence and direction of expert opinions among the barriers were conducted to obtain an initial direct relationship matrix shown in Table A1. The average direct-relation matrix was calculated using (1) to combine the experts' ratings shown in Table A2. Table A3 presents the total influence matrix for each factor, and this matrix represents the direct and indirect influence between barriers and is calculated using the normalized direct influence matrix using (2) and (3). Further, (7) and (8) are used to derive the relation and influence vectors. Table 4 lists the relation and influence vectors based on these 22 barriers; they are indicated by (r + c) and (r-c), respectively. Finally, Fig. 2 shows a causal diagram created using (r-c) and (r + c); this diagram organizes barriers based on cause and effect.

In the last stage, the NRM is constructed based on important relationships from the total influence matrix. A threshold of 0.136 based on the average matrix was set to filter important relationships. Therefore, only relationships values greater than the threshold should be considered to construct the NRM (Table A4).

Fig. 3 shows an initial NRM composed of 22 barriers 213 important links produced by Gephi connects. The barriers are indicated as nodes, and arrows indicate their influence interrelationships. The network-level metrics need to be calculated to obtain a clear insight into the network configuration quantitatively. The density of the network was 0.461, according to the Gephi analysis; however, it indicates that the barrier network was semi-dense. The network diameter and average path length between nodes were 3 and 1.7, respectively; they indicate the longest and average of the shortest path for all conceivable pairs of network nodes respectively. These results suggest that barriers in the network map are close to each other.

Modularity statistics are employed for recognizing barrier clusters within the NRM. The clusters are illustrated in Fig. 3; each color represents a community of clusters. Four clusters in the network were hindered by the use of BT by Indian construction companies. The purple cluster stands apart in Fig. 3, boasting the greatest concentration of connections at 31.82%. The green cluster trails close at 27.27%, while the orange and blue clusters lag far behind at 22.73% and 18.18%, respectively. Despite their differences, these four clusters are all intricately connected, as indicated by the low modularity of 0.022, signaling strong communication between each cluster.

The influence of each barrier on the entire NRM can be determined by detecting its significance based on the measurements of 1) betweenness centrality, 2) closeness centrality, 3) eigenvector centrality, and 4) weighted degree. Table 5 lists the closeness centrality, betweenness centrality, and eigenvector centrality scores, Fig. 4(a)–(d) show the barrier network maps for the four measures. Br13, Br8, and Br7 have the highest closeness centrality scores, and thus, they have the shortest path to other barriers. Fig. 4(b) shows that the network is centralized around Br8, Br13, and Br7 because these barriers have the highest betweenness centrality scores, which implies that these barriers control the influences among the barriers. Table 6 and Fig. 4(c) indicate that Br8, Br13, and Br 21 had the highest eigenvector centrality scores because of their links with highly influential nodes; although Br21 did not affect the other barriers, it continues to influence the entire network map because Br21 has important connections and is affected by other barriers. Lastly, other barriers like Br2 have the lowest rank compared to the top 3 three barrier scores (Br8, Br13, and Br7) based on closeness

Table 4
Influence and cause degree for each barrier.

Codes	Br1	Br2	Br3	Br4	Br5	Br6	Br7	Br8	Br9	Br10	Br11	Br12	Br13	Br14	Br15	Br16	Br17	Br18	Br19	Br20	Br21	Br22
D-R	−0.23	1.20	−0.58	0.26	1.26	−1.29	1.19	0.12	−0.24	−0.23	0.09	1.05	0.45	−1.17	0.07	0.15	1.06	−0.90	1.21	0.45	−1.64	−2.26
D + R	7.06	6.21	6.63	4.82	6.05	6.12	6.54	7.83	6.20	5.02	5.42	6.33	7.60	6.06	5.21	5.15	6.20	5.61	5.80	6.99	5.69	2.77

centrality, betweenness centrality, and eigenvector centrality measurements.

Previous studies on SNA calculated the nodal degree as the sum of links to other nodes directly connected to the node (Dehdasht et al., 2022); however, they did not calculate the nodal weighted degree, which indicates the weight of the factor's influence on the whole network. FDSNA can overcome this limitation; DEMATEL calculates the weight of the barrier's influence, which applies to the SNA approach in network analysis. Therefore, FDSNA not only computes the nodal degree but also calculates the nodal weight degree.

Fig. 4 (d) presents the layout of barriers based on weighted nodal degrees (i.e., the sum of nodal weighted out-degree and weighted in-degree). The thickness of the arrows indicates the influence level of the interconnections among the barriers. Barriers with larger links, such as Br8, Br13, and Br1, are more central to the visualization; barriers with smaller connections are positioned outside. Table 6 presents other valuable information, such as the net weight degree and net degree. Despite the positive value of the net degree of Br1, it can be considered an effect factor because of the negative value of its net weight degree. As indicated in Table 6, Br5, Br2, and Br19 have the highest net weight degree, whereas Br5, Br2, and Br17 have the top three nodal degrees. This implies that a higher net nodal degree does not correspond to a higher net influence on other barriers; this indicates the priority of FDSNA compared with that of the SNA approach.

SNA metrics and statistics can be used to recognize the key drivers. Barriers with larger SNA metrics scores (e.g., higher closeness and betweenness centrality, higher eigenvector centrality, and higher weighted degree) receive more consideration. Considering the outcomes of SNA metrics, a list of the top three barriers for 5 SNA indicators is presented in Table 7. Br8 and Br13 are the most important key barriers and have four times the frequency of the top three SNA metrics.

4.2. *Sensitivity analysis*

A sensitivity analysis was conducted to explore the robustness of the proposed NRM. The NRM was assumed to be sensitive to the removal of key barriers. We remove Br8 and Br13 as the main barriers and construct a new network with 20 nodes and 143 edges, as shown in Fig. 5. Three conclusions can be drawn when comparing this new network to the original network:

(1) The new network is less complex, and its density decreases to 0.376 compared to the initial density of 0.461.
(2) The network diameter and average path length increase to 4 and 1.774, respectively, as opposed to the initial network (3 and 1.7, respectively).
(3) Removing Br8 and Br 13 affects the SNA metrics of the entire network (Table 8).

Therefore, this new network is sensitive to several nodes. The outcome of the new network suggested that removing Br8 and Br13, which had the highest interrelationships with other barriers, led to decreased network complexity and increased difficulty in information sharing. The results illustrate that the proposed FDSNA is an effective and robust approach for visualizing the complex interrelations among barriers and identifying key barriers.

4.3. *Reliability and validity*

The reliability of the responses was assessed using several indices. The FDSNA results were tested for reliability using raw numbers provided by experts as per the recommendation of (Mohandes et al., 2022); linguistic variables provided by experts were replaced with raw numbers between 0 and 1. The consistency was determined if the calculated value for all experts' responses exceeded 0.70. Otherwise, the experts were required to recollect their responses. Overall, all selected experts had an

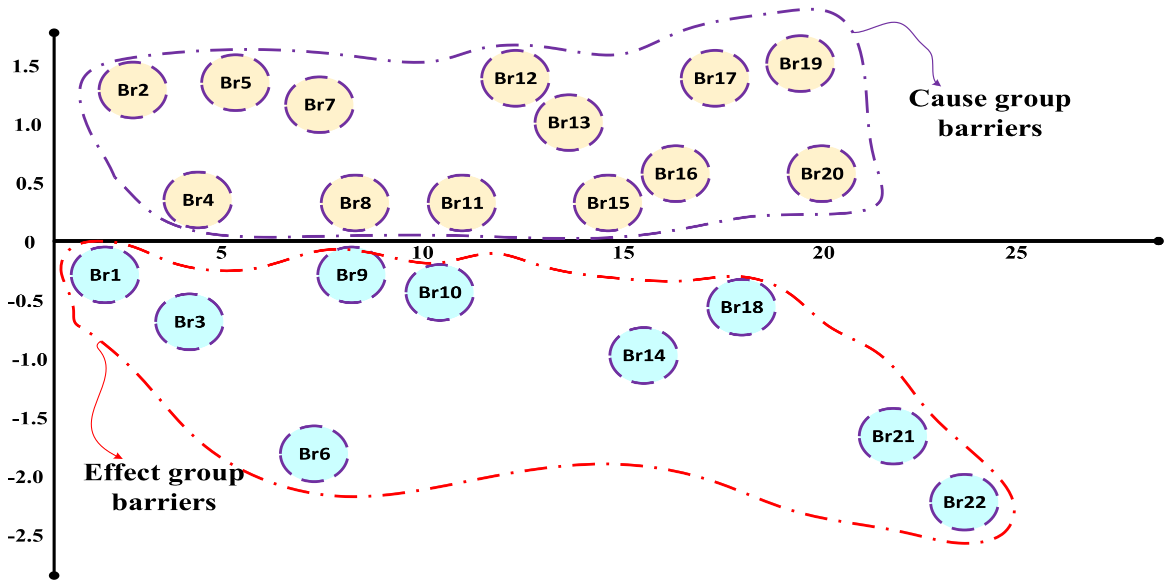

Fig. 2. Causal diagram for barriers.

