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Identifying and Prioritizing Barriers to Blockchain Adoption in Construction Supply Chain Management Using a Fuzzy Multi-Criteria Decision-Making Approach

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Abstract

This study aims to investigate the barriers to blockchain adoption in construction supply chain management using a fuzzy-based Multi-Criteria Decision-Making (MCDM) approach. In terms of its objective, the study is applied research; in terms of its research design, it is descriptive-survey research; and in terms of data analysis, it adopts a mixed qualitative and quantitative approach. The study population for identifying the barriers consisted of experts in the construction industry, selected based on criteria including professional expertise in construction, familiarity with blockchain technology, and relevant scientific and research publications. Data were collected using a questionnaire, whose validity was assessed using the Content Validity Ratio (CVR), while its reliability was evaluated using Cronbach's alpha coefficient. The findings indicate that technical and infrastructural challenges, with a weight of 0.289, ranked first, followed by organizational and human resource challenges with a weight of 0.288, economic and financial challenges with a weight of 0.249, and legal, security, and governance challenges with a weight of 0.175. At the individual barrier level, lack of standardization ranked first (0.175), followed by scalability problems (0.174), insufficient Information and Communication Technology (ICT) infrastructure (0.148), lack of employee knowledge and training (0.118), resistance to change and technology adoption (0.084), low or absence of transaction fees (0.078), use in the underground economy (0.067), and contractual risks (0.063). The results highlight the importance of addressing technological, organizational, economic, and institutional barriers to facilitate successful blockchain adoption in construction supply chain management.

Keywords: Blockchain technology, Construction, Supply chain management, Fuzzy multi-criteria decision-making.

1 | Introduction

The construction industry is characterized by fragmented organizational structures, temporary project-based relationships, complex contractual arrangements, and the involvement of numerous contractors,

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subcontractors, suppliers, clients, and other stakeholders. These characteristics make coordination, information exchange, transaction management, and supply chain integration particularly challenging. The fragmentation of construction supply chains can lead to information asymmetry, limited transparency, inefficient communication, weak coordination, and difficulties in monitoring the movement of materials, financial transactions, and contractual obligations. Consequently, improving transparency, traceability, trust, and coordination has become an important objective in the digital transformation of construction supply chains [1], [2].

Blockchain technology has emerged as one of the digital technologies with considerable potential to address some of these challenges. A blockchain provides a distributed ledger in which transactions and records can be securely shared among network participants. Immutability, traceability, decentralization, transparency, and the ability to execute predefined transactions through smart contracts are among the characteristics that distinguish blockchain from conventional information systems. These characteristics have encouraged researchers to investigate blockchain as a potential mechanism for improving information sharing, transaction traceability, process automation, and trust among supply chain participants [3], [4].

The potential application of blockchain is particularly relevant to construction supply chains because transactions and information flows frequently cross organizational boundaries. Blockchain can potentially support procurement processes, supplier management, material traceability, payment processes, contractual transactions, documentation, and financial activities. A recent systematic review of 197 studies demonstrated that blockchain research in construction supply chains has developed across strategic, managerial, operational, technological, and business dimensions, confirming that blockchain is increasingly being considered as a broader supply chain management technology rather than merely a financial or information technology [5]. This growing body of research indicates that blockchain may contribute to greater transparency, collaboration, efficiency, and traceability within construction supply chains.

Despite these potential benefits, the adoption of blockchain in construction remains challenging. The availability of a promising technology does not necessarily translate into successful implementation because adoption requires changes in organizational practices, technological infrastructure, stakeholder relationships, and existing business processes. Construction organizations may face uncertainty regarding blockchain maturity, implementation costs, scalability, interoperability, security, and the availability of appropriate technical capabilities. These challenges can significantly influence the willingness and ability of organizations to adopt blockchain [6], [7].

One of the most important characteristics of blockchain adoption in construction supply chains is its interorganizational nature. In contrast to technologies that can be adopted independently by a single organization, blockchain generates greater value when multiple supply chain participants participate in a common network. Contractors, subcontractors, suppliers, clients, and other stakeholders therefore need to demonstrate a certain level of willingness and readiness to participate. Differences in technological capabilities, organizational interests, investment capacity, and perceptions of benefits and risks can consequently create significant barriers to collective adoption [8], [9].

Technological barriers represent an important dimension of this problem. Blockchain networks may face limitations related to scalability, interoperability, transaction speed, system performance, cybersecurity, and technological maturity. These issues become particularly important in construction supply chains because a large number of organizations may generate and exchange information simultaneously. In addition, organizations may already rely on established information systems, making integration with blockchain technically and financially demanding. Consequently, the perceived complexity and uncertainty of blockchain technology can discourage organizations from adopting it [6], [10].

Human and organizational capabilities constitute another important group of barriers. Blockchain adoption requires employees and managers to understand the principles, applications, risks, and limitations of the technology. A shortage of specialized knowledge and training may therefore reduce organizational readiness.

