A Roadmap for Overcoming Barriers to Implementation of Blockchain-Enabled Smart Contracts in Sustainable Construction Projects

Abstract

Purpose: This study delves into the challenges obstructing the integration of blockchain-enabled smart contracts (BESC) in the construction industry. Its primary objective is to identify these barriers and propose a roadmap to streamline BESC adoption, thereby promoting sustainability and resilience in building engineering.

Design/Methodology/Approach: Employing a unique approach, this study combines the Technology-Organization-Environment-Social (TOE + S) framework with the IF-Delphi-HF-DEMATEL-IFISM methodology. Data is collected through surveys and expert interviews, enabling a comprehensive analysis of BESC implementation barriers.

Findings: The analysis reveals significant hindrances in the construction industry's adoption of BESC. Key obstacles include economic and market conditions, insufficient awareness and education about blockchain technology among stakeholders, and limited digital technology integration in specific cultural and societal contexts. These findings shed light on the complexities faced by the industry in embracing blockchain solutions.

Originality: The research makes a significant contribution by combining the TOE + S framework with the IF-Delphi-HF-DEMATEL-IFISM methodology, resulting in a comprehensive roadmap to address barriers in implementing BESC in Sustainable Construction Projects. Noteworthy for its practicality, this roadmap provides valuable guidance for construction stakeholders. Its impact extends beyond the industry, influencing both academic discourse and practical applications.

Keywords: Construction projects; Blockchain technology; Smart contracts; Construction industry; Fuzzy sets theory.

1. Introduction

The construction industry (CI) significantly contributes to national economic development through infrastructure provision, employment generation, and economic growth (Gavish and Gavish, 2012), thus playing an instrumental role in shaping the building engineering landscape

(Umbenhauer and Younger, 2018). Moreover, the pivotal role of the construction industry in achieving sustainable development goals underscores its significance in the broader context of socio-environmental equilibrium (Awuzie and Monyane, 2020). However, the industry faces challenges such as low efficiency, inadequate payment methods, communication issues, and contract disagreements (Wuni and Shen, 2020), with its productivity estimated to be $1.6 trillion lower than other sectors (Tripoli and Schmidhuber, 2018), although implementing efficient contracting practices could enhance productivity by 8-10% (McKinsey Global Institute, 2017). Suffice it to state that the highly fragmented construction industry faces challenges relating to contracting. Traditional contracts, which are used to procure construction projects, involve extensive documentation and information. As a result, some contractual processes, such as preparing interim payment applications, can become inefficient, insecure, and prone to errors (Figueiredo *et al.*, 2022). Researchers, professionals, and industry leaders are starting to see digital technologies as a way to address contract-related challenges experienced in the construction industry. BESC has emerged as a potential solution to these challenges among the various technological innovations. BESC promotes transparency, accountability, and collaboration (Hunhevicz and Hall, 2020). BT can potentially create a more collaborative work environment for all parties involved in a project. BT provides immutability, security, and traceability, which can increase trust, minimize disputes, and ensure all parties are aligned (Zhang *et al.*, 2019). By automating contract transactions and replacing paper-based traditional contracts, BESC can improve the efficiency and security of contractual processes, reducing the risk of forgery and delays in communication between contracting parties(Singh and Prasath Kumar, 2022).

Smart contracts have a crucial application in automating transactions and payments in construction projects. Smart contracts enabled by BT can streamline transactions and payments within a project. These contracts allow for automated payments to all relevant parties once their obligations are fulfilled. The terms and payment schedules are pre-defined in the smart contract code before it is executed. A payment processing system is essential for addressing late or non-payments and adverse cash flow problems (Altay and Motawa, 2020). Smart contracts enabled by blockchain technology can improve cash flow and help manage cash flow problems in the construction industry (Hamledari and Fischer, 2021a). This is particularly beneficial for an industry that often struggles with cash flow issues.

Smart contracts can monitor and manage construction progress on the blockchain. The collapse of Carillion PLC in the UK, a significant construction and facilities management company, is an example of the severe consequences of cash flow problems. The company had £1.5 billion in late payments and was in debt. Carillion's collapse had a ripple effect throughout its supply chain because of its 120-day payment period (Sharma and Kumar, 2020). Blockchain technology can help solve these supply chain problems by holding funds centrally on a decentralized system and releasing them only when work is completed and verified, which reduces or eliminates intermediaries and make it less likely for clients and contractors to withhold payments, improving the chances of construction projects being completed as planned (Xu *et al.*, 2021).

In Past studies, the construction industry has been fascinated by the potential of blockchain-based smart contracts (BESC) for effective project management (Tezel *et al.*, 2020). In line with Sheng et al. (2020) recommends that the real-life examples showcasing their usage are limited, primarily due to a scarcity of research on their implementation in construction projects and the industry's unfamiliarity with the technology. This lack of practical examples has left the factors influencing the adoption or rejection of smart contracts in construction projects largely unknown. Additionally, the construction sector is known for its slow adoption of new technologies.

Addressing these challenges, this study focuses on exploring the perspectives of construction professionals regarding the key factors affecting the implementation of smart contracts, specifically BESC, at the project level. The aim is to uncover barriers hindering implementation and provide a roadmap for improvement. To evaluate these barriers comprehensively, our study employs two frameworks: the Technology-Organization-Environment-Social (TOE + S) framework and the IF-Delphi-HF-DEMATEL-IFISM (Hesitant Fuzzy-Decision Making Trial and Evaluation Laboratory- an Intuitionistic Fuzzy Interpretive Structural Modeling) framework. The integration of these frameworks aims to fill existing research gaps and achieve the following research objectives:

1. To identify the barriers to implementing BESC and classified into TOE + S framework.
2. To analyze the relationship between the identified barriers and their impact on implementing BESC.
3. To establish a structured hierarchy of hindrances negating BESC implementation.

4. To articulate a roadmap for overcoming the identified implementation barriers and evaluate its effectiveness in conquering these barriers.

The research makes a significant contribution to the field by uncovering the barriers to implementation, creating a roadmap to address them, and encouraging the use of BESC in construction projects. This roadmap can be useful for professionals and researchers looking to implement BESC in the construction industry. The study underscores the crucial role of standardization, trust-building, education and awareness, and regulation in ensuring the successful implementation of BESC in the construction sector.