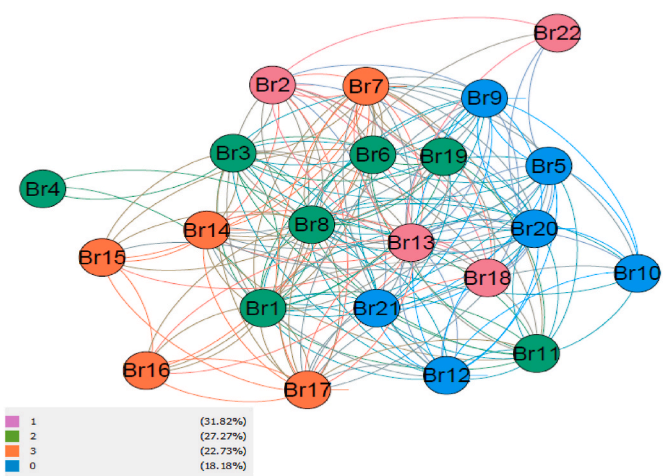

Fig. 3. Clusters of the 22 barriers.

average of 0.7479, which indicates that the results obtained were consistent. A CR greater than 0.1 was calculated for each pairwise comparison made by each expert to demonstrate the consistency of the results from the proposed DSNA. If CR were not greater than 0.1, a new survey would have to be completed by the respective expert. The significant differences between the FDSNA results obtained by all experts were their average CR values, which exceeded the threshold value of 0.093.

Following the predictions of Mohandes and Zhang (2021), this study validated the construction engineering and management predictions using four types of validation. This study achieved good internal validity because competent experts were involved in identifying barriers, as suggested by Zhang and Mohandes (2020). Further, good face validity can also be attributed to the involvement of qualified experts throughout the research process. Four senior expert panelists conducted a pilot test of the survey questionnaires before collecting the required data. Therefore, this study demonstrated strong face validity. The objectives of the study were evaluated based on the framework provided.

For external validation, several semi-structured interviews with qualified experts were conducted as explained in Section 3. Table 9 presents the selected experts' perspectives on validation. The results

Table 5
Ranking of barriers based on the betweenness, closeness, and eigenvector centrality status.

Barriers	Closeness	Rank	Betweenness	Rank	Eigenvector	Rank
Br1	0.77778	5	20.1429	5	0.82973	5
Br2	0.82973	7	0.9833	15	0.36365	18
Br3	0.36365	11	20.2000	4	0.81777	6
Br4	0.81777	17	0.0000	18	0.07979	22
Br5	0.07979	6	1.0667	13	0.24675	20
Br6	0.24675	19	1.4095	11	0.81777	7
Br7	0.84000	3	29.8429	3	0.62586	11
Br8	0.91304	2	66.9357	1	1.00000	1
Br9	0.65625	12	0.7595	16	0.72058	9
Br10	0.50000	18	0.2000	17	0.50875	14
Br11	0.63636	13	5.5333	7	0.62024	12
Br12	0.72414	9	1.0357	14	0.51937	13
Br13	0.95455	1	41.9690	2	0.90532	2
Br14	0.53846	15	2.4000	9	0.86560	4
Br15	0.55263	14	1.3333	12	0.37113	17
Br16	0.53846	16	1.7000	10	0.40452	16
Br17	0.80769	4	5.1357	8	0.40687	15
Br18	0.00000	20	0.0000	18	0.72058	10
Br19	0.70000	10	0.0000	18	0.14919	21
Br20	0.75000	8	6.3524	6	0.78143	8
Br21	0.00000	20	0.0000	18	0.90194	3
Br22	0.00000	20	0.0000	18	0.32192	19

obtained in the main study and those of the validation study showed a reasonable degree of consistency; thus, it is possible to generalize the results to a broader scope.

5. Discussion

5.1. Findings

Though the utilization of blockchain within the realm of building and construction has increased dramatically in recent years, there has been dearth of a study investigating the complex relationships among the related barriers. Thus, this study proposed a novel method called FDSNA to detect significant correlations among barriers and construct an NRM. The results revealed that the SNA approach not only verified the acquired results of DEMATEL but also provided additional information to decision-makers and managers for accurately selecting critical barriers to successfully implementing BCP in Indian construction

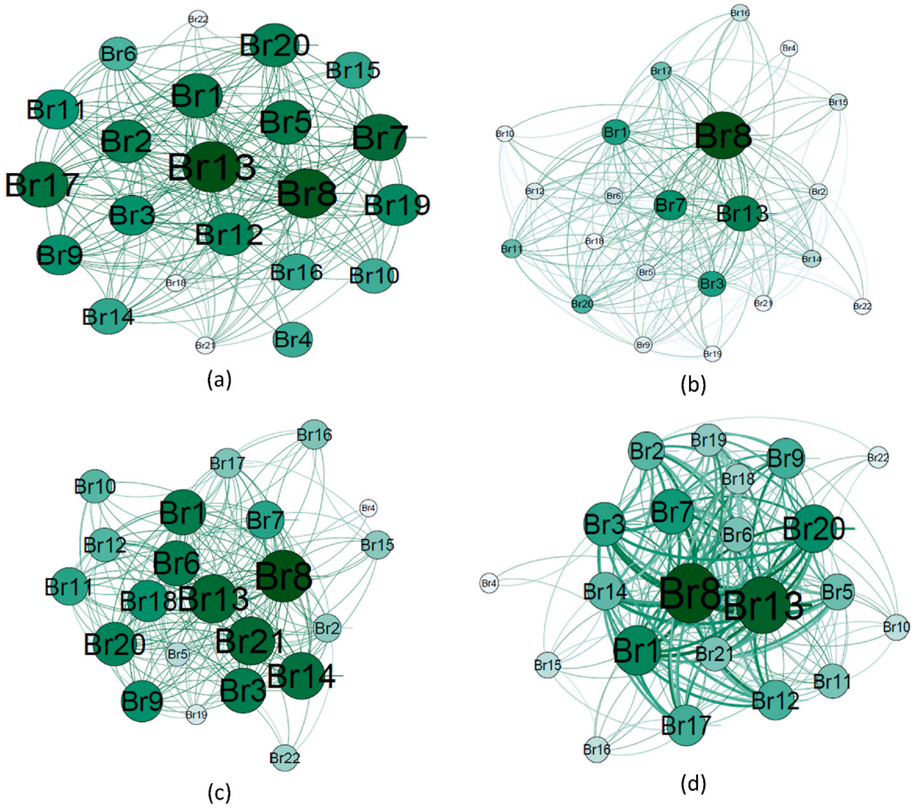

Fig. 4. NRM based on: (a) betweenness centrality, (b) closeness centrality, (c) weighted degree, and (d) eigenvector centrality status.

Table 6
Status of net weight degree.

Label	Weight degree	Rank	Weighted out-degree	Net weight	Rank	Out-degree	Degree	Net Degree	Rank
Br1	5.5425	3	2.6432	−0.2561	12	16	31	1	10
Br2	3.5688	10	2.8148	2.0608	2	15	20	10	2
Br3	4.5061	6	1.7405	−1.0251	18	11	25	−3	16
Br4	0.4266	22	0.2836	0.1406	10	2	3	1	11
Br5	3.192	12	2.7645	2.337	1	15	18	12	1
Br6	2.9733	13	0.1448	−2.6837	21	1	15	−13	21
Br7	4.7875	5	3.3317	1.8759	5	18	28	8	5
Br8	7.1902	1	3.7198	0.2494	9	20	38	2	8
Br9	3.918	8	1.7187	−0.4806	15	11	23	−1	13
Br10	1.465	18	0.2842	−0.8966	17	2	10	−6	18
Br11	2.8984	15	1.3044	−0.2896	14	9	20	−2	14
Br12	3.8504	9	2.675	1.4996	6	14	22	6	6
Br13	6.7377	2	3.9001	1.0625	7	21	36	6	7
Br14	3.4448	11	0.7151	−2.0146	19	5	19	−9	19
Br15	1.4639	19	0.7272	−0.0095	11	5	10	0	12
Br16	1.447	20	0.5875	−0.272	13	4	10	−2	15
Br17	4.0278	7	3.0097	1.9916	4	17	24	10	3
Br18	2.1933	17	0	−2.1933	20	0	12	−12	20
Br19	2.5614	16	2.2855	2.0096	3	12	14	10	4
Br20	5.206	4	2.8554	0.5048	8	15	28	2	9
Br21	2.9014	14	0	−2.9014	22	0	15	−15	22
Br22	0.7093	21	0	−0.7093	16	0	5	−5	17

projects. In fact, the novelty of this study is twofold; firstly, it is the first study of its kind that investigates the relationships and inner-dependencies among the identified barriers, and secondly, it develops a novel hybridization of a fuzzy-based MCDM technique with SNA for the first time in the body of literature.

DEMATEL was used to assess the direct/indirect influential correlation between barriers (Tables A3 and A4) and categorize the barriers as cause or effect factors (Fig. 4) to help managers in decision-making. The causal diagram depicts that Br8, Br13, and Br20 are the most significant barriers because they have the highest number of interactions with the other barriers; further, they are net cause barriers because of the high rate of $D+R$ and positive value of $D-R$, respectively. Further, the results show that Br5, Br19, and Br2 are the most causal barriers because they have the highest positive value of $D-R$ and mostly affect other barriers. This outcome indicates that experts in the Indian construction industry believe that it is necessary to first pay attention to “technology immaturity,” “market uncertainty and competition,” and “technology accessibility” for BCP adoption. The market is nascent, and a clear recipe for success is yet to emerge. Many companies do not see a return on investment because of unstructured experimentation with blockchain

Table 7
Key barriers to employing BT in Indian construction companies.