Furthermore, resistance to organizational change can limit the willingness of employees and managers to replace familiar procedures with blockchain-based processes. Existing research on construction blockchain adoption has identified inadequate knowledge and employee training as important factors influencing adoption decisions [11].

Economic considerations can also constrain blockchain adoption. Implementing blockchain may require investment in hardware, software, network infrastructure, system development, employee training, cybersecurity, and organizational restructuring. These costs may be particularly problematic for smaller organizations with limited financial and technological resources. At the same time, the benefits of blockchain may not be distributed equally among supply chain participants. An organization may bear a substantial portion of implementation costs while some of the resulting benefits are realized by other members of the supply chain. Such uncertainty can reduce the economic attractiveness of blockchain adoption [12], [13].

Contractual and regulatory uncertainty represents another significant challenge. Construction supply chains are strongly dependent on contractual relationships, legal obligations, regulatory requirements, and established procedures for managing disputes and payments. The use of blockchain and smart contracts may create questions concerning legal recognition, responsibility for digital records, data ownership, privacy, contractual enforceability, and liability. Consequently, uncertainty surrounding the regulatory and legal environment can discourage organizations from investing in blockchain-based systems [14], [15].

Trust and stakeholder participation also have a critical role in blockchain adoption. Although blockchain is frequently promoted as a technology capable of enhancing trust, the implementation of a blockchain network itself requires trust and cooperation among participating organizations. Stakeholders may be reluctant to share information because of concerns regarding confidentiality, competitive disadvantages, data ownership, or misuse of information. Moreover, differences in organizational interests may make it difficult to establish common governance mechanisms for a shared blockchain network [8], [16].

An additional challenge is that blockchain adoption barriers are not independent of one another. Technological, organizational, economic, contractual, regulatory, and human barriers can interact and reinforce each other. For example, insufficient employee knowledge may increase organizational resistance, while technological uncertainty may increase perceived implementation costs. Similarly, regulatory uncertainty may discourage investment, while limited stakeholder participation may reduce the expected economic benefits of blockchain. Therefore, evaluating each barrier independently may provide an incomplete representation of the adoption problem [11], [17].

Recent studies have increasingly recognized this interdependent nature of blockchain adoption barriers. Singh et al. [11], for example, specifically examined barriers to blockchain adoption in construction supply chain management using a Pythagorean fuzzy DEMATEL approach. Their findings identified market-based risks, high costs associated with sustainability, and the use of blockchain in underground economic activities as influential barriers, while inadequate knowledge and employee training, contractual risks, and scalability issues played important central roles. This evidence demonstrates that blockchain adoption should be examined as a complex system of interconnected barriers rather than as a simple technological adoption decision.

Similarly, more recent research has moved toward integrated frameworks for understanding blockchain adoption in construction. Wu et al. [18] combined the Technology–Organization–Environment framework with fuzzy DEMATEL to identify and analyze blockchain adoption barriers. Their findings demonstrate that technological, organizational, and environmental factors interact within the adoption process, reinforcing the need for approaches capable of capturing relationships among barriers rather than simply ranking them independently.

Although the literature on blockchain in construction has expanded considerably, important research gaps remain. A large proportion of existing studies have focused on the potential applications and benefits of blockchain, whereas comparatively fewer studies have systematically examined the complete set of barriers that can prevent adoption specifically within construction supply chain management. Moreover, the fragmented nature of construction supply chains means that adoption barriers may differ from those observed in other industries or in individual construction organizations.

Therefore, the central issue is not simply whether blockchain can provide benefits to construction supply chains, but rather which barriers most strongly influence its adoption and how these barriers interact with one another. Addressing this issue is particularly important because resources for technological transformation are limited and organizations need to identify the barriers that should receive priority. A systematic assessment of adoption barriers can therefore provide valuable information for construction organizations, supply chain stakeholders, policymakers, and technology developers.

Accordingly, this study focuses on identifying and prioritizing the barriers to blockchain adoption in construction supply chain management. Considering the qualitative and uncertain nature of many adoption barriers and the dependence of their assessment on expert judgments, a fuzzy Multi-Criteria Decision-Making (MCDM) approach provides an appropriate methodological perspective. The study seeks to contribute to the existing literature by providing a comprehensive assessment of the technological, organizational, economic, human, contractual, regulatory, and stakeholder-related barriers that influence blockchain adoption in construction supply chains.

2 | Literature Review

Research on blockchain adoption has developed from early conceptual discussions of blockchain capabilities toward empirical investigations of adoption determinants and barriers. Early studies primarily examined the characteristics and potential applications of blockchain, while subsequent research increasingly investigated why organizations may resist or delay adoption. This evolution has demonstrated that blockchain adoption is influenced not only by technological characteristics but also by organizational readiness, economic considerations, institutional conditions, and stakeholder relationships [3], [6].