Subsequent sections of this paper are as follows. Section 2 consists of an extensive review of relevant literature on BESC implementation barriers. Section 3 unveils a framework for evaluating the significance of these barriers to implementing BESC into construction projects. A justification and rendition of the research methodology used for the study, including data collection and analysis using the HF-DEMATEL-IFISM (Hesitant Fuzzy-Decision Making Trial and Evaluation Laboratory- an Intuitionistic Fuzzy Interpretive Structural Modeling) approach, are outlined in Section 4. Section 5 details a comprehensive analysis of the barriers, followed by in-depth discussions and implications of the results in Section 6. The articulation of a roadmap for overcoming these barriers is presented in Section 7. Section 8 provides a summary and conclusion of the study.

2. Literature review

Implementing BESC in the construction industry can revolutionize how construction projects are managed and executed (Chatterjee *et al.*, 2021). However, the implementation of this technology has its challenges. Various scholars have established a plethora of factors as negating the implementation of digital technologies in the construction industry (Aghimien *et al.*, 2022; Akinradewo *et al.*, 2022; Bajpai and Misra, 2022; Opoku *et al.*, 2023; Sepasgozar and Davis, 2018; Wang *et al.*, 2022). Other studies have focused on eliciting blockchain technology implementation barriers in the construction industry (Akinradewo *et al.*, 2022; Perera *et al.*, 2020; Sadeghi *et al.*, 2022; Xu *et al.*, 2021). Similarly, scholars have explored the implementation of smart contracts in the construction industry (Badi *et al.*, 2021; Li and Kassem, 2021; Mason, 2017; McNamara and Sepasgozar, 2021; Rathnayake *et al.*, 2022; Ye *et al.*, 2022) Furthermore, the barriers to the implementation of smart/intelligent contracts as well as BESC in the construction have been articulated in Ye et al., (2022) and A. McNamara & Sepasgozar, (2018) among others.

These scholars have adopted various approaches for categorizing the barriers to smart contracts and blockchain-enabled smart contract implementation. For instance, Akinradewo et al. (2022) used a principal component analysis to delineate blockchain implementation barriers in the South African construction industry into organizational, social, and technological clusters. In another study, Badi et al. (Badi *et al.*, 2021) relied on the technological, organizational and environmental (TOE) theoretical framework in classifying the determinants of smart contract implementation in the United Kingdom. Also, C. Li et al. (2022) applied the TOE theoretical framework in exploring the factors influencing the performance of blockchain technology in the construction industry. Impliedly, the use of the TOE framework for understanding blockchain-based smart contract implementation barriers appears to be gaining ascendancy recently. Aligning with this reality, this study adopts the TOE as a foundational theoretical framework for engaging with blockchain-enabled smart contract implementation barriers within the developing context, focusing on India.

2.1 The TOE framework

The Technology, Organization, and Environment (TOE) framework is a theoretical framework used in several past studies to identify barriers preventing organizations from achieving their goals (Ng *et al.*, 2022). The TOE framework is based on the idea that all organizations have a set of internal and external factors that can act as barriers to success (Sadiq Jajja *et al.*, 2021). These barriers can be categorized into three main categories: technical, organizational, and environmental, as seen in Figure E1 (Cruz-Jesus *et al.*, 2019). For brevity, the readers can refer to (Sadiq Jajja *et al.*, 2021; Ullah *et al.*, 2021) to grasp more about the TOE framework.

Technical barriers refer to the limitations that are inherent in the technology or systems that the organization uses (Bosch-Rekveldt *et al.*, 2011). For example, an organization may be using outdated technology that is not capable of meeting the needs of the organization. Organizational barriers refer to inherent limitations in structure, culture, and processes. These include poor communication, lack of collaboration, or clear roles and responsibilities (Ali and Kidd, 2015; Shukla and Shankar, 2022) Environmental barriers refer to the limitations imposed by the external environment, such as regulations, competition, or economic conditions (Dadhich and Hiran, 2022).

The TOE (Technology, Organization, and Environment) theoretical framework provides a holistic approach to understanding the barriers to implementation and how they interact and affect each outlined in Figure C1 (See in Appendix C).

In summary, the utility of the TOE framework for barrier identification for identifying barriers that organizations may face in achieving their goals has been highlighted (Abed, 2020). However, other authors have argued about adding the personal or social component to the TOE framework. For instance, Akinradewo et al. (2022) and Huang et al. (2022) posit the significance of the social facet to implementation in organizations besides the conventional technical, organizational and environmental factors embodied in the TOE framework. These personal or social barriers refer to the limitations imposed by the individuals within the organization, such as a lack of skills, motivation, or commitment (Basloom *et al.*, 2022). Therefore, this study adopts the TOE + S theoretical lens for exploring the phenomenon being understudied in this study. Detailed explanation of TOE + S based barriers are in appendix A.

2.2 Identification of Blockchain-based smart contract implementation barriers.

The journey to unravel the depths of research in construction projects and decision sciences begins with an initial pilot search of extant literature. The researchers delved into the vast pools of knowledge in two of the most prominent databases, Scopus and Web of Science. With its vast repository of journal articles, Scopus proved to be the biggest of the two (Norris & Oppenheim, 2007). According to Comerio & Strozzi (2019), the publication coverage in Scopus was a whopping 60% more comprehensive compared to the Web of Science. The PRISMA guidelines guided the search process, and articles were selected based on their content. Adding keywords to the Scopus database led to the discovery of 2673 articles. The researchers restricted their search to English-language articles to ensure the language, source, and document type were consistent.

As a result, 307 articles were found in the Scopus database, categorized into two subjects - 'construction projects and industry' and 'decision sciences.' Web of Science, on the other hand, produced 161 articles through the keyword search. The language and publication type were further restricted to English and academic journals, respectively, resulting in 69 results. Snowballing and cross-referencing added 29 more articles to the pool, and after removing duplicates, the researchers were left with 329 documents. However, the journey was far from over. The abstract screening process saw 243 documents being excluded, and after a thorough screening of the remaining articles, only 67 were found to be relevant to the research. The PRISMA flow diagram, as shown in Figure C2 (see in Appendix C), portrays the method of selection and exclusion of studies in the research process.

2.2.1 Technological barriers

Technological barriers are perhaps the most obvious, as they relate directly to technology. One of the main technological barriers to implementation is construction professionals' complexity and lack of understanding of blockchain technology. This lack of understanding can lead to a lack of trust in the technology and a reluctance to adopt it (Aslam *et al.*, 2022; Singh, Kumar, Hu, *et al.*, 2023). Another technological barrier is the inadequate infrastructure and technical capabilities to support BESC (Sanka *et al.*, 2021). Construction companies need the hardware and software to implement blockchain-based smart contracts, which can be a significant cost (Upadhyay, 2020). Additionally, the current blockchain technology is not fully developed, and it still has limited scalability, privacy, and security concerns which can be a barrier (Roth *et al.*, 2022).