Barrier ID	Key barriers	SNA indicator
Br8	Inadequacies in implementing blockchain-based policies	Betweenness centrality
Br13	Unawareness and resistance to BT among customers	Betweenness centrality
Br7	Inaction and lack of commitment by the management	Betweenness centrality
Br13	Unawareness and resistance to BT among customers	Closeness centrality
Br8	Inadequacies in implementing blockchain-based policies	Closeness centrality
Br7	Inaction and lack of commitment by the management	Closeness centrality
Br8	Inadequacies in implementing blockchain-based policies	Eigenvector centrality
Br13	Unawareness and resistance to BT among customers	Eigenvector centrality
Br21	Involvement of industry in blockchain adoption, ethics, and safety	Eigenvector centrality
Br8	Inadequacies in implementing blockchain-based policies	Weighted degree
Br13	Unawareness and resistance to BT among customers	Weighted degree
Br1	Challenges in cybersecurity	Weighted degree
Br5	Technology immaturity	Net weighted degree
Br2	Technology accessibility	Net weighted degree
Br19	Market uncertainty and competition	Net weighted degree

solutions with no systematic evaluation of the value at stake or its feasibility.

Given this context, how can companies determine whether blockchain can be used for strategic purposes to justify major investments? Therefore, several functions of the blockchain must be utilized in the CP to improve trust, visibility, resource efficiency, and traceability. These functions remove some barriers to CP adoption. The current literature indicates that these blockchain technologies can be remedied by integrating other enabling technologies such as IoT, BDA, and cloud computing (Götz et al., 2020) and (Košťál et al., 2019). Further, governments have implemented oppressive policies toward Bitcoin, which has negatively affected the development of other blockchain-based solutions (Niranjanamurthy et al., 2019).

The most prominent issues in specific procurement challenges include procurement collaboration, communication, coordination, and the integration of CP with BT. A collaborative ecosystem can be developed for technological advancement to overcome these obstacles (Benzidia et al., 2021). For successful blockchain adoption, finding the right collaborators to develop effective governance structures (Liu et al., 2022). Therefore, clear disclosure policies are required to protect sensitive and proprietary information. Instead of sharing information about poor or critical sustainability practices in the initial stages, less sensitive information about good sustainability practices will be beneficial for enhancing adoption (Shou and Domenech, 2022). Sharing and collaborating information on environmental and social practices, continuous improvement, and developmental information can be considered another approach (Khan et al., 2022). A positive experience from CP information-sharing using blockchain can help bring competitive advantages to more companies through positive practices and collaborations.

An NRM was constructed using SNA based on the recognized influential correlations among the barriers (Table A4) to reveal the complex relationships between barriers. Different SNA metrics were used to analyze the NRM; the results reveal the following remarkable information:

1) The four identified barrier clusters showed strong relationships that facilitated the flow of information in the network. Thus, treating any barrier can rapidly affect the entire NRM. Therefore, selecting a specific barrier and solving it to successfully employ BT within Indian construction companies without considering its relationship with other barriers cannot guarantee the desired results.
2) Barriers such as "inadequacies in implementing blockchain-based policies," "unawareness and resistance to BT among customers," and "inaction and lack of commitment by the management," with the highest betweenness centrality scores, are pivotal to the flow of communication and information in the network. However, these barriers have the highest closeness centrality scores. Thus, understanding the factors with the highest closeness centrality is crucial because they play a key role in speeding up the necessary information to have on-time competitive information (Xu et al., 2021). Thus, the three barriers mentioned above are crucial in rapidly tackling the entire barrier network.
3) Although barriers such as "Inadequacies in implementing blockchain-based policies," "Unawareness and resistance to BT among customers," and "Challenges in Cybersecurity" with the

Table 8
SNA new metrics score after sensitivity analysis.

Barriers	Closeness		Betweenness centrality		Net Weighted degree		Eigenvector centrality	
	New	Original	New	Original	New	Original	New	Original
Br1	0.76000	0.77778	57.9500	20.1429	0.1603	−0.2561	0.88595	0.82973
Br2	0.73077	0.82973	2.5000	0.9833	−1.9252	2.0608	0.25527	0.36365
Br3	0.59375	0.36365	29.4667	20.2000	0.8955	−1.0251	0.86238	0.81777
Br4	0.45238	0.81777	0.0000	0.0000	0.0032	0.1406	0.12457	0.07979
Br5	0.73077	0.07979	1.6667	1.0667	−2.1919	2.337	0.08943	0.24675
Br6	0.46341	0.24675	11.4667	1.4095	2.2145	−2.6837	0.86238	0.81777
Br7	0.82609	0.84000	54.8833	29.8429	−1.7307	1.8759	0.61882	0.62586
Br9	0.59375	0.65625	1.9833	0.7595	0.3873	−0.4806	0.73957	0.72058
Br10	0.38000	0.50000	0.3333	0.2000	0.7442	−0.8966	0.43521	0.50875
Br11	0.57576	0.63636	19.0833	5.5333	0.2642	−0.2896	0.57173	0.62024
Br12	0.70370	0.72414	3.8000	1.0357	−1.3555	1.4996	0.45116	0.51937
Br14	0.33333	0.53846	7.0000	2.4000	1.8425	−2.0146	0.96097	0.86560
Br15	0.46341	0.55263	17.0000	1.3333	−0.144	−0.0095	0.26724	0.37113
Br16	0.47500	0.53846	6.4667	1.7000	0.2723	−0.272	0.29705	0.40452
Br17	0.79167	0.80769	13.8667	5.1357	−1.8649	1.9916	0.26386	0.40687
Br18	0.00000	0.00000	0.0000	0.0000	1.7779	−2.1933	0.73957	0.72058
Br19	0.67857	0.70000	0.0000	0.0000	−1.7361	2.0096	0.08943	0.14919
Br20	0.73077	0.75000	22.5333	6.3524	−0.4782	0.5048	0.82335	0.78143
Br21	0.00000	0.00000	0.0000	0.0000	2.4325	−2.9014	1.00000	0.90194
Br22	0.00000	0.00000	0.0000	0.0000	0.4321	−0.2561	0.17019	0.32192

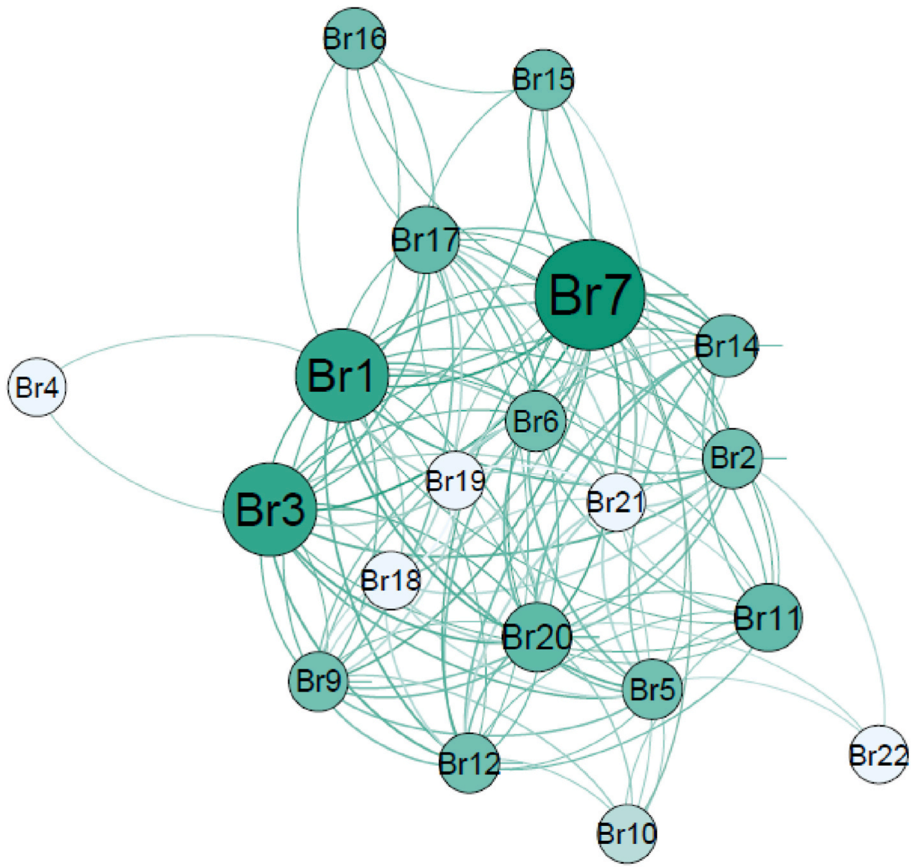

Fig. 5. Results of sensitivity analysis.

Table 9
Results of the validation.