Within supply chain management, blockchain has been proposed as a mechanism for improving transparency, traceability, information sharing, and coordination among supply chain participants. Ghode et al. [6] investigated factors influencing blockchain adoption in supply chains and emphasized that adoption is influenced by a combination of technological and organizational factors. Similarly, Vadgama and Tasca [7] reviewed blockchain adoption in supply chains and showed that adoption research increasingly considers technological, organizational, and interorganizational dimensions.

Construction supply chains present particularly complex conditions for blockchain adoption. Unlike relatively stable supply networks, construction supply chains are often temporary, project-based, geographically dispersed, and characterized by a large number of independent organizations. Tezel et al. [2] argued that construction supply chains require considerable preparation before blockchain can be effectively adopted because existing fragmentation and organizational structures can limit technological implementation. Their findings emphasize that blockchain adoption should be considered within the broader context of construction supply chain characteristics.

The application of blockchain to construction supply chains has received increasing scholarly attention. Heydari and Shojaei [5] conducted a systematic literature review of 197 studies and classified the existing research into strategic, managerial, operational, technological, and business areas. Their findings indicate that blockchain has potential to improve efficiency, transparency, collaboration, traceability, and financial processes within construction supply chains. At the same time, their review identifies continuing research gaps concerning implementation and the interaction between blockchain and the broader construction supply chain environment.

A major stream of research has specifically examined barriers to blockchain adoption. Singh et al. [11] represent one of the most directly relevant studies because their research focuses specifically on blockchain adoption in construction supply chain management. Using Pythagorean fuzzy DEMATEL, they investigated the relationships among adoption barriers and found that market-related risks and financial issues were among the most influential factors. They also identified inadequate knowledge and employee training, contractual risks, and scalability issues as important elements within the barrier system.

Another study by Singh et al. [17] examined barriers to blockchain technology adoption in sustainable construction projects. Their findings reinforce the argument that blockchain adoption involves multiple dimensions, including technological, organizational, economic, and sustainability-related issues. This research is important because it demonstrates that the barriers associated with blockchain adoption cannot be separated from the broader organizational and operational context in which construction projects are implemented.

Singh et al. [19] further investigated barriers to blockchain-based transparency and sustainability in the construction industry using Pythagorean fuzzy AHP. Their research identified and prioritized barriers associated with blockchain implementation and demonstrated the usefulness of fuzzy MCDM methods for dealing with the uncertainty inherent in expert evaluations. The study is particularly relevant to the present research because it demonstrates that fuzzy approaches can provide a structured mechanism for evaluating blockchain barriers in construction.

Okanlawon et al. [15] examined barriers to blockchain implementation in construction supply chain management in Nigeria. Their study provides empirical evidence that blockchain implementation is affected by multiple technological, organizational, financial, and institutional barriers. The context-specific nature of their findings also demonstrates the importance of considering the characteristics of the construction environment when evaluating blockchain adoption.

Research outside the construction sector also provides useful insights into blockchain adoption barriers. Khan et al. [20] investigated barriers to blockchain adoption in supply chains in the Indian context and demonstrated that technological and organizational challenges can significantly influence adoption. Such findings are relevant to construction because construction supply chains similarly depend on multiple independent organizations and require coordination among participants before network-based technologies can generate their full value.

Kouhizadeh et al. [9] examined barriers to blockchain adoption in sustainable supply chains and emphasized the importance of organizational, technological, and institutional factors. Their research demonstrates that the sustainability and supply chain context can introduce additional complexity into blockchain adoption decisions. This finding is relevant to construction supply chains because environmental, economic, and organizational objectives increasingly need to be considered simultaneously.

Economic and financial barriers have received particular attention in blockchain adoption research. Kaur et al. [12] examined barriers to blockchain adoption for supply chain finance among Indian SMEs and highlighted the importance of financial constraints and organizational capabilities. Smaller firms may face greater difficulties because they often have fewer resources for technological investment, employee training, and system development. Since construction supply chains commonly involve numerous small and medium-sized subcontractors and suppliers, these financial constraints may represent an important barrier to collective blockchain adoption.

Technological barriers are another recurring theme in the literature. Blockchain scalability is particularly important because large supply chains may generate substantial volumes of transactions and data. Interoperability is also critical because blockchain platforms need to interact with existing information systems. In addition, concerns regarding cybersecurity and smart contract reliability can increase perceived technological risk. Wu et al. [18] demonstrated that technological barriers may have causal relationships with other barriers and therefore should not be considered independently.

Moraes et al. [13] examined technological barriers to blockchain adoption in supply chains through a diffusion-of-innovation perspective. Their work emphasizes that technological characteristics such as compatibility, complexity, and perceived benefits influence the diffusion of blockchain. These findings support the argument that blockchain adoption requires not only technological availability but also compatibility with organizational processes and existing technological environments.

Organizational readiness has also been identified as an important determinant of adoption. Organizations require adequate managerial support, employee capabilities, financial resources, and internal processes to successfully implement blockchain. Lack of knowledge and insufficient training can increase uncertainty and resistance among employees. Singh et al. [11] identified inadequate knowledge and employee training as a pivotal factor in the construction supply chain blockchain adoption system, emphasizing the importance of human capabilities in addition to technological readiness.