2.2.2 Organizational barriers

Organizational barriers are also a significant challenge when implementing blockchain-based smart contracts. One of the main organizational barriers is resistance to change, as many construction companies are reluctant to adopt new technologies, especially untested and unproven. This can be a major obstacle to implementation, as it can be difficult to get buy-in from the organization's leadership (Sharma *et al.*, 2021). Another organizational barrier is the lack of standardization and guidelines for implementing blockchain-based smart contracts. Without clear standards and guidelines, construction companies may struggle to know how to implement the technology and may be hesitant to do so (Ji *et al.*, 2022). Additionally, regulatory challenges and compliance issues can be a major concern for construction companies, as they may be unsure how to comply with existing regulations regarding BESC (Dong *et al.*, 2021; Singh, Kumar, Shoaib, *et al.*, 2023).

2.2.3 Environmental barriers

Environmental barriers are also a significant challenge when it comes to the implementation of BESC in the construction industry. One of the main environmental barriers is the limited industry-wide implementation and the need for more standardization. With a critical mass of companies using blockchain-based smart contracts, it can be easier for individual companies to justify the cost of implementation (Singh, Kumar, Irfan, *et al.*, 2023; Werner *et al.*, 2021). Another environmental barrier is the lack of government support or regulation. Without government support, construction companies may be hesitant to implement BESC, as they may be unsure how to comply with existing regulations (Sheng *et al.*, 2020). Additionally, the lack of trust among stakeholders and understanding of the benefits of BESC can be a significant barrier to implementation (Espinoza Pérez *et al.*, 2022; Singh, Kumar, Dehdasht, *et al.*, 2023).

2.2.4 Social barriers

Social barriers also play a significant role in hindering the implementation of BESC in construction projects. One significant challenge is the lack of trust and collaboration among stakeholders in the industry (Celik *et al.*, 2023). The construction industry is known for its complex supply chain, and many parties involved may not trust each other (Govindan, 2022; Mani *et al.*, 2022; Parmentola *et al.*, 2022). This lack of trust can make it challenging to implement blockchain technology, which requires trust and transparency to function effectively (Sigalov *et al.*, 2021). Another social barrier is resistance to change. The construction industry is often slow to implement new technologies, and BESC is no exception. Many construction professionals may resist changing their traditional way of doing things, which could hinder the implementation of this new technology. Furthermore, the lack of standardization in the construction industry is also a social barrier to implementing BESC. Creating smart contracts that work across different projects and organizations can be challenging without standardized processes and procedures. Overall, while BESC has the potential to revolutionize the construction industry, several barriers to implementation must be overcome. The TOE + S framework provides a holistic approach to understanding these barriers and how they interact and affect each other. By addressing these barriers, construction companies can pave the way for the successful implementation of BESC and reap the benefits of this innovative technology.

2.3 Point of departure

An examination of pertinent literature underscores the implementation of smart contracts across diverse industries for structured data processing and issue resolution (Hamledari and Fischer, 2021b). Integrating smart contracts and blockchain technology has garnered heightened attention among researchers and practitioners (Björklund and Vincze, 2019; Hamledari and Fischer, 2021c). Nevertheless, incorporating blockchain-enabled smart contracts (BESC) remains nascent in the construction sector. This inference is drawn from the contemporaneous nature of related literature. Notably, minimal research has been conducted on BESC within developing countries like India. Addressing this void, the current study aims to delineate and assess the barriers impeding BESC implementation within an Indian construction company. This endeavor is accomplished through the application of the TOE + S theoretical framework and the HF-DEMATEL-IFISM approach. Furthermore, this study's distinctiveness lies in its presentation of relationships between identified barriers through causal diagrams, which bestows a novel perspective on the subject matter.

3. Method

This research employed a hybrid approach that combined three techniques: Intuitionistic Fuzzy Delphi (IF-Delphi), Hesitant fuzzy-DEMATEL, and IF-ISM methods. The following sections provide an overview of each technique and explain the reasoning behind their integration.

3.1. Background of Delphi method

Delphi is commonly used as a group-based process when experts cannot agree on a proposal due to limited or unclear information. Trivedi et al. (Trivedi *et al.*, 2021) pointed out that the methodology initially developed by (Rouhanizadeh & Kermanshachi, 2022) has gained popularity as a useful approach for making well-informed decisions when the objectives and criteria are unclear. A classic Delphi approach involves experts giving numerical judgments of their subjective opinions, resulting in confusion, vagueness, and uncertainty (Durdyev *et al.*, 2018). The Intuitionistic Fuzzy Delphi (IF-Delphi) technique was developed by Sadeghi et al. (2023) to address these issues. Triangular or trapezoidal fuzzy numbers are commonly used to analyze these opinions, which are derived from experts' opinions expressed in natural language. Both the fuzzy Delphi and Delphi techniques have been applied in various fields, including engineering (Chatterjee *et al.*, 2021), business (Gölcük and Baykasoǧlu, 2016), technology (Mattoni *et al.*, 2020), public transit mode choice (Nguyen and Robinson Fayek, 2022), and education (Tawalare *et al.*, 2020). The purpose of this study was to identify the barriers to the implementation of BESC in construction using the IF-Delphi method.

3.2 Background of Fuzzy Hesitant DEMATEL technique

The hesitant fuzzy DEMATEL method is a well-established tool widely used in previous research studies to analyze barriers. This method is based on the traditional DEMATEL method, a causal analysis technique that helps identify the interdependencies and relationships among different factors (Erol *et al.*, 2022). However, the hesitant fuzzy DEMATEL method goes beyond the traditional DEMATEL method by incorporating the inherent uncertainty and subjectivity in the studied barriers. The hesitant fuzzy DEMATEL method typically involves the construction of a causal network that represents the interdependencies and relationships among the barriers. The causal network is then analyzed using mathematical modelling and fuzzy logic techniques to identify the most important barriers and their relationships (Zhou *et al.*, 2021). The analysis is based on the hesitant fuzzy preference relations of the barriers, which allow for the incorporation of uncertainty and subjectivity into the analysis. One of the key benefits of the hesitant fuzzy DEMATEL method is that it enables the analysis of conflicting opinions and viewpoints, which is crucial for achieving a comprehensive understanding of the barriers and their interdependencies. The method also allows for the prioritization of actions based on their potential impact, taking into account the conflicting opinions and viewpoints of the stakeholders (Chen *et al.*, 2022).