Interviews	Experts' involvement in validation							Aggregation of responses
Barriers	1st Expert	2nd Expert	3rd Expert	4th Expert	5th Expert	6th Expert	7th Expert	
Br1	2	3	5	1	4	5	3	3.333
Br2	5	5	5	5	5	5	5	5.000
Br3	3	2	5	2	4	3	5	3.167
Br4	4	5	3	2	5	3	5	3.667
Br5	5	5	4	5	4	5	5	4.667
Br6	3	2	3	3	4	4	5	3.167
Br7	3	1	4	3	2	4	3	2.833
Br8	2	2	4	2	1	3	5	2.333
Br9	2	1	3	4	3	2	1	2.500
Br10	3	2	3	3	4	4	5	3.167
Br11	3	1	3	3	2	4	3	2.667
Br12	2	2	4	2	1	3	5	2.333
Br13	2	1	3	4	3	2	1	2.500
Br14	3	2	3	3	4	4	5	3.167
Br15	3	1	1	3	2	4	3	2.333
Br16	2	3	4	3	1	3	5	2.667
Br17	2	4	3	4	3	2	1	3.000
Br18	2	3	4	2	1	3	5	2.500
Br19	4	4	5	5	4	4	5	4.333
Br20	3	1	1	3	2	4	3	2.333
Br21	2	3	4	5	1	3	2	3.000
Br22	2	2	3	4	3	2	1	2.667

Barriers show critical values from 1 to 5, with 1 being the lowest and 5 the highest.

highest weighted degree have the most interaction with other barriers, barriers such as "Technology immaturity," "Technology accessibility," and "Market uncertainty and competition" have the highest net weight degree and largest influence on other barriers. These results suggest that these three barriers mostly affect other barriers, as is evident in the causal diagram.

4) The SNA analysis results indicated that despite the "Involvement of industry in blockchain adoption, ethics, and safety" barrier having the lowest score in the four SNA static indicators, it remains a significant barrier with a high eigenvector centrality score; therefore, it can influence the entire NRM. "Involvement of industry in blockchain adoption, ethics, and safety" is a key barrier because it is

inextricably connected with the barriers that have a high influence. The NRM reveals that the "involvement of industry in blockchain adoption, ethics, and safety" can be improved effectively if all other barriers can be tackled and treated wisely.

5) The outcomes summarized in Table 8 indicate that "Inadequacies in implementing block-chain-based policies" and "Unawareness and resistance to BT among customers" are the main obstacles to the successful implementation of BT in Indian construction companies.

The construction industry has been less enthusiastic about blockchain because of its naive nature (Surendra et al., 2020). According to this study, "unawareness of BT among customers" and "inadequacies in implementing blockchain-based policies" pose significant barriers to adopting BT in construction. Further, the study's conclusions coincide with two well-known surveys conducted by Deloitte and PwC on blockchain in 2018. The Reserve Bank of India has ruled out virtual currencies since December 2013 and posted a circular in September 2018 stating the same; cross-border trade requires KYC details, as required by the "Prevention of Money Laundering Act (2002)." In addition, the "Unregulated Deposit Schemes Bill 2018" prohibits unregulated deposits, essentially restricting "initial coin offerings" on Ethereum (C. Z. Li et al., 2021). Thus, it is imperative that the government frame appropriate regulations regarding blockchain adoption.

Blockchain technology is emerging as a promising solution for improving the transparency, traceability, and accountability of supply chains in construction, thereby reducing waste and emissions and supporting the transition to a circular economy (Almeida et al., 2022; Upadhyay et al., 2021). Previous works have also highlighted the importance of addressing the barriers to adopting new technologies to ensure their successful implementation in the construction industry (Shojaei et al., 2021). This research supports this perspective by identifying several critical barriers to adopting blockchain technology in sustainable construction projects, including a lack of education and awareness, the need for tailored solutions, and the challenge of investment (Hrouga et al., 2022).

An international cooperative agreement accepted universally by all nations can also be signed. Most procurements are not geographically isolated but connected by trade globally, and therefore, widespread blockchain use can facilitate international adoption (Friedman and Ormiston, 2022). Further, the use of blockchain will result in increased trust among construction stakeholders, which can mitigate any uncertainty regarding its use (Figueiredo et al., 2022b). In India, a great example can be found in the land acquisition undertaken by the Andhra Pradesh government to build Amravati, the state's new capital. In addition, the government can promote blockchain usage among construction stakeholders by implementing appropriate measures, which is expected to fuel the adoption rate of BT in the construction industry. The development of blockchain systems also needs to address privacy, security, and interoperability issues to reduce the complexity of system design (Shou and Domenech, 2022). In addition to these issues, construction stakeholders remain skeptical about using blockchain-based systems. Improving the user experience and increasing consumer satisfaction can be achieved by resolving these issues (Wu et al., 2022a).

Finally, government agencies and related agencies actively support such initiatives for the benefit of the masses in this day and age. A public-private partnership (PPP) is expected between the government and the private sector to help reduce barriers to blockchain adoption in construction (Jovanovic et al., 2022). A few findings from this study are relevant to international perspectives; the conditions in many developing countries are similar to those in India. Consequently, the results of this study can be applied to other countries based on their context and requirements, with little to zero modifications.

The findings of this research also align with previous works that have emphasized the importance of considering the impact of new technologies on sustainability. For example, research has shown that some technologies, such as the Internet of Things, can enhance resource efficiency but may also contribute to the problem of e-waste (Balzarova et al., 2022). Similarly, this research highlights the need to consider blockchain technology's energy consumption and carbon footprint to ensure that its deployment does not negatively impact sustainability (Fichter et al., 2023; Nogueira et al., 2023; Sadawi et al., 2021).

5.2. Implications

The investigation into the barriers to the adoption of blockchain technology in sustainable construction projects concerning sustainability highlights several key implications for both theory and practice. Firstly, the study results indicate a need for increased education and awareness about blockchain technology among construction professionals. This is important to ensure that professionals are equipped with the knowledge and understanding that is vital to implement blockchain solutions in sustainable construction projects effectively. Secondly, the study suggests that the development of tailored blockchain solutions that address the specific challenges faced by the construction industry is crucial for widespread adoption. This will require collaboration between construction professionals, policymakers, and technology providers to develop common standards and protocols for using blockchain in construction.

Thirdly, the study's results highlight the need for greater investment in blockchain technology to support its development and implementation in the construction sector. This will help address the challenges associated with implementation costs and scalability and allow for the development of more accessible and effective blockchain solutions. Additionally, it will be important to consider the distribution of benefits and the potential for unequal impacts of blockchain technology to ensure that its deployment is responsible and equitable.

Finally, the use of blockchain technology in sustainable construction projects has the potential to enhance the transparency and traceability of supply chains, improving the overall sustainability of construction projects. However, it is important to consider the potential for unintended consequences and ensure that blockchain solutions are designed with sustainability. For example, it will be important to consider blockchain technology's energy consumption and carbon footprint and ensure that its deployment does not contribute to the problem of e-waste. To effectively harness the potential of blockchain technology, it will be necessary to address the barriers to adoption and to consider the impact of its deployment on sustainability. This will require collaboration, investment, education, and the development of tailored solutions designed with sustainability in mind. By doing so, the construction industry can take full advantage of blockchain technology's potential and help create a more sustainable and efficient built environment.

Overall, this research connects to the broader body of literature on cleaner production and sustainability by highlighting the importance of incorporating new technologies and innovative approaches to enhance the sustainability of construction projects. The research findings contribute to this literature by providing specific insights into the barriers to adopting blockchain technology in sustainable construction projects and emphasizing the need to address these barriers to ensure its successful deployment. This research helps advance the conversation on cleaner production and sustainability and supports the development of more sustainable and efficient construction practices.

6. Conclusion

This study aimed to meticulously investigate the barriers impeding the adoption of BT within CPM. For this purpose, a novel hybrid methodological approach was proposed based on the amalgamation of the FDEMATEL method and SNA. Based on the data collected from qualified experts having rich experience in the respective domain, the following major contributions are made to the body of relevant knowledge:

1) Identification of barriers that are stumbling blocks to the adoption of BT-based technologies using a comprehensive literature review together with experts' interviews.
2) Unravel the causal interrelationships among barriers to assess the effect and intensity between barriers using the FDEMATEL method. The results showed that to tackle barriers efficiently, the concerned decision-makers must tackle critical "causal" barriers, including "technology immaturity," "market uncertainty and competition," and "technology accessibility".
3) Construct an NRM of important barriers and uncover the complex relationships using the SNA. It is revealed that "Inadequacies in implementing blockchain-based policies" and "Unawareness and resistance to BT among customers" are the most critical barriers to BCP adoption in the respective industry.

The above outcomes imply that BT is still a new concept in the Indian construction industry and cannot succeed without focusing on the systematic training of managers, decision-makers, and indigenous industry experts. Therefore, the Indian government, besides the private sector, must prepare more facilities to encourage the Indian construction industry to implement BT in their companies, which is beneficial for promoting sustainability in the Indian construction industry. The outcomes of fuzzy DSNA can help leaders, policymakers, and decision-makers focus on the most important barriers and choose the optimal strategy based on prevailing circumstances. The results assist in bridging the gap between theory and practice in sustainable lean construction, which can help promote broader (and essential) discussions.

CRediT authorship contribution statement

Atul Kumar Singh: Investigation, Data curation, Formal analysis, Methodology, Project administration, Software, Visualization, Writing – original draft, Writing – review & editing. **V.R. Prasath Kumar:** Supervision, Writing – original draft. **Gholamreza Dehdasht:** Formal analysis, Methodology, Writing – original draft. **Saeed Reza Mohandes:** Conceptualization, Supervision, Writing – original draft, Writing – review & editing. **Patrick Manu:** Writing – original draft. **Farzad Pour Rahimian:** Writing – original draft.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2023.136840.

References

Abdelmegid, M.A., González, V.A., Poshdar, M., O'Sullivan, M., Walker, C.G., Ying, F., 2020. Barriers to adopting simulation modelling in construction industry. Autom. ConStruct. 111 (December 2019), 103046 https://doi.org/10.1016/j.autcon.2019.103046.