Stakeholder-related barriers are particularly important in construction because blockchain adoption often requires participation across organizational boundaries. A blockchain network becomes more valuable when a larger number of relevant participants contribute information and use the system. However, organizations may have different strategic objectives, levels of technological readiness, and perceptions of risk. Balci and Surucu-Balci [8], although focusing on the maritime supply chain, demonstrated that stakeholder characteristics and barriers to participation are important considerations when blockchain adoption involves interconnected supply chain actors.

The regulatory and institutional environment represents another important dimension. Construction organizations operate within established legal and contractual frameworks, and the introduction of blockchain can raise questions regarding data ownership, privacy, legal responsibility, digital records, and smart contract enforceability. Uncertainty in these areas can increase perceived risk and reduce organizational willingness to adopt blockchain. Recent construction research has consequently emphasized the importance of environmental and policy conditions alongside technological and organizational factors [18].

The literature also demonstrates an increasing use of MCDM methods to analyze blockchain adoption barriers. Fuzzy methods are particularly suitable because expert assessments of technological and organizational barriers are often subjective and imprecise. Singh et al. [11] used Pythagorean fuzzy DEMATEL to identify causal relationships among construction supply chain barriers, while Singh et al. [19] applied Pythagorean fuzzy AHP to prioritize blockchain-related barriers in sustainable construction. These studies demonstrate that fuzzy MCDM methods can capture uncertainty while allowing complex barrier structures to be systematically analyzed.

Recent research suggests that the field is moving toward more comprehensive and empirically validated models of blockchain adoption. Karacigan et al. [21] proposed an empirically validated framework for blockchain adoption in construction and emphasized the importance of technological, motivational, and industry-related dimensions. This development indicates that blockchain adoption research is gradually moving beyond identifying individual barriers toward understanding the broader conditions necessary for successful adoption.

Overall, the literature indicates that blockchain adoption in construction supply chain management is influenced by a multidimensional set of barriers. These include technological limitations, organizational readiness, employee knowledge, financial constraints, contractual risks, regulatory uncertainty, stakeholder participation, scalability, interoperability, cybersecurity, and uncertainty regarding economic benefits. Existing studies provide valuable evidence regarding individual categories, but the relationships among these barriers remain insufficiently explored.

A further gap concerns the specific focus on construction supply chain management. While several studies investigate blockchain adoption in the general construction industry, supply chain management presents distinct challenges because adoption requires coordination among multiple independent organizations. The willingness of one organization to adopt blockchain may therefore depend on the readiness and participation of other organizations. Consequently, a barrier-based analysis that explicitly considers construction supply chain management can provide more targeted insights than a general assessment of blockchain adoption in construction.

Another important gap is the need to integrate technological, organizational, economic, contractual, regulatory, and human barriers within a unified framework. Existing studies have often examined selected categories of barriers or focused on specific applications. Although fuzzy MCDM approaches have been increasingly employed, further research is needed to comprehensively identify and prioritize barriers while considering their relative importance and interdependence.

Therefore, the present study extends the existing literature by focusing specifically on the barriers to blockchain adoption in construction supply chain management and by evaluating these barriers through a structured multi-criteria perspective. The study considers the uncertainty associated with expert judgments and recognizes that adoption barriers may influence one another. Such an approach can provide a more realistic representation of the adoption problem and help identify the barriers that should receive greater attention when developing strategies for blockchain implementation in construction supply chains.

3 | Research Methodology

Scientific research is a systematic, purposeful, and methodology-based process that seeks to investigate and explain phenomena and the relationships among them in order to generate, develop, and validate knowledge. In this process, after defining the research problem and formulating the research objectives and questions or hypotheses, the researcher must select the most appropriate research method according to the nature of the problem, type of data, and research objectives. Determining the statistical population, sampling method, data collection instruments, and data analysis techniques are also among the most important stages of research design. Appropriate selection of these components plays a decisive role in enhancing the validity, reliability, and generalizability of research findings.

Methodology constitutes the foundation of any scientific study, and the quality of research findings largely depends on the compatibility of the selected methodology with the objectives and nature of the research. Therefore, the selection of a research method is not merely an optional decision; rather, it depends on the type of research problem, intended objectives, characteristics of the study population, and available research resources. Employing an appropriate methodology provides the basis for obtaining valid, reliable, and meaningful findings that can adequately address the research questions.

The present study aims to identify, prioritize, and analyze the challenges associated with the implementation of blockchain technology in the construction industry. To achieve this objective, the Delphi technique is initially employed to identify, refine, and establish expert consensus regarding the relevant challenges. Subsequently, the Analytic Network Process (ANP) is used to determine the relative importance of the identified challenges and analyze the interrelationships among them. In this chapter, the research methodology and its implementation stages are first described. Subsequently, the statistical population, sample, and sampling method are presented. The data collection instruments and procedures, the measurement of the research variables, and the methods used for data analysis are then explained in detail.