3.3 Background of Interpretive Structural Modeling (ISM) method

An ISM extracts the relationships between variables and schematizes them in a graphic model, but it does not account for the strength of these relationships (Trivedi et al., 2021). Using the fuzzy method and ISM, this limitation can be overcome. A variety of fields have benefited from the use of ISM, including mine production safety (Trivedi *et al.*, 2021), safety behaviour planning (Tan *et al.*, 2019), supplier selection (Arif *et al.*, 2019), fire investigation (Kumar and Dixit, 2018), construction (Kannan *et al.*, 2009), and OHSAS 18001 implementation. ISM has many applications in fields such as mine production safety, safety behaviour planning, supplier selection, fire investigation, construction (Kouhizadeh *et al.*, 2021), and OHSAS 18,001 implementation (Erol *et al.*, 2022). DEMATEL lacks an in-depth analysis of the interrelationships of factors, making ISM superior (Yadav *et al.*, 2022). This study used the IF-ISM method to establish the hierarchical structure of the barriers to implementing BESC in construction projects.

3.4 The proposed hybrid algorithm

The research design of this study unfolds in four key steps, each strategically chosen to comprehensively investigate and analyze barriers to the implementation of BESC in construction projects. The initial step involved gathering information on these barriers through an extensive literature review and consulting experts using the IF-Delphi method. This combination ensured a thorough understanding of the current landscape and expert insights. Moving on to the second stage, the authors employed expert scoring to create original matrices, quantifying the influence degree and properties of the identified barriers. The Hesitant fuzzy-DEMATEL method was specifically chosen for its ability to handle uncertainty and hesitancy in expert judgments, providing a robust foundation for evaluating the relationships among barriers.

In the third stage, the authors utilized the ISM method to further analyze the hesitant fuzzy-DEMATEL results. This step aimed at determining the hierarchical structure and relationships between the identified barriers, offering a deeper understanding of their interconnections. The combined use of IF-Delphi, Hesitant fuzzy-DEMATEL, and IF-ISM methods in this study was intentional, as it allowed for a systematic, multi-method approach that leverages the strengths of each technique. IF-Delphi ensured a comprehensive exploration of barriers, Hesitant fuzzy-DEMATEL handled the uncertainty inherent in expert judgments, and IF-ISM delved into the hierarchical relationships, collectively providing a nuanced and thorough analysis of BESC implementation barriers in construction projects. This methodological choice was driven by the need for a robust, holistic approach to uncover, evaluate, and understand the complexities surrounding BESC implementation in the construction industry.

Finally, the authors examined the results and provided a roadmap for improving the implementation and implications of the study. The framework, specific processes, and contents of the study are illustrated in Figure 1. Appendix A outlines the IF-Delphi method, hesitant fuzzy sets transformation, hesitant fuzzy DEMATEL technique, and IFISM methodology employed in the study, providing a comprehensive step-by-step explanation of each.

3.1.1 Stage 1: Identify barriers to the implementation of BESC

During this stage, the barriers to implementing BESC in construction projects are identified through a comprehensive analysis of relevant literature and industry reports. A step in the implementation process of BESC in construction projects is to identify the most critical factors that hinder their implementation. A five-point linguistic Likert scale is employed in an IF-

Delphi questionnaire to assess the significance of the identified barriers ("No influence," "Low influence," "Medium influence," "High influence," "Very high influence").

A group of experts is selected, and the questionnaire is circulated to them for evaluation. According to Kumar et al. (2023) and Mohandes et al. (2022), a group of eight to twelve individuals with sufficient knowledge and experience in the relevant field was considered adequate to conduct the study.. In this research, construction organizations specializing in smart contract implementation in construction projects are chosen as experts. To reach a consensus, the difference between each expert's opinion and the average of all expert opinions should be computed using Table 1; then, the difference should be calculated using sub-steps 1-4 (see in appendix A).

4. Results

4.1 Data collection Protocol

A literature review and analysis of industrial reports were conducted to identify the barriers to implementing BESC in construction projects. This resulted in the identification of four TOE + S framework categories - technological barriers, organizational barriers, environmental barriers and social barriers- as the most significant. Initially, 47 factors were identified and sorted into three categories. Table 1 shows that 30 barriers were approved after consulting three industry project managers with at least seven years of experience.

To identify the implementation barriers of BESC in construction projects, an IF-Delphi questionnaire was developed and a total of 16 experts were selected based on their qualifications, designations, and years of experience in the field (see in Figure 2). These experts include project managers with diverse backgrounds and qualifications. Among them, 10 experts hold a Bachelor of Science (BSc) degree, while the remaining 6 experts possess a Master of Science (MSc) degree. Their designations are consistent, with all of them working as project managers. The years of experience range from more than 20 years to 7 to 10 years, ensuring varied expertise and practical knowledge. This selection of experts with different qualifications, designations, and experience levels aims to capture various perspectives and insights on the barriers to blockchain-enabled smart contracts implementation in the construction industry. An evaluation scale based on linguistic Likert points was used to assess their significance for each barrier. Any disagreements among the experts were resolved after the questionnaire results were collected. The managers were then asked to review and revise their previous opinions, leading to the obtainment of the importance of each barrier (see in Table 1).

A pairwise comparison questionnaire was created and sent to the experts to analyze the impact of these barriers on each other. Based on an intuitionistic fuzzy linguistic scale, the experts assessed the direct relationship between the factors. Regularly evaluating the effectiveness of a roadmap to improve implement BESC into construction projects is crucial to ensure that the implementation of BESC is successful. To obtain feedback on the plan's effectiveness, a Likert scale is often used to measure attitudes, opinions, and perceptions (Durdyev *et al.*, 2022; Tabatabaee *et al.*, 2019). This allows stakeholders, including contractors, architects, and engineers, to provide valuable insights into the progress and impact of the strategy (see in Figure 2). Experts' opinions are also sought to gauge the plan's efficacy by rating it on a scale of 1 to 10.