Abdul, S., Khan, R., Tabish, M., Zhang, Y., 2023. Embracement of industry 4 . 0 and sustainable supply chain practices under the shadow of practice-based view theory : ensuring environmental sustainability in corporate sector. J. Clean. Prod. 398 (February), 136609 https://doi.org/10.1016/j.jclepro.2023.136609.

Alam-tabriz, A., Rajabani, N., Farrokh, M., 2014. An integrated fuzzy DEMATEL-ANP-TOPSIS methodology for supplier selection problem. Global Journal of Management Studies and Researches 1 (2), 85–99.

Almeida, D., Jos, M., Cardoso, W., Maria, C., Villas, B., Pinto, A, Jr, J., Contador, C., Giannetti, B.F., De De Lima, A.F., Aurelio, M., 2022. Industry 4 . 0 Implementation : the Relevance of Sustainability and the Potential Social Impact in a Developing Country, vol. 337. https://doi.org/10.1016/j.jclepro.2022.130456. August 2021.

Amoozad Mahdiraji, H., Govindan, K., Yaftiyan, F., Garza-Reyes, J.A., Razavi Hajiagha, S.H., 2023. Unveiling coordination contracts' roles considering circular economy and eco-innovation toward pharmaceutical supply chain resiliency: evidence of an emerging economy. J. Clean. Prod. 382 (October 2022), 135135 https://doi.org/10.1016/j.jclepro.2022.135135.

Anticona, P., 2020. Digital transformation of standard contracts into E-contracting. PM World J. 9 (1), 1–40. https://pmworldlibrary.net/wp-content/uploads/2020/01/pmwj89-Jan2020-Anticona-digital-transformation-of-standard-contracts-into-e-contracts.pdf.

Boonpheng, Apichart, Waranon Kongsong, Dr, Dr, Usahanunth, Nopagon, Chaiwat Pooworakulchai, Dr, 2020. Bringing blockchain technology to construction engineering management. Int. J. Eng. Res. V9, 172–177. https://doi.org/10.17577/ijertv9is010037, 01.

Badi, S., Ochieng, E., Nasaj, M., Papadaki, M., 2021. Technological, organisational and environmental determinants of smart contracts adoption: UK construction sector viewpoint. Construct. Manag. Econ. 39 (1), 36–54. https://doi.org/10.1080/01446193.2020.1819549.

Bag, S., Viktorovich, D.A., Sahu, A.K., Sahu, A.K., 2021. Barriers to adoption of blockchain technology in green supply chain management. J. Glob. Oper. Strat. Sour. 14 (1), 104–133. https://doi.org/10.1108/JGOSS-06-2020-0027.

Bai, C., Dallasega, P., Orzes, G., Sarkis, J., 2020. Industry 4.0 technologies assessment: a sustainability perspective. Int. J. Prod. Econ. 229, 107776 https://doi.org/10.1016/j.ijpe.2020.107776.

Balci, G., Surucu-Balci, E., 2021. Blockchain adoption in the maritime supply chain: examining barriers and salient stakeholders in containerized international trade. Transport. Res. E Logist. Transport. Rev. 156 (September) https://doi.org/10.1016/j.tre.2021.102539.

Balzarova, M., Dyer, C., Falta, M., 2022. Perceptions of blockchain readiness for fairtrade programmes. Technol. Forecast. Soc. Change 185 (February), 122086. https://doi.org/10.1016/j.techfore.2022.122086.

Bartocci, L., Amui, L., Jose, C., Jabbour, C., Beatriz, A., De Sousa, L., Kannan, D., 2017. Sustainability as a dynamic organizational capability : a systematic review and a future agenda toward a sustainable transition. J. Clean. Prod. 142, 308–322. https://doi.org/10.1016/j.jclepro.2016.07.103.

Beatriz, A., De Sousa, L., Charbel, J., Chiappetta, J., Godinho, M., David, F., 2018a. Industry 4 . 0 and the circular economy : a proposed research agenda and original roadmap for sustainable operations. Ann. Oper. Res. 270 (1), 273–286. https://doi.org/10.1007/s10479-018-2772-8.

Beatriz, A., De Sousa, L., Jose, C., Jabbour, C., Foropon, C., 2018b. Technological Forecasting & Social Change When titans meet – can industry 4 . 0 revolutionise the environmentally- sustainable manufacturing wave ? The role of critical success factors. Technol. Forecast. Soc. Change 132 (October 2017), 18–25. https://doi.org/10.1016/j.techfore.2018.01.017.

Benzidia, S., Makaoui, N., Subramanian, N., 2021. Impact of ambidexterity of blockchain technology and social factors on new product development: a supply chain and Industry 4.0 perspective. Technol. Forecast. Soc. Change 169 (November 2020), 120819. https://doi.org/10.1016/j.techfore.2021.120819.

Bildirici, M., 2023. Nexus between Industry 4 . 0 and Environmental Sustainability : A Fourier Panel Bootstrap Cointegration and Causality Analysis, vol. 386. https://doi.org/10.1016/j.jclepro.2022.135786. December 2022.

Cheng, M., Liu, G., Xu, Y., Chi, M., 2021. When blockchain meets the aec industry: present status, benefits, challenges, and future research opportunities. Buildings 11 (8). https://doi.org/10.3390/buildings11080340.

CHO, Y.K., Leite, F., Behzadan, A., Wang, C., 2019. Computing in Civil Engineering 2019, vol. 1, pp. 105–113. In: http://toc.proceedings.com/49478webtoc.pdf.

Ciotta, V., Mariniello, G., Asprone, D., Botta, A., Manfredi, G., 2021. Integration of blockchains and smart contracts into construction information flows: proof-of-concept. Autom. ConStruct. 132 (August), 103925 https://doi.org/10.1016/j.autcon.2021.103925.

Dal Mas, F., Massaro, M., Ndou, V., Raguseo, E., Cowden, B., Tang, J., Santana, C., Albareda, L., 2022. Blockchain technologies for sustainability in the agrifood sector: a literature review of academic research and business perspectives. Technol. Forecast. Soc. Change 180 (August 2021), 121806. https://doi.org/10.1016/j.techfore.2022.122155.

Das, M., Luo, H., Cheng, J.C.P., 2020. Securing interim payments in construction projects through a blockchain-based framework. Autom. ConStruct. 118 (May), 103284 https://doi.org/10.1016/j.autcon.2020.103284.

Das, M., Tao, X., Cheng, J.C.P., 2021. A secure and distributed construction document management system using blockchain. In: Lecture Notes in Civil Engineering, vol. 98. Springer International Publishing. https://doi.org/10.1007/978-3-030-51295-8_59.

Dehdasht, G., Ferwati, M.S., Mohandes, S.R., El-Sabek, L., Edwards, D.J., 2022. Towards expediting the implementation of sustainable and successful lean paradigm for construction projects: a hybrid of DEMATEL and SNA approach. Engineering. Construct. Architect. Manag. https://doi.org/10.1108/ECAM-02-2022-0121.

Dey, K., Shekhawat, U., 2021. Blockchain for sustainable e-agriculture: literature review, architecture for data management, and implications. J. Clean. Prod. 316 (June), 128254 https://doi.org/10.1016/j.jclepro.2021.128254.

Diabat, A., Govindan, K., 2011. An analysis of the drivers affecting the implementation of green supply chain management. Resour. Conserv. Recycl. 55 (6), 659–667. https://doi.org/10.1016/j.resconrec.2010.12.002.

Diakiv, A., 2021. Blockchain in public sector. Theor. Appl. Issues. Econ. 43, 207–216. https://doi.org/10.17721/tppe.2021.43.20.

Dou, Y., Sarkis, J., Bai, C., 2014. Government green procurement: a Fuzzy-dematel analysis of barriers. Stud. Fuzziness Soft Comput. 313, 567–589. https://doi.org/10.1007/978-3-642-53939-8_24.

Durdyev, S., Ashour, M., Connelly, S., Mahdiyar, A., 2022. Barriers to the implementation of building information modelling (BIM) for facility management. J. Build. Eng. 46 (November), 103736 https://doi.org/10.1016/j.jobe.2021.103736.

Dwivedi, A., De Carvalho, D.E., 2022. Technological Forecasting & Social Change Integrating the Circular Economy and Industry 4 . 0 for Sustainable Development : Implications for Responsible Footwear Production in a Big Data-Driven World ☆, vol. 175 https://doi.org/10.1016/j.techfore.2021.121335. November 2021.

El Baz, J., Tiwari, S., Akenroye, T., Cherrafi, A., Derrouiche, R., 2022. A framework of sustainability drivers and externalities for Industry 4.0 technologies using the Best-Worst Method. J. Clean. Prod. 344 (February), 130909 https://doi.org/10.1016/j.jclepro.2022.130909.

Elghaish, F., Hosseini, M.R., Matarneh, S., Talebi, S., Wu, S., Martek, I., Poshdar, M., Ghodrati, N., 2021. Blockchain and the 'Internet of Things'' for the construction industry: research trends and opportunities. Autom. ConStruct. 132 (December 2020), 103942 https://doi.org/10.1016/j.autcon.2021.103942.

Ershadi, M., Jefferies, M., Davis, P., Mojtahedi, M., 2021. Barriers to achieving sustainable construction project procurement in the private sector. Cleaner Eng. Technol. 3 (May), 100125 https://doi.org/10.1016/j.clet.2021.100125.