In terms of its objective, the present study is classified as applied research. In terms of its implementation method, it is a descriptive-survey study, while in terms of data analysis, it adopts a mixed qualitative and quantitative approach.

The qualitative phase of the study focuses on identifying the challenges associated with implementing blockchain technology in the construction industry. These challenges are identified through a review of the existing literature and previous studies. The quantitative phase involves analyzing and weighting the identified criteria using a MCDM approach. This approach enables the relative importance of the identified challenges to be evaluated and provides a systematic basis for prioritizing them.

4 | Research Findings

4.1 | Delphi Section

In the first stage of this study, the Delphi technique was employed to identify, extract, integrate, and finalize the most important criteria and factors contributing to barriers to blockchain technology adoption in construction supply chain management. Due to its reliance on expert judgments and its ability to facilitate consensus among specialists, the Delphi technique is considered one of the most appropriate methods for identifying and validating indicators in exploratory studies and conceptual model development.

Accordingly, an expert panel was established using purposive sampling based on criteria such as specialized knowledge, academic and professional experience, practical experience in supply chain management, blockchain technology, and the construction industry. The panel consisted of 10 experts and specialists with diverse and relevant areas of expertise. Their opinions were collected and analyzed over several rounds. At the beginning of the Delphi process, an initial set of indicators and components was identified based on a comprehensive review of the research literature, previous studies, and expert opinions. Subsequently, these indicators were provided to the panel members for evaluation in terms of their importance, necessity, clarity, and relevance to the research topic. The Delphi process was conducted over three consecutive rounds. After each round, the results of the response analysis were presented to the experts, allowing them to reconsider, revise, or supplement their opinions based on an understanding of the views expressed by other panel members. This process continued until an acceptable level of consensus was achieved among the experts.

Ultimately, following the completion of the three Delphi rounds, 18 indicators grouped into four main dimensions were confirmed by the experts as the most important factors contributing to barriers to blockchain technology adoption in construction supply chain management. The results obtained from the Delphi process and the level of expert agreement regarding each indicator are presented in *Table 1*.

Table 1. Summary of the results of the first Delphi round.

Code	Sub-Criterion	N	Mean	SD	Variance	Range	Min.	Max.
A1	Scalability problems	20	3.35	1.34	1.18	0.40	1	5
A2	Integration problems	20	3.70	1.12	1.27	0.31	2	5
A3	Lack of standardization	20	3.90	0.91	0.83	0.23	2	5
A4	Deployment and implementation complexity	20	2.95	1.46	2.15	0.50	1	5
A5	Technological risks	20	3.70	1.08	1.16	0.29	2	5
A6	Cyberattack risks	20	1.20	1.11	1.25	0.36	2	5
A7	Lack of ICT infrastructure	20	3.35	1.22	1.50	0.37	2	5
A8	Limited interoperability and compatibility with other systems	20	2.60	0.94	0.88	0.26	2	5
B1	Lack of employee knowledge and training	20	3.30	1.17	1.37	0.36	2	5
B2	Lack of cooperation and trust among stakeholders	20	—	—	—	—	—	—
B3	Resistance to change and technology adoption	20	3.70	1.03	1.06	0.28	2	5
C1	Market-based risks	20	3.50	1.31	1.73	0.38	2	5
C2	High sustainability costs	20	3.05	1.05	1.10	0.34	2	5
C3	Low or no transaction fees	20	3.40	1.14	1.30	0.34	2	5
D1	Regulatory and legal uncertainties	20	3.20	1.54	2.37	0.48	1	5
D2	Privacy-related risks	20	2.95	1.46	2.15	0.50	1	5
D3	Use in the underground economy	20	3.10	1.25	1.56	0.40	1	5
D4	Contractual risks	20	3.35	1.34	1.18	0.40	1	5

In the first round of the Delphi technique, 18 indicators within four main components were presented to the experts for evaluation. At this stage, the experts assessed each indicator in terms of importance, relevance to the research topic, and necessity for inclusion in the model. The analysis of expert opinions showed that four indicators "deployment and implementation complexity," "cyberattack risks," "limited interoperability and compatibility with other systems," and "privacy-related risks" failed to achieve the predetermined threshold of agreement and consensus. Therefore, these indicators were removed from the initial model.

Accordingly, after the first round, the number of research indicators decreased from 18 to 14, while the number of main components remained four. The remaining indicators were then used as the basis for the second Delphi round to reassess the level of expert agreement and further refine the conceptual model. The indicators excluded during the Delphi process were removed based on the mean scores assigned by the experts.

Table 2. Results of the second Delphi round.