4.2 Findings

A thorough review of the relevant literature and industry reports identified 30 BESC implementation barriers in the construction industry. These factors were subsequently classified into four categories: technological (6 barriers), organizational (5 barriers), environmental (5 barriers) and social (5 barriers). An IF-Delphi method was used to screen these factors further, resulting in 21 main factors that received at least 86% of the points with a threshold limit value of 0.56, as shown in Table 1.

4.2.1 Findings from fuzzy-DEMATEL

For the fuzzy DEMATEL analysis, a total of 37 experts were carefully selected based on their qualifications, designations, and years of experience in the field (see in Figure 2). These experts comprise project managers who bring a diverse range of knowledge and expertise to the study. Out of the 37 experts, 22 hold a Bachelor of Science (BSc) degree, while the remaining 15 possess a Master of Science (MSc) degree. All of them share the common designation of Project Manager, ensuring consistency in their professional roles. The years of experience among the experts span a wide range, with some having more than 20 years of experience, while others have between 7 to 10, 11 to 14, or 15 to 18 years of experience. With their varied qualifications, designations, and experience levels, this diverse group of experts provides a comprehensive and well-rounded perspective on the barriers to be considered in implementing blockchain-enabled smart contracts in the construction industry. Table B1 displays the total relation matrix. Table 2 presents a comprehensive overview of the net causes and net effects corresponding to each retained barrier. The arrangement of the 16 chosen barriers is delineated in Figure 3, structured according to their net cause scores.

In Table 2 and Figure 2, it becomes evident that construction professionals face their most significant challenge in understanding the intricate nature of blockchain technology. This is closely followed by the complexity of blockchain itself, limited leadership support, and challenges related to cultural integration. Factors like standardization, technical expertise, and market conditions have a lesser impact on BESC adoption. Resistance to change also hinders implementation. Figure 3 visually depicts 21 barriers, with the vertical axis representing net cause and the horizontal axis indicating net effect, allowing for a clear positioning of each barrier in terms of its impact on BESC implementation.The findings from Table B2 and Figure C3 paint a picture of the challenges facing the widespread implementation of BESC. Out of the 21 hindrances studied, an equal number can be attributed to root causes and consequences. When it comes to the barriers with the greatest impact, it's evident that the effects are substantial. The lack of infrastructure and technical expertise, restrictions on scalability, worries about privacy and security, scarcity of trained professionals, sparse industry-wide acceptance, distrust among those involved, insufficient awareness of the advantages, and economic strain or shortage of funds are all counted among the top five effect barriers. Table B3 summarizes the average scores for each category of barriers within the TOE + S framework, as viewed through a categorical construct level. The categories are arranged in order of the average barriers score within each category.

Table B3 shows that the social, organizational and technological barriers have the highest average scores, while environmental barriers have the lowest average. This suggests that implementing BESC in construction projects is mainly driven by the benefits offered by the technology compared to other existing technologies, such as improved data integrity, increased data availability, reduced transaction costs, and pressure from customers and government authorities. On the contrary, the preparedness of the environment exhibits minimal influence on the decision to implement BESC. This implies that BESC adoption might proceed irrespective of environmental barriers and could potentially instigate broader environmental transformations. This discovery is bolstered by prior studies on digital transformation, which have highlighted that the implementation of new technologies often culminates in environmental digitalization.

4.2.2 Findings from ISM

Table B4 elucidates the hierarchical structure of barriers to BESC implementation within construction projects. The designated level for each barrier corresponds to its interconnectedness and influence over other barriers. While certain barriers exert substantial influence on higher-level barriers (Level 1), their impact from higher levels is relatively marginal. These barriers share common intersection and reachability attributes.

Figure C4 and Table B4 collectively present the hierarchical arrangement of barriers, a product of the IFISM methodology employed. These barriers are categorized across ten levels, each representing the extent of impact on other barriers. Level 1 encompasses barriers that are shaped by other barriers while exerting minimal influence on BESC implementation. In our study, barriers E6, S1, S2, S4, and S7 were allocated to Level 1. Higher-level barriers, such as those at Level 10, significantly disrupt BESC implementation and subsequently influence barriers across diverse levels. These higher-level barriers typically function as the fundamental catalysts for implementation challenges. For instance, barriers T1 and O1 were positioned at Level 7, indicative of their substantial influence on BESC implementation within construction projects.

The insight into obstacles impeding BESC implementation in construction projects is encapsulated within Figure 4. This visual representation underscores the pivotal roles of T1, O1, and T3 as key barriers characterized by robust driving forces and low dependence. This delineates their profound impact on inhibiting BESC implementation within the construction sector. Furthermore, Figure 4 illustrates that T1, O1, T2, T3, T4, T8, and E10 inhabit the quadrant of linkage variables due to their elevated driving power and instability. This signifies that changes in these variables possess the potential to substantially influence the entire system. On the other hand, O7, E8, E10, E6, S7, S1, and S2 are categorized as dependent variables because of their high dependence power but low driving power. Also, S5, O2, O3, E1, E2, O5 and S4 fall into the autonomous variable’s quadrant due to their low driving and dependence power. These barriers have varying levels of drive/dependence power and are considered important regarding their impact and effectiveness. In the independent quadrants, none of these factors belongs.

4.3 The Implementation Improvement Roadmap

The roadmap in this study seeks to conquer the obstacles blocking the integration of BESC into the construction sector. It entails the participation of essential stakeholders, crafting a solution specifically for the construction industry, and educating and assisting professionals in the field. By executing this roadmap, as depicted in Figure 5, the construction industry will be able to maximize the perks of blockchain technology, such as heightened transparency, augmented efficiency, and diminished expenses.

4.3.1 Effectiveness of the proposed roadmap

Ongoing assessment of the efficacy of integrating BESC into construction projects holds paramount importance. Valuable insights into the strategy's advancement and influence can be gleaned through surveys, interviews, and focus groups involving key stakeholders. Essential for gauging progress, impact assessments offer a robust mechanism for informed decision-making and refinement of the plan. In-depth interviews and focused group discussions enable pinpointed feedback and the opportunity for follow-up inquiries. Rigorous analysis of collated data and feedback is pivotal to comprehensively grasp the plan's effectiveness and to identify domains warranting additional attention.

Employing a Likert scale is a common practice to solicit feedback, utilizing statements and response options to gauge attitudes, opinions, and perceptions. This approach facilitates quantification and comparison of feedback across diverse stakeholders—ranging from contractors to architects and engineers—thus highlighting successful aspects of the plan. Recent expert polling sought to evaluate the efficacy of a roadmap designed to enhance BESC implementation within the construction sector. Experts were requested to rate the roadmap's effectiveness on a scale of 1 to 3, where one signifies low effectiveness and ten indicates high effectiveness. The poll's outcomes, derived from input received from 7 stakeholders, are succinctly presented in Table B5.