Espinoza Pérez, A.T., Rossit, D.A., Tohmé, F., Vásquez, Ó.C., Xu, Y., Chong, H.Y., Chi, M., Baek, S., Jung, W., Han, S.H., Farooque, M., Jain, V., Zhang, A., Li, Z., 2022. Blockchain in the AECO industry: current status, key topics, and future research agenda. Autom. ConStruct. 134 (December 2020), 104101 https://doi.org/10.1016/j.autcon.2021.104101.

Feng, C., Ma, R., 2020. Identification of the factors that influence service innovation in manufacturing enterprises by using the fuzzy DEMATEL method. J. Clean. Prod. 253 https://doi.org/10.1016/j.jclepro.2020.120002.

Fichter, K., Lüdeke-Freund, F., Schaltegger, S., Schillebeeckx, S.J.D., 2023. Sustainability impact assessment of new ventures: an emerging field of research. J. Clean. Prod. 384 (December 2022), 135452 https://doi.org/10.1016/j.jclepro.2022.135452.

Figueiredo, K., Hammad, A.W.A., Haddad, A., Tam, V.W.Y., 2022a. Assessing the usability of blockchain for sustainability: extending key themes to the construction industry. J. Clean. Prod. 343 (February), 131047 https://doi.org/10.1016/j.jclepro.2022.131047.

Figueiredo, K., Hammad, A.W.A., Haddad, A., Tam, V.W.Y., 2022b. Assessing the usability of blockchain for sustainability: extending key themes to the construction industry. J. Clean. Prod. 343 (September 2021), 131047 https://doi.org/10.1016/j.jclepro.2022.131047.

Friedman, N., Ormiston, J., 2022. Blockchain as a sustainability-oriented innovation?: opportunities for and resistance to Blockchain technology as a driver of sustainability in global food supply chains. Technol. Forecast. Soc. Change 175 (November 2021), 121403. https://doi.org/10.1016/j.techfore.2021.121403.

Galati, F., 2021. Blockchain adoption in supply networks: a social capital perspective. Supply Chain Manag. https://doi.org/10.1108/SCM-12-2019-0448. May 2020.

Gölcük, I., Baykasoḷlu, A., 2016. An analysis of DEMATEL approaches for criteria interaction handling within ANP. Expert Syst. Appl. 46, 346–366. https://doi.org/10.1016/j.eswa.2015.10.041.

Götz, C.S., Karlsson, P., Yitmen, I., 2020. Exploring applicability, interoperability and integrability of Blockchain-based digital twins for asset life cycle management. Smart and Sustain. Built Environ. https://doi.org/10.1108/SASBE-08-2020-0115.

Gupta, H., Kumar, A., Wasan, P., 2021. Industry 4 . 0 , cleaner production and circular economy : an integrative framework for evaluating ethical and sustainable business performance of manufacturing organizations. J. Clean. Prod. 295, 126253 https://doi.org/10.1016/j.jclepro.2021.126253.

Hamledari, H., Fischer, M., 2021a. Construction payment automation using blockchain-enabled smart contracts and robotic reality capture technologies. Autom. ConStruct. 132 (March), 103926 https://doi.org/10.1016/j.autcon.2021.103926.

Hamledari, H., Fischer, M., 2021b. Measuring the impact of blockchain and smart contracts on construction supply chain visibility. Adv. Eng. Inf. 50 (April), 101444 https://doi.org/10.1016/j.aei.2021.101444.

Hamledari, H., Fischer, M., 2021c. The application of blockchain-based crypto assets for integrating the physical and financial supply chains in the construction & engineering industry. Autom. ConStruct. 127 (December 2020), 103711 https://doi.org/10.1016/j.autcon.2021.103711.

Haque, B., Hasan, R., Zihad, O.M., 2021. SmartOil: blockchain and smart contract-based oil supply chain management. IET Blockchain 1 (2–4), 95–104. https://doi.org/10.1049/blc2.12005.

Harichandran, A., Raphael, B., Mukherjee, A., 2021. A hierarchical machine learning framework for the identification of automated construction operations. J. Inf. Technol. Construct. 26 (April), 591–623. https://doi.org/10.36680/j.itcon.2021.031.

Hellwig, D., Karlic, G., Huchzermeier, A., 2020. Build your own blockchain: a practical guide to distributed ledger technology. In: Management for Professionals. http://link.springer.com/10.1007/978-3-030-40142-9.

Hijazi, A.A., Perera, S., Calheiros, R.N., Alashwal, A., 2021. Rationale for the integration of BIM and blockchain for the construction supply chain data delivery: a systematic literature review and validation through focus group. J. Construct. Eng. Manag. 147 (10), 03121005 https://doi.org/10.1061/(asce)co.1943-7862.0002142.

Hrouga, M., Sbihi, A., Chavallard, M., 2022. The potentials of combining Blockchain technology and Internet of Things for digital reverse supply chain: a case study. J. Clean. Prod. 337 (September 2021), 130609 https://doi.org/10.1016/j.jclepro.2022.130609.

Hu, S., Liang, Y.C., Xiong, Z., Niyato, D., 2021. Blockchain and artificial intelligence for dynamic resource sharing in 6G and beyond. IEEE Wireless Commun. 28 (4), 145–151. https://doi.org/10.1109/MWC.001.2000409.

Hughes, L., Dwivedi, Y.K., Misra, S.K., Rana, N.P., Raghavan, V., Akella, V., 2019. Blockchain research, practice and policy: applications, benefits, limitations, emerging research themes and research agenda. Int. J. Inf. Manag. 49 (February), 114–129. https://doi.org/10.1016/j.ijinfomgt.2019.02.005.

Hultgren, M., Pajala, F., 2018. Blockchain Technology in Construction Industry: Transparency and Traceability in Supply Chain, vols. 1–55. http://www.diva-portal.org/smash/get/diva2:1229861/FULLTEXT01.pdf.

Hunhevicz, J.J., Hall, D.M., 2020. Do you need a blockchain in construction? Use case categories and decision framework for DLT design options. Adv. Eng. Inf. 45 (March), 101094 https://doi.org/10.1016/j.aei.2020.101094.

Hunhevicz, J.J., Motie, M., Hall, D.M., 2022. Digital building twins and blockchain for performance-based (smart) contracts. Autom. ConStruct. 133 (May) https://doi.org/10.1016/j.autcon.2021.103981.

Jalaei, F., Jrade, A., 2014. Construction research congress 2014 ©ASCE 2014 140. Construct. Res. Congr. 2014, 140–149, 2008.

Jovanovic, M., Kostić, N., Sebastian, I.M., Sedej, T., 2022. Managing a blockchain-based platform ecosystem for industry-wide adoption: the case of TradeLens. Technol. Forecast. Soc. Change 184 (September 2021). https://doi.org/10.1016/j.techfore.2022.121981.

Khan, H.H., Malik, M.N., Konečná, Z., Chofreh, A.G., Goni, F.A., Klemeš, J.J., 2022. Blockchain technology for agricultural supply chains during the COVID-19 pandemic: benefits and cleaner solutions. J. Clean. Prod. 347 (March) https://doi.org/10.1016/j.jclepro.2022.131268.

Kim, K., Lee, G., Kim, S., 2020. A study on the application of blockchain technology in the construction industry. KSCE J. Civ. Eng. 24 (9), 2561–2571. https://doi.org/10.1007/s12205-020-0188-x.

Kochupillai, M., Gallersdörfer, U., Köninger, J., Beck, R., 2021. Incentivizing research & innovation with agrobiodiversity conserved in situ: possibilities and limitations of a blockchain-based solution. J. Clean. Prod. 309 (May) https://doi.org/10.1016/j.jclepro.2021.127155.

Košt'ál, K., Helebrandt, P., Belluš, M., Ries, M., Kotuliak, I., 2019. Management and monitoring of IoT devices using blockchain. Sensors 19 (4). https://doi.org/10.3390/s19040856.

Kouhizadeh, M., Saberi, S., Sarkis, J., 2021a. Blockchain technology and the sustainable supply chain: theoretically exploring adoption barriers. Int. J. Prod. Econ. 231 (May 2020), 107831 https://doi.org/10.1016/j.ijpe.2020.107831.

Kouhizadeh, M., Saberi, S., Sarkis, J., Sahebi, I.G., Masoomi, B., Ghorbani, S., Kiani Mavi, R., Standing, C., Kouhizadeh, M., Saberi, S., Sarkis, J., Zhou, J., Wu, Y., Liu, F., Tao, Y., Gao, J., Chen, Z., Ming, X., Zhang, X., et al., 2021b. Blockchain technology and the sustainable supply chain: theoretically exploring adoption barriers. Int. J. Prod. Econ. 231 (May 2020), 107831 https://doi.org/10.1016/j.ijpe.2020.107831.

Kumar, P., Kumar, R., Gupta, G.P., Tripathi, R., 2021. A Distributed framework for detecting DDoS attacks in smart contract-based Blockchain-IoT Systems by leveraging Fog computing. Trans. Emerg. Telecommun. Technol. 32 (6), 1–31. https://doi.org/10.1002/ett.4112.

Leduc, G., Kubler, S., Georges, J.P., 2021. Innovative blockchain-based farming marketplace and smart contract performance evaluation. J. Clean. Prod. 306, 127055 https://doi.org/10.1016/j.jclepro.2021.127055.

Lee, D., Lee, S.H., Masoud, N., Krishnan, M.S., Li, V.C., 2021. Integrated digital twin and blockchain framework to support accountable information sharing in construction projects. Autom. ConStruct. 127 (March), 103688 https://doi.org/10.1016/j.autcon.2021.103688.