Code	Sub-Criterion	N	Mean	SD	Variance	Range	Min.	Max.
A1	Scalability problems	20	3.75	1.37	1.88	0.37	1	5
A2	Integration problems	20	1.50	1.54	2.37	0.48	2	5
A3	Lack of standardization	20	3.95	0.94	0.89	0.24	2	5
A5	Technological risks	20	1.35	1.31	1.73	0.38	1	5
A7	Lack of ICT infrastructure	20	3.35	1.22	1.50	0.37	1	5
B1	Lack of employee knowledge and training	20	3.65	1.30	1.71	0.36	2	5
B2	Lack of cooperation and trust among stakeholders	20	1.45	0.60	0.36	0.42	1	3
B3	Resistance to change and technology adoption	20	3.70	1.03	1.06	0.28	2	5
C1	Market-based risks	20	1.35	1.31	1.73	0.38	1	5
C2	High sustainability costs	20	3.40	1.14	1.30	0.34	1	5
C3	Low or no transaction fees	20	3.55	1.14	1.31	0.32	2	5
D1	Regulatory and legal uncertainties	20	1.85	1.50	1.26	0.49	1	5
D3	Use in the underground economy	20	3.10	1.25	1.56	0.40	1	5
D4	Contractual risks	20	3.75	1.37	1.88	0.37	1	5

In the second Delphi round, the 14 indicators remaining from the first round, categorized into four main components, were once again presented to the expert panel for evaluation. The experts reassessed their importance and relevance to the research objectives while considering the findings of the first round.

The results indicated that four indicators "integration problems," "lack of cooperation and trust among stakeholders," "market-based risks," and "regulatory and legal uncertainties"—failed to achieve the minimum required level of expert agreement. Consequently, these indicators were removed from the research model. At the end of the second round, the number of indicators decreased from 14 to 9, while the overall structure of the model, consisting of four main components, remained unchanged. The remaining indicators, having achieved an acceptable level of expert consensus, were used in the third Delphi round to finalize the research model.

Table 3. Results of the third Delphi round.

Code	Sub-Criterion	N	Mean	SD	Variance	Range	Min.	Max.
A1	Scalability problems	20	3.75	1.37	1.88	0.37	1	5
A2	Lack of standardization	20	3.95	0.94	0.89	0.24	2	5
A3	Lack of ICT infrastructure	20	3.35	1.22	1.50	0.37	1	5
B1	Lack of employee knowledge and training	20	3.65	1.30	1.71	0.36	2	5
B2	Resistance to change and technology adoption	20	3.70	1.03	1.06	0.28	2	5
C1	High sustainability costs	20	3.40	1.14	1.30	0.34	1	5
C2	Low or no transaction fees	20	3.55	1.14	1.31	0.32	2	5
D1	Use in the underground economy	20	3.10	1.25	1.56	0.40	1	5

D2	Contractual risks	20	3.75	1.37	1.88	0.37	1	5

In the third Delphi round, nine indicators within four main components were evaluated. No indicator or main component was eliminated at this stage. Therefore, all nine indicators and four main components were retained in the final model.

One of the fundamental requirements of the Delphi technique is to determine when an adequate level of agreement and consensus among experts has been achieved and, consequently, when the Delphi rounds should be terminated. One statistical approach for assessing the degree of agreement among experts is Kendall's coefficient of concordance. Accordingly, Kendall's coefficient of concordance was employed in this study to evaluate the consistency and agreement among the experts' opinions.

Table 4. Results of Kendall's coefficient of concordance test.

Delphi Round	Number of Indicators	Number of Experts	Kendall's W	df	Significance
First round	19	20	0.623	18	0.000
Second round	17	20	0.523	16	0.000
Third round	13	20	0.753	14	0.000

According to the results presented in *Table 4*, Kendall's coefficient of concordance in the first Delphi round was 0.623, indicating a satisfactory level of agreement and convergence among the experts' opinions. The significance level was 0.000, which is below the 0.05 threshold, indicating that the observed agreement was statistically significant. Accordingly, the indicators whose mean scores fell below the predetermined threshold were excluded from the model, while the remaining indicators were carried forward to the second Delphi round.

In the second round, Kendall's coefficient of concordance was 0.523. Although this value still indicated an acceptable level of agreement among the expert panel, a third round was conducted to achieve greater consensus and finalize the indicators.

In the third round, Kendall's coefficient increased to 0.753, indicating a substantial improvement in the degree of consensus and convergence among the experts compared with the previous two rounds. This result demonstrates that an appropriate level of agreement had been achieved among the panel members. It also suggests that the revisions and modifications made to the indicators throughout the Delphi process contributed to stabilizing the experts' opinions. Therefore, given the achievement of a satisfactory and stable level of consensus, the Delphi process was concluded after the third round, and the final validated indicators were used as the basis for subsequent analyses.

4.2 | Calculation of the Final Weights of the Indicators

The final weight of each sub-criterion is obtained by multiplying the weight of the main indicator associated with each sub-criterion by the corresponding sub criterion weight.

Table 5. Final weights of the sub-criteria.