Analyzing responses from stakeholders spanning contractors, architects, and engineers unearthed insights into the roadmap's pronounced effectiveness. This evaluation elucidated areas where the roadmap yielded the most substantial impact and illuminated pathways for further enhancement, all aimed at elevating its overall efficacy.

5. Discussion

This section explores the outcomes from the previous section in greater detail by examining the overall impact of the barriers based on the categorization provided by the TOE + S framework discussed in Section 3. Our focus here is on the most significant barriers and how they interact and influence the rest of the system.

BESC in construction projects faces several challenges that must be overcome to enable successful implementation. The top five barriers, as revealed by Table 4, include the complexity and lack of understanding of blockchain technology among construction professionals, the absence of standards and guidelines, incompatibility with current systems and software, limited interoperability between blockchain platforms, and regulatory difficulties. To understand the impact of these barriers, we can analyze the total relation matrix (T). However, due to many barriers, we will focus on the most crucial relationships using a threshold value, a commonly used technique in DEMATEL-related studies. The values remaining in the total relation matrix (T) are presented in Table B4.

Efficient implementation of BESC within construction projects necessitates the identification and resolution of impediments. The TOE + S framework, encompassing technology, organization, and environment, offers a valuable perspective for comprehending these obstacles. In the context of blockchain's role in construction, two pivotal barriers come to light. Firstly, there exists an awareness gap and lack of familiarity with this technology among construction professionals. Addressing this entails targeted education and training initiatives to empower them with the requisite insights for harnessing blockchain's potential. Secondly, the absence of uniformity and compatibility across diverse blockchain platforms hinders progress. To mitigate this, the establishment of industry-wide norms and guidelines holds the key to seamless integration and cross-industry collaboration.

A significant challenge emerges in the form of diminished stakeholder trust, which can be ameliorated by employing the HF-DEMATEL-IFISM method to discern critical relationships and devise trust-building strategies. Furthermore, the uncertain legal and regulatory landscape necessitates engagement with governmental and regulatory entities to establish a clear and facilitative framework. The pathway to success involves tackling these barriers through targeted educational initiatives, standardization efforts, fostering collaboration, and proactive engagement with legal entities. With these initiatives in place, the construction industry stands to reap the substantial benefits of blockchain technology, including heightened transparency, efficiency gains, and cost reduction.

5.1 Implications of findings

This study offers a comprehensive understanding of the obstacles hindering the implementation of BESC in construction projects, such as the absence of standardization, lack of trust, insufficient education, and inadequate regulation. With this understanding, practitioners and researchers can develop effective plans to overcome these barriers and promote using BESC in the construction sector. The proposed roadmap for conquering these barriers includes recommendations for standardization, trust-building, education, and a supportive regulatory framework, which can guide professionals and researchers seeking to introduce BESC in construction projects. This roadmap can help navigate the complex process of implementing these technologies and ensure their success.

From a practical perspective, this study makes a salient contribution to the practical implication of this research is the potential for improved project governance and contract management in the construction industry through the implementation of BESC. By leveraging blockchain technology's transparency, immutability, and automation features, BESC can enhance trust, streamline processes, and mitigate disputes in project contracts. This practical implication suggests that construction companies can adopt BESC to revolutionize their project management practices, ensuring more efficient and reliable execution of contracts, reducing administrative overhead, and enhancing overall project outcomes. This implementation can contribute to the industry's digital transformation and pave the way for increased efficiency, accountability, and collaboration among project stakeholders.

Theoretically, the study makes a salient contribution to the TOE framework by adding the social nexus. The TOE has been extensively deployed in previous literature to understudy implementation enabling or deterring factors within organizations. However, the tendency for the impact of the social components on the implementation process to be left underexplored through the TOE framework was observed, hence the decision to incorporate the social component into the extant framework, resulting in the TOE + S framework. This relevance of the addition to the TOE framework was validated in the current study and can be applied in further studies seeking to study phenomena relating to organizational implementation performance.

Overall, the study provides valuable insights for practitioners and researchers in the construction industry, offering a clear understanding of the barriers to implementing BESC, a roadmap to overcome these barriers, and an appreciation of the potential benefits of these technologies. Additionally, the study suggests essential areas for future research, which can further advance our understanding of these technologies in the construction sector.

6. Conclusion

This research study investigates the barriers to implementing BESC in construction projects using a hybrid hesitant fuzzy-based algorithm. The study gathered data from qualified experts having rich experience in the application of BT within the realm of construction projects. From the results obtained, the following conclusions are noted:

1. Based on a comprehensive literature review and industry reports, 30 BESC implementation barriers in construction were identified and categorized into technological, organizational, environmental, and social factors. Through the IF-Delphi method, 21 main factors emerged, meeting a threshold of at least 86% points and a limit value 0.56.
2. The average scores indicate that social, organizational, and technological barriers are prominent, highlighting the dominance of BESC implementation driven by its benefits like enhanced data integrity, increased availability, reduced costs, and pressure from customers and authorities. In contrast, environmental barriers exhibit the lowest average, indicating lesser influence in construction projects.
3. The matrix analysis reveals that T1, O1, and T3 are the key barriers hindering BESC implementation, with a strong driving force and low dependence. T1, O1, T2, T3, T4, T8, and E10 fall into the linkage variables quadrant, indicating high driving power and instability. O7, E8, E10, E6, S7, S1, and S2 are dependent variables, while S5, O2, O3, E1, E2, O5, and S4 are autonomous variables. None of these factors falls into the independent quadrants, underscoring their varying levels of impact and effectiveness.
4. A roadmap was developed based on the findings, suggesting standardization, trust-building, education, and regulatory framework to address the identified barriers. The roadmap was validated through case studies and field experiments, demonstrating its effectiveness in overcoming barriers and promoting BESC implementation in the construction industry.

6.1 Limitations and Future research

This study delves into the implementation of BESC in the construction sector, highlighting key findings and proposing a roadmap. However, it is essential to acknowledge certain limitations. The study's applicability may be confined to the construction industry, limiting its relevance across diverse sectors. Additionally, the reliance on questionnaire surveys and expert interviews introduces a potential bias due to the restricted sample size, raising concerns about the representativeness of stakeholders involved in BESC implementation. The subjective nature of researchers and experts may also influence barrier selection and proposed solutions, emphasizing the need for cautious interpretation. Considering the dynamic nature of technology, the identified challenges and solutions may become outdated over time.