Leng, J., Jiang, P., Xu, K., Liu, Q., Zhao, J.L., Bian, Y., Shi, R., 2019. Makerchain: a blockchain with chemical signature for self-organizing process in social manufacturing. J. Clean. Prod. 234, 767–778. https://doi.org/10.1016/j.jclepro.2019.06.265.

Li, C.Z., Chen, Z., Xue, F., Kong, X.T.R., Xiao, B., Lai, X., Zhao, Y., 2021. A blockchain- and IoT-based smart product-service system for the sustainability of prefabricated housing construction. J. Clean. Prod. 286, 125391 https://doi.org/10.1016/j.jclepro.2020.125391.

Li, J., Greenwood, D., Kassem, M., 2019. Blockchain in the built environment and construction industry: a systematic review, conceptual models and practical use cases. Autom. ConStruct. 102 (August 2018), 288–307. https://doi.org/10.1016/j.autcon.2019.02.005.

Li, W., Duan, P., Su, J., 2021. The effectiveness of project management construction with data mining and blockchain consensus. J. Ambient Intell. Hum. Comput., 0123456789 https://doi.org/10.1007/s12652-020-02668-7.

Liu, C., Le Roux, L., Körner, C., Tabaste, O., Lacan, F., Bigot, S., 2022. Digital twin-enabled collaborative data management for metal additive manufacturing systems. J. Manuf. Syst. 62 (May), 857–874. https://doi.org/10.1016/j.jmsy.2020.05.010.

Loosemore, M., Alkilani, S.Z., Murphy, R., 2021. The institutional drivers of social procurement implementation in Australian construction projects. Int. J. Proj. Manag. 39 (7), 750–761. https://doi.org/10.1016/j.ijproman.2021.07.002.

Mackey, T.K., Shah, N., Miyachi, K., Short, J., Clauson, K., 2019. A framework proposal for blockchain-based scientific publishing using shared governance. Front. Blockchain 2 (November), 1–12. https://doi.org/10.3389/fbloc.2019.00019.

Martino, G., Giuda, D., Pattini, G., Seghezzi, E., Schievano, M., Paleari, F., 2020. Through the Integration of Blockchain Technology. Springer International Publishing. https://doi.org/10.1007/978-3-030-33570-0.
Maslin, M., Watt, M., Yong, C., 2019. Research methodologies to support the development of blockchain standards. J. ICT Standard. 7 (3), 249–268. https://doi.org/10.13052/jicts2245-800X.734.
Mason, J., 2017. Intelligent contracts and the construction industry. J. Leg. Aff. Dispute Resolut. Eng. Constr. 9 (3), 04517012 https://doi.org/10.1061/(asce)la.1943-4170.0000233.
Mishra, H., Maheshwari, P., 2021. Blockchain in Indian Public Distribution System: a conceptual framework to prevent leakage of the supplies and its enablers and disablers. J. Glob. Oper. Strat. Sour. 14 (2), 312–335. https://doi.org/10.1108/JGOSS-07-2020-0044.
Mohandes, S.R., Karasan, A., Erdoğan, M., Ghasemi Poor Sabet, P., Mahdiyar, A., Zayed, T., 2022a. A comprehensive analysis of the causal factors in repair, maintenance, alteration, and addition works: a novel hybrid fuzzy-based approach. Expert Syst. Appl. (June), 208. https://doi.org/10.1016/j.eswa.2022.118112.
Mohandes, S.R., Sadeghi, H., Fazeli, A., Mahdiyar, A., Hosseini, M.R., Arashpour, M., Zayed, T., 2022b. Causal analysis of accidents on construction sites: a hybrid fuzzy Delphi and DEMATEL approach. Saf. Sci. 151 (March), 105730 https://doi.org/10.1016/j.ssci.2022.105730.
Mohandes, S.R., Zhang, X., 2021. Developing a Holistic Occupational Health and Safety risk assessment model: an application to a case of sustainable construction project. J. Clean. Prod. 291 https://doi.org/10.1016/j.jclepro.2021.125934.
Muthukrishnan, A., Muralidharan, T.R., Subash, J., Lathamangeswari, C., 2020. Association of poor sleep quality with risk factors after coronary artery bypass graft surgery—a prospective cohort study. J. Vasc. Nurs. 38 (2), 83–92. https://doi.org/10.1016/j.jvn.2020.02.001.
Muzumdar, A., Modi, C., Vyjayanthi, C., 2022. A permissioned blockchain enabled trustworthy and incentivized emission trading system. J. Clean. Prod. 349 https://doi.org/10.1016/j.jclepro.2022.131274. July 2021.
Nawari, N.O., Ravindran, S., 2019a. Blockchain and the built environment: potentials and limitations. J. Build. Eng. 25 (June) https://doi.org/10.1016/j.jobe.2019.100832.
Nawari, N.O., Ravindran, S., 2019b. Blockchain technology and BIM process: review and potentialapplications. J. Inf. Technol. Construct. 24 (May), 209–238.
Niranjanamurthy, M., Nithya, B.N., Jagannatha, S., 2019. Analysis of Blockchain technology: pros, cons and SWOT. Cluster Comput. 22 (s6), 14743–14757. https://doi.org/10.1007/s10586-018-2387-5.
Nogueira, C., Marques, J.F., Pinto, H., 2023. Civil economy as a path towards sustainability: an empirical investigation. J. Clean. Prod. 383 (December 2022) https://doi.org/10.1016/j.jclepro.2022.135486.
Park, C., Lee, D., Khan, N., Cho, S., 2020. Blockchain based concept model for construction quality management. In: (IPCMC2020)Proceedings of the 6th International Project and Construction Management Conference. November. https://www.researchgate.net/publication/345673550.
Parn, E.A., Edwards, D., 2019. Cyber threats confronting the digital built environment: common data environment vulnerabilities and block chain deterrence. Eng. Construct. Architect. Manag. 26 (2), 245–266. https://doi.org/10.1108/ECAM-03-2018-0101.
Pattini, G., Di Giuda, G.M., Tagliabue, L.C., 2020. Blockchain application for contract schemes in the construction industry. Proc. Int. Struct. Eng. Construct. 7 (1) https://doi.org/10.14455/ISEC.res.2020.7(1).AAE-21.
Penzes, B., 2018. Technology in the. In: THE CONSTRUCTION INDUSTRY Digital Transformation for High Productivity. BLOCKCHAIN TECHNOLOGY, December.
Perera, S., Nanayakkara, S., Rodrigo, M.N.N., Senaratne, S., Weinand, R., 2020. Blockchain technology: is it hype or real in the construction industry? J. Ind. Inf. Integr. 17 (August 2019), 100125 https://doi.org/10.1016/j.jii.2020.100125.
Piccarozzi, M., Silvestri, C., Aquilani, B., Silvestri, L., 2022. Is this a new story of the 'Two Giants'? A systematic literature review of the relationship between industry 4.0, sustainability and its pillars. Technol. Forecast. Soc. Change 177 (November 2021), 121511. https://doi.org/10.1016/j.techfore.2022.121511.
Pinto Lopes, D., Rita, P., Treiblmaier, H., 2021. The impact of blockchain on the aviation industry: findings from a qualitative study. Res. Transport. Bus. Manag. 41 (May), 100669 https://doi.org/10.1016/j.rtbm.2021.100669.
Qi, Y., Wang, W., Quan, X., Fan, C., Ge, B., Xu, C., Cui, M., Yue, Q., Gao, B., Gao, Y., He, K., 2023. Blockchain-like Eα analysis strategy for two distinct "White-box" modeling methodologies to simulate the incineration of oily sludge. J. Clean. Prod. 384 (October 2022) https://doi.org/10.1016/j.jclepro.2022.135678.
Queiroz, M.M., Fosso Wamba, S., Chiappetta Jabbour, C.J., Lopes de Sousa Jabbour, A. B., Machado, M.C., 2022. Adoption of Industry 4.0 technologies by organizations: a maturity levels perspective. Ann. Oper. Res. https://doi.org/10.1007/s10479-022-05006-6.
Raj, A., Jeyaraj, A., 2022. Antecedents and consequents of industry 4.0 adoption using technology, organization and environment (TOE) framework: a meta-analysis. Ann. Oper. Res. https://doi.org/10.1007/s10479-022-04942-7.
Al Sadawi, A., Madani, B., Saboor, S., Ndiaye, M., Abu-Lebdeh, G., 2021. A comprehensive hierarchical blockchain system for carbon emission trading utilizing blockchain of things and smart contract. Technol. Forecast. Soc. Change 173 (September), 121124. https://doi.org/10.1016/j.techfore.2021.121124.
Sanka, A.I., Irfan, M., Huang, I., Cheung, R.C.C., 2021. A survey of breakthrough in blockchain technology: adoptions, applications, challenges and future research. Comput. Commun. 169 (September 2020), 179–201. https://doi.org/10.1016/j.comcom.2020.12.028.
Sheng, D., Ding, L., Zhong, B., Love, P.E.D., Luo, H., Chen, J., 2020. Construction quality information management with blockchains. Autom. ConStruct. 120 (July), 103373 https://doi.org/10.1016/j.autcon.2020.103373.
Shojaei, A., 2019. Exploring applications of blockchain technology in the construction industry. In: ISEC 2019 - 10th International Structural Engineering and Construction Conference. https://doi.org/10.14455/isec.res.2019.78. May.
Shojaei, A., Flood, I., Moud, H.I., Hatami, M., Zhang, X., 2020. An implementation of smart contracts by integrating BIM and blockchain. Adv. Intell. Syst. Comput. 1070, 519–527. https://doi.org/10.1007/978-3-030-32523-7_36.
Shojaei, A., Ketabi, R., Razkenari, M., Hakim, H., Wang, J., 2021. Enabling a circular economy in the built environment sector through blockchain technology. J. Clean. Prod. 294, 126352 https://doi.org/10.1016/j.jclepro.2021.126352.
Shou, M., Domenech, T., 2022. Integrating LCA and blockchain technology to promote circular fashion – a case study of leather handbags. J. Clean. Prod. 373 (August), 133557 https://doi.org/10.1016/j.jclepro.2022.133557.
Sigalov, K., Ye, X., König, M., Hagedorn, P., Blum, F., Severin, B., Hettmer, M., Hückinghaus, P., Wölkerling, J., Groß, D., 2021. Automated payment and contract management in the construction industry by integrating building information modeling and blockchain-based smart contracts. Appl. Sci. 11 (16) https://doi.org/10.3390/app11167653.
Smith, Stanley Benjamin, 2015. Method and System To Usea Block Chain Infrastructure and Smart Contracts To Monetize Data Transactions Involving Changesto Data Included Into a Data Supply Chain 1 (19).
Su, D., Zhang, L., Peng, H., Saeidi, P., Tirkolaee, E.B., 2023. Technical challenges of blockchain technology for sustainable manufacturing paradigm in Industry 4.0 era using a fuzzy decision support system. Technol. Forecast. Soc. Change 188 (December 2022), 122275. https://doi.org/10.1016/j.techfore.2022.122275.
Surendra, V., Singh, A.R., Raut, R.D., Hareesh, U., 2020. Resources , Conservation & Recycling Blockchain technology adoption barriers in the Indian agricultural supply chain : an integrated approach. Resour. Conserv. Recycl. 161 (November 2019), 104877 https://doi.org/10.1016/j.resconrec.2020.104877.
Tabatabaee, S., Mahdiyar, A., Mohandes, S.R., Ismail, S., 2022. Towards the development of a comprehensive lifecycle risk assessment model for green roof implementation. Sustain. Cities Soc. 76, 103404 https://doi.org/10.1016/j.scs.2021.103404.
Tao, X., Das, M., Liu, Y., Cheng, J.C.P., 2021. Distributed common data environment using blockchain and Interplanetary File System for secure BIM-based collaborative design. Autom. ConStruct. 130 (July), 103851 https://doi.org/10.1016/j.autcon.2021.103851.
Tariq, S., Hussein, M., Wang, R.D., Zayed, T., 2021. Trends and developments of on-site crane layout planning 1983–2020: bibliometric, scientometric and qualitative analyzes. Construct. Innovat. https://doi.org/10.1108/CI-02-2021-0015.
Tezel, A., Febrero, P., Papadonikolaki, E., Yitmen, I., 2021. Insights into blockchain implementation in construction: models for supply chain management. J. Manag. Eng. 37 (4), 1–19. https://doi.org/10.1061/(asce)me.1943-5479.0000939.
Tezel, A., Papadonikolaki, E., Yitmen, I., Hilletofth, P., 2020. Preparing construction supply chains for blockchain technology: an investigation of its potential and future directions. Front. Eng. Manag. 7 (4), 547–563. https://doi.org/10.1007/s42524-020-0110-8.
Triana Casallas, J.A., Cueva-Lovelle, J.M., Rodríguez Molano, J.I., 2020. Smart contracts with blockchain in the public sector. Int. J. Interact. Multimed. Artif. Int. 6 (3), 63. https://doi.org/10.9781/ijimai.2020.07.005.
Umbenhauer, B., Younger, L., 2018. Leadership: Driving Innovation and Delivering Impact. In: The Deloitte Global Chief Procurement Officer Survey 2018. In Deloitte. https://www2.deloitte.com/at/de/seiten/strategy-operations/articles/global-cpo-survey.html.
Upadhyay, A., Mukhuty, S., Kumar, V., Kazancoglu, Y., 2021. Blockchain technology and the circular economy: implications for sustainability and social responsibility. J. Clean. Prod. 293, 126130 https://doi.org/10.1016/j.jclepro.2021.126130.
Uriarte, R.B., Zhou, H., Kritikos, K., Shi, Z., Zhao, Z., De Nicola, R., 2021. Distributed service-level agreement management with smart contracts and blockchain. Concurrency Comput. Pract. Ex. 33 (14), 1–17. https://doi.org/10.1002/cpe.5800.
Vadgama, N., Tasca, P., 2021. An analysis of blockchain adoption in supply chains between 2010 and 2020. Front. Blockchain 4 (March), 1–14. https://doi.org/10.3389/fbloc.2021.610476.
Venkatesh, V.G., Zhang, A., Luthra, S., Dubey, R., Subramanian, N., Mangla, S., 2017. Barriers to coastal shipping development: an Indian perspective. Transport. Res. Transport Environ. 52, 362–378. https://doi.org/10.1016/j.trd.2017.03.016.
Wang, S., Ouyang, L., Yuan, Y., Ni, X., Han, X., Wang, F.Y., 2019. Blockchain-Enabled smart contracts: architecture, applications, and future trends. IEEE Trans. Syst. Man. Cybern.: Systems 49 (11), 2266–2277. https://doi.org/10.1109/TSMC.2019.2895123.
Wang, Y., Men, S., Guo, T., 2021. Application of blockchain technology in value chain of procurement in manufacturing enterprises. Wireless Commun. Mobile Comput. https://doi.org/10.1155/2021/1674412, 2021.
Wang, Zeyu, Zhang, S., Zhao, Y., Chen, C., Dong, X., 2023. Risk prediction and credibility detection of network public opinion using blockchain technology. Technol. Forecast. Soc. Change 187 (July 2022), 122177. https://doi.org/10.1016/j.techfore.2022.122177.
Wang, Zhaojing, Wang, T., Hu, H., Gong, J., Ren, X., Xiao, Q., 2020. Blockchain-based framework for improving supply chain traceability and information sharing in precast construction. Autom. ConStruct. 111 (December 2019), 103063 https://doi.org/10.1016/j.autcon.2019.103063.
Werner, F., Basalla, M., Schneider, J., Hays, D., Vom Brocke, J., 2021. Blockchain adoption from an interorganizational systems perspective–A mixed-methods approach. Inf. Syst. Manag. 38 (2), 135–150. https://doi.org/10.1080/10580530.2020.1767830.