Sub-Criteria	Technical and Infrastructure Challenges	Organizational and Human Resource Challenges	Economic and Financial Challenges	Legal, Security, and Governance Challenges	Final Weight
Scalability problems	0.21	0.123	0.25	0.106	0.174050
Lack of standardization	0.19	0.145	0.19	0.188	0.175183
Lack of ICT infrastructure	0.16	0.094	0.11	0.234	0.148450
Lack of employee knowledge and training	0.13	0.120	0.09	0.108	0.118833
Resistance to change and technology adoption	0.10	0.079	0.11	0.059	0.084483

High sustainability costs	0.08	0.116	0.09	0.075	0.089650
Low or nonexistent transaction fees	0.05	0.135	0.06	0.073	0.078183

Table 5. Continued.

Sub-Criteria	Technical and Infrastructure Challenges	Organizational and Human Resource Challenges	Economic and Financial Challenges	Legal, Security, and Governance Challenges	Final Weight
Use in the underground economy	0.04	0.094	0.05	0.071	0.067300
Contractual risks	0.04	0.093	0.05	0.086	0.063550

Based on the results presented in the table, the indicators influencing the barriers to blockchain technology adoption in construction industry supply chain management were prioritized according to their final weights. The results show that "Lack of Standardization," with a final weight of 0.175183, ranked first. This finding indicates that the absence of common standards and frameworks is considered the most important barrier to the adoption and implementation of blockchain technology in supply chain management from the experts' perspective.

In second place, "Scalability Problems," with a final weight of 0.174050, were ranked second, with only a very small difference from the first-ranked indicator. This finding demonstrates that technical limitations associated with network expansion and increased transaction-processing capacity are among the major concerns of experts regarding the implementation of this technology.

"Lack of Information and Communication Technology (ICT) Infrastructure," with a final weight of 0.148450, ranked third. This result indicates that the lack of adequate hardware, software, and communication infrastructure constitutes one of the most important barriers to the development and implementation of blockchain technology in construction industry supply chain management.

Furthermore, "Lack of Employee Knowledge and Training," with a final weight of 0.118833, ranked fourth. This finding highlights the importance of enhancing specialized knowledge, developing human resources, providing appropriate training, and increasing organizational awareness regarding the adoption of this technology.

Subsequently, "High Sustainability Costs," with a final weight of 0.089650, ranked fifth, while "Resistance to Change and Technology Adoption," with a final weight of 0.084483, ranked sixth. These findings indicate that, in addition to technical barriers, economic and behavioral factors also play a significant role in blockchain technology adoption.

Furthermore, "Low or Nonexistent Transaction Fees," with a final weight of 0.078183, ranked seventh; "Use in the Underground Economy," with a final weight of 0.067300, ranked eighth; and "Contractual Risks," with a final weight of 0.063550, ranked ninth. Although these indicators were considered less important than the other factors, they are nevertheless recognized by experts as influential barriers to blockchain technology adoption.

Overall, the prioritization results indicate that experts attach the greatest importance to technical and infrastructural barriers, particularly lack of standardization, scalability problems, and insufficient ICT infrastructure. In contrast, factors such as use in the underground economy and contractual risks received lower priorities. These findings indicate that addressing technical challenges, establishing common standards, and strengthening technological infrastructure should be prioritized in planning and policymaking related to the implementation of blockchain technology in construction industry supply chain management.

Table 6. Final weights of the indicators.

Component	Indicator	Final Weight of Indicator	Component Weight
Technical and infrastructure challenges	Scalability problems	0.17405	0.45
	Lack of standardization	0.175183	
	Lack of ICT infrastructure	0.14845	
Organizational and human resource challenges	Lack of employee knowledge and training	0.118833	0.25
	Resistance to change and technology adoption	0.084483	

Table 6. Continued.

Component	Indicator	Final Weight of Indicator	Component Weight
Economic and financial challenges	High sustainability costs	0.08965	0.16
	Low or nonexistent transaction fees	0.078183	
Legal, security, and governance challenges	Use in the Underground Economy	0.06730	0.14
	Contractual Risks	0.06355	

Based on the results presented in the table, the four main components of barriers to blockchain technology adoption in construction industry supply chain management were prioritized according to their final weights. The results show that "Technical and Infrastructure Challenges," with a final weight of 0.45, ranked first. This finding indicates that, from the experts' perspective, the most important barriers to blockchain technology adoption are related to technical issues, standardization, and the infrastructure required for implementing this technology. The presence of indicators such as lack of standardization, scalability problems, and insufficient ICT infrastructure within this component demonstrates its high importance compared with the other components.

The "Organizational and Human Resource Challenges" component, with a final weight of 0.25, ranked second. This result indicates that factors such as lack of employee knowledge and training, resistance to change, and resistance to technology adoption have the greatest influence on blockchain non-adoption after technical challenges. Therefore, developing employees' specialized knowledge, providing continuous training, and implementing effective change management can play an important role in increasing organizational readiness for the implementation of this technology.