To address these limitations, future research avenues should be explored. Comparative analyses across industries can uncover industry-specific hurdles, while longitudinal studies and case analyses provide insights into the evolving landscape of BESC implementation. The integration of emerging technologies like the Internet of Things (IoT) and Artificial Intelligence (AI) must be considered, and cultural dynamics across regions should be explored for effective strategy tailoring. By carefully addressing these limitations and pursuing these research directions, a more comprehensive understanding of BESC integration in construction can be achieved, potentially influencing broader technological advancements across industries.

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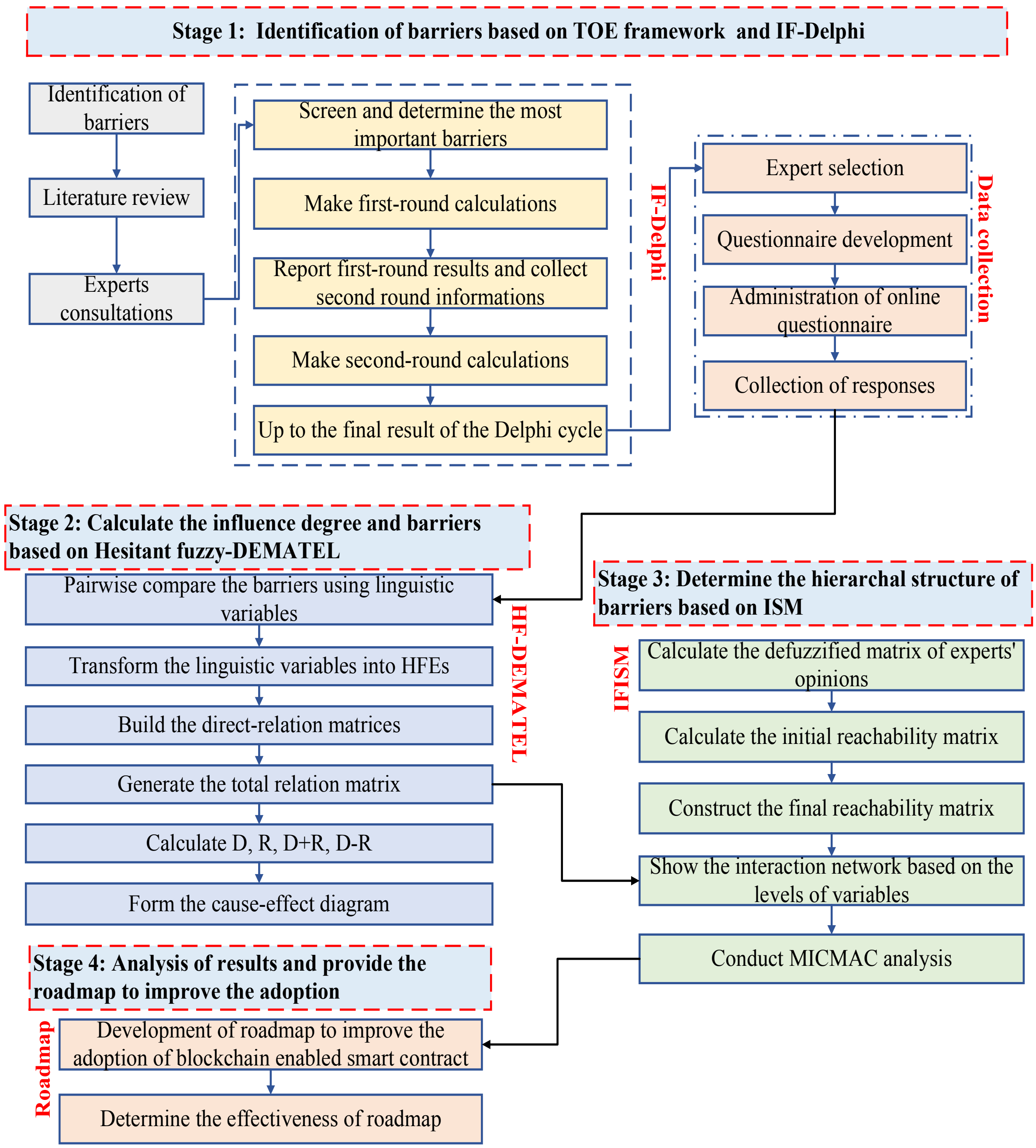

Figure 1: The research framework

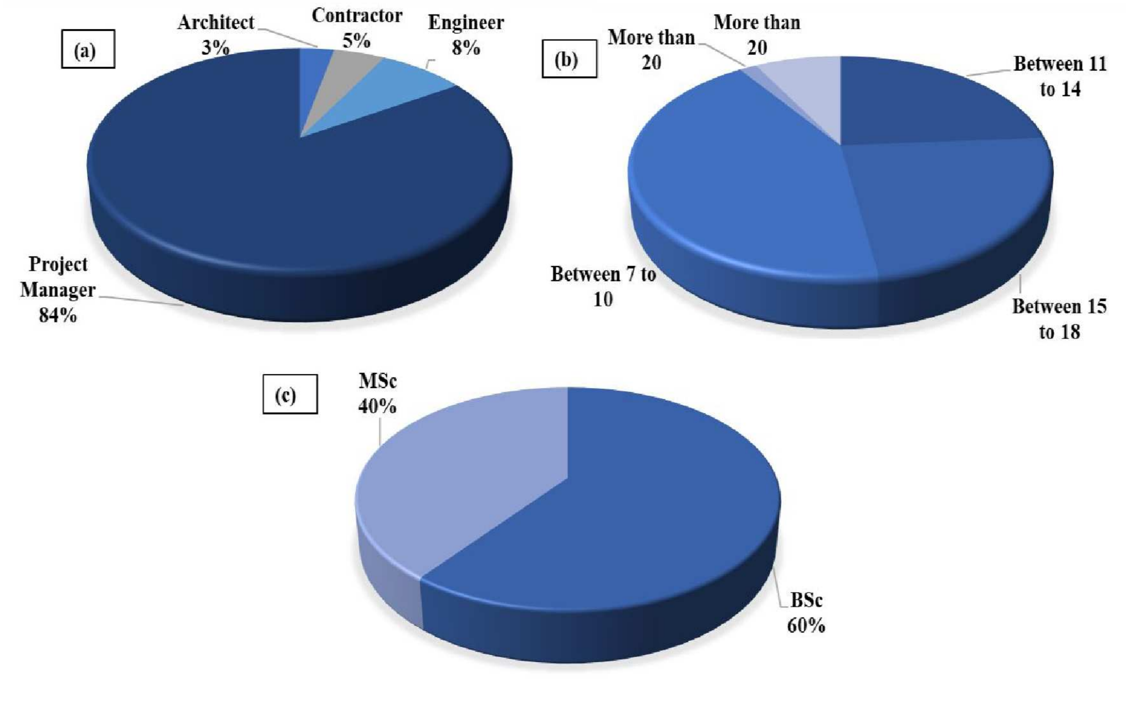

Figure 2: Expert details for the study: (a) designation, (b) years of experience and (c) degree.