Winship, C., Wasserman, S., Faust, K., 1996. Social network analysis: methods and applications. J. Am. Stat. Assoc. 91 (435), 1373. https://doi.org/10.2307/2291756.
Wu, W.W., 2012. Segmenting critical factors for successful knowledge management implementation using the fuzzy DEMATEL method. Appl. Soft Comput. J. 12 (1), 527–535. https://doi.org/10.1016/j.asoc.2011.08.008.
Wu, L., Li, X., Zhao, R., Lu, W., Xu, J., Xue, F., 2022a. A blockchain-based model with an incentive mechanism for cross-border logistics supervision and data sharing in modular construction. J. Clean. Prod. 375 (June), 133460 https://doi.org/10.1016/j.jclepro.2022.133460.
Wu, Y., Liu, F., Wu, J., He, J., Xu, M., Zhou, J., 2022b. Barrier identification and analysis framework to the development of offshore wind-to-hydrogen projects. Energy 239, 122077. https://doi.org/10.1016/j.energy.2021.122077.
Xu, Y., Chong, H.Y., Chi, M., 2021. Modelling the blockchain adoption barriers in the AEC industry. Engineering, Construction and Architectural Management. https://doi.org/10.1108/ECAM-04-2021-0335.
Yang, L., Zou, H., Shang, C., Ye, X., Rani, P., 2023. Adoption of information and digital technologies for sustainable smart manufacturing systems for industry 4.0 in small, medium, and micro enterprises (SMMEs). Technol. Forecast. Soc. Change 188 (December 2022), 122308. https://doi.org/10.1016/j.techfore.2022.122308.
Yang, R., Wakefield, R., Lyu, S., Jayasuriya, S., Han, F., Yi, X., Yang, X., Amarasinghe, G., Chen, S., 2020. Public and private blockchain in construction business process and information integration. Autom. ConStruct. 118 (May), 103276 https://doi.org/10.1016/j.autcon.2020.103276.
Yaqoob, I., Salah, K., Jayaraman, R., Al-Hammadi, Y., 2021. Blockchain for healthcare data management: opportunities, challenges, and future recommendations. Neural Comput. Appl., 0123456789 https://doi.org/10.1007/s00521-020-05519-w.
Yavuz, O., Uner, M.M., Okumus, F., Karatepe, O.M., 2023. Industry 4.0 technologies, sustainable operations practices and their impacts on sustainable performance. J. Clean. Prod. 387 (December 2022), 135951 https://doi.org/10.1016/j.jclepro.2023.135951.
Yuan, M., Li, Z., Li, X., Luo, X., 2021. Managing stakeholder-associated risks and their interactions in the life cycle of prefabricated building projects: a social network analysis approach. J. Clean. Prod. 323 (September), 129102 https://doi.org/10.1016/j.jclepro.2021.129102.
Zhang, X., Mohandes, S.R., 2020. Occupational Health and Safety in green building construction projects: a holistic Z-numbers-based risk management framework. J. Clean. Prod. 275 https://doi.org/10.1016/j.jclepro.2020.122788.