The "Economic and Financial Challenges" component, with a final weight of 0.16, ranked third. This finding indicates that although economic issues, including the high costs of technology implementation and sustainability, as well as factors related to transaction fees, influence organizations' decisions to adopt blockchain, their importance was assessed as lower than that of technical and organizational challenges.

Finally, the "Legal, Security, and Governance Challenges" component, with a final weight of 0.14, ranked fourth. This component, which includes the indicator "Use in the Underground Economy," received the lowest weight among the main components. This finding suggests that although legal, security, and governance issues are among the concerns associated with blockchain technology adoption, they are considered by experts to have a lower priority than technical, organizational, and economic challenges.

Overall, the results indicate that more than half of the importance of the barriers to blockchain technology adoption is attributed to technical/infrastructural and organizational challenges. This finding demonstrates that successful implementation of blockchain technology in construction industry supply chain management primarily requires the development of technical infrastructure, formulation of common standards, enhancement of human-resource knowledge and skills, and creation of organizational readiness for the adoption of emerging technologies.

5 | Conclusion

The results of this study showed that "Technical and Infrastructure Challenges," with the highest final weight (0.45), constitute the most important barrier to blockchain technology adoption in construction industry supply chain management. This finding indicates that, from the experts' perspective, successful blockchain implementation depends more than any other factor on the availability of technical infrastructure, common standards, network scalability, and information technology readiness. In fact, even when economic and managerial incentives are present, the lack of adequate infrastructure can constitute the primary obstacle to implementing this technology. This finding is consistent with the results of previous studies. In a study conducted using the Fuzzy DEMATEL method, scalability problems, lack of standardization, and insufficient technical knowledge were identified as some of the most important barriers to blockchain adoption. The researchers emphasized that these barriers had the greatest interactions with other barriers and exerted a significant influence on the overall network of barriers. The results of that study also indicated that establishing common standards and developing information technology infrastructure are essential prerequisites for blockchain development in construction supply chains.

The second important finding of the present study was the ranking of "Organizational and Human Resource Challenges" in second place, with a weight of 0.25. This result indicates that the mere availability of technical infrastructure is not sufficient for blockchain adoption and that organizational readiness and human capital also play a decisive role in the successful implementation of this technology. Factors such as insufficient specialized knowledge among employees, the lack of targeted training programs, resistance to change, and a weak organizational culture can create significant challenges for the technology adoption process. This finding is also consistent with previous studies. In a study based on Fuzzy DEMATEL, "Lack of Employee Knowledge and Training" was identified as the most important barrier to blockchain adoption and obtained the highest value of the D+R index. The network of relationships among the barriers also showed that this factor was associated with all other barriers and that addressing it could reduce the effects of other barriers as well. Therefore, investment in training, development of digital skills, and organizational change management can play a key role in accelerating blockchain adoption.

The findings of the study also showed that "Economic and Financial Challenges," with a weight of 0.16, ranked third. This finding indicates that although the costs of implementing, maintaining, and developing blockchain technology—particularly costs associated with infrastructure, energy, and data processing—affect organizations' decisions, their importance is lower than that of technical and organizational challenges from the experts' perspective. This finding is consistent with the results of previous studies. Earlier research has identified high sustainability costs and the energy consumption associated with blockchain technology as influential factors. However, researchers have concluded that these factors are more strongly influenced by technical and infrastructural limitations and are therefore assigned a lower priority than technical and knowledge-related barriers. Accordingly, reducing technology-related costs without addressing technical problems and developing organizational capabilities would have a limited impact on expanding blockchain adoption.

Another finding of this study was the fourth-place ranking of "Legal, Security, and Governance Challenges," with a weight of 0.14. Although this component received the lowest weight among the main components, this does not imply that it is unimportant. Rather, it indicates that, from the experts' perspective, these challenges have a lower priority than technical and organizational issues during the early stages of technology implementation. This finding differs to some extent from previous studies. Some studies have identified privacy risks, regulatory uncertainty, and contractual risks as important barriers to blockchain adoption. However, those studies have also emphasized that a significant proportion of these challenges can be managed through the development of clear regulations, legal standards, and appropriate governance frameworks. Therefore, it can be argued that experts in the construction industry are more concerned with establishing technical infrastructure and enhancing organizational capabilities than with legal issues at the initial stage of blockchain implementation.

Overall, the findings of this study indicate that more than 70% of the importance of barriers to blockchain technology adoption is attributed to the two components of "Technical and Infrastructure Challenges" and "Organizational and Human Resource Challenges." This result demonstrates that successful blockchain implementation in construction industry supply chain management primarily requires the development of information technology infrastructure, formulation of common standards, improvement of system scalability, enhancement of employees' knowledge and skills, and creation of an organizational culture that supports innovation.

Only after these prerequisites have been established can economic, legal, and security-related barriers be expected to be managed more effectively, thereby creating the necessary conditions for the widespread adoption of blockchain technology in the construction industry.

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