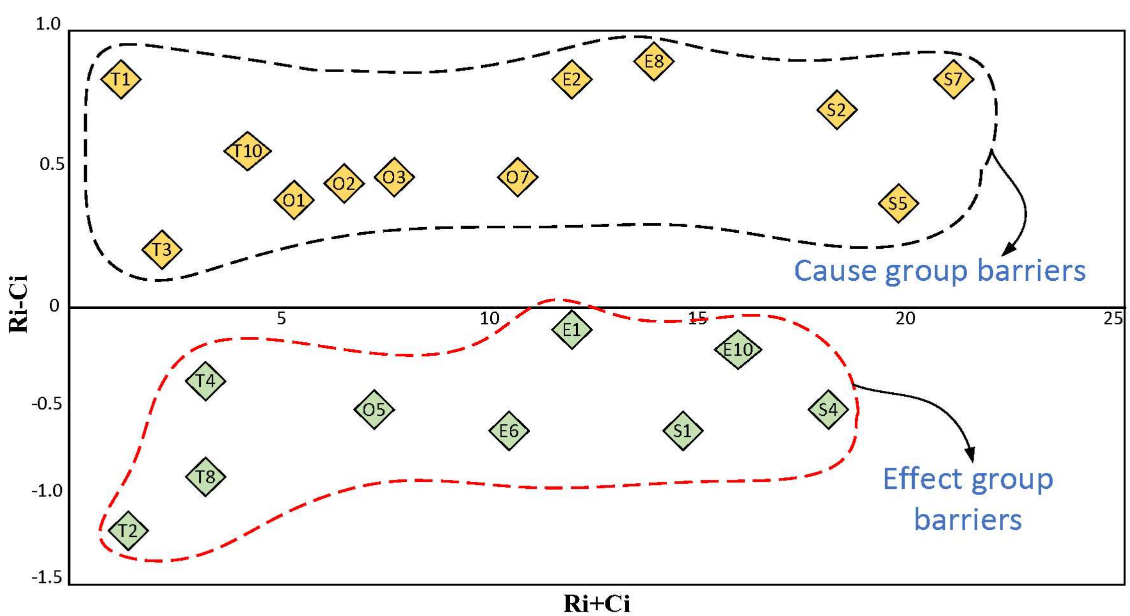

Figure 3: Net cause and net effect diagram

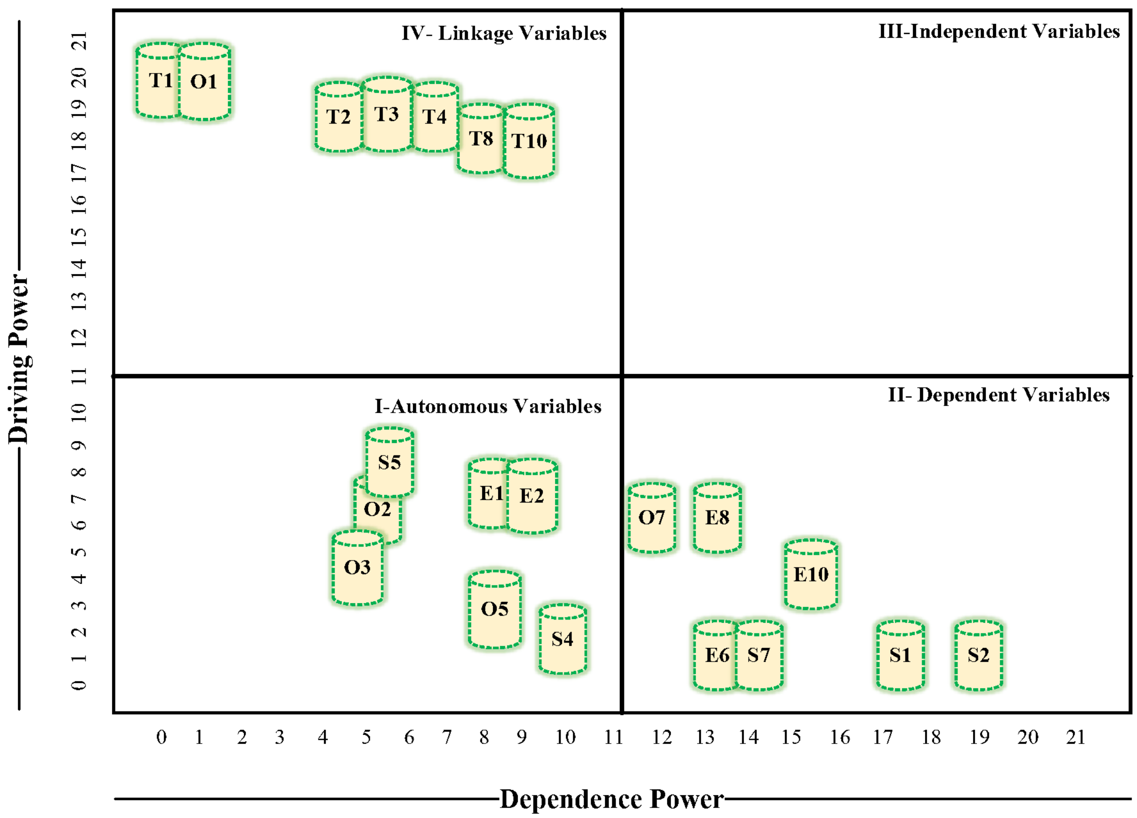

Figure 4: The drive-dependence matrix of the barriers to implementing BESC in construction projects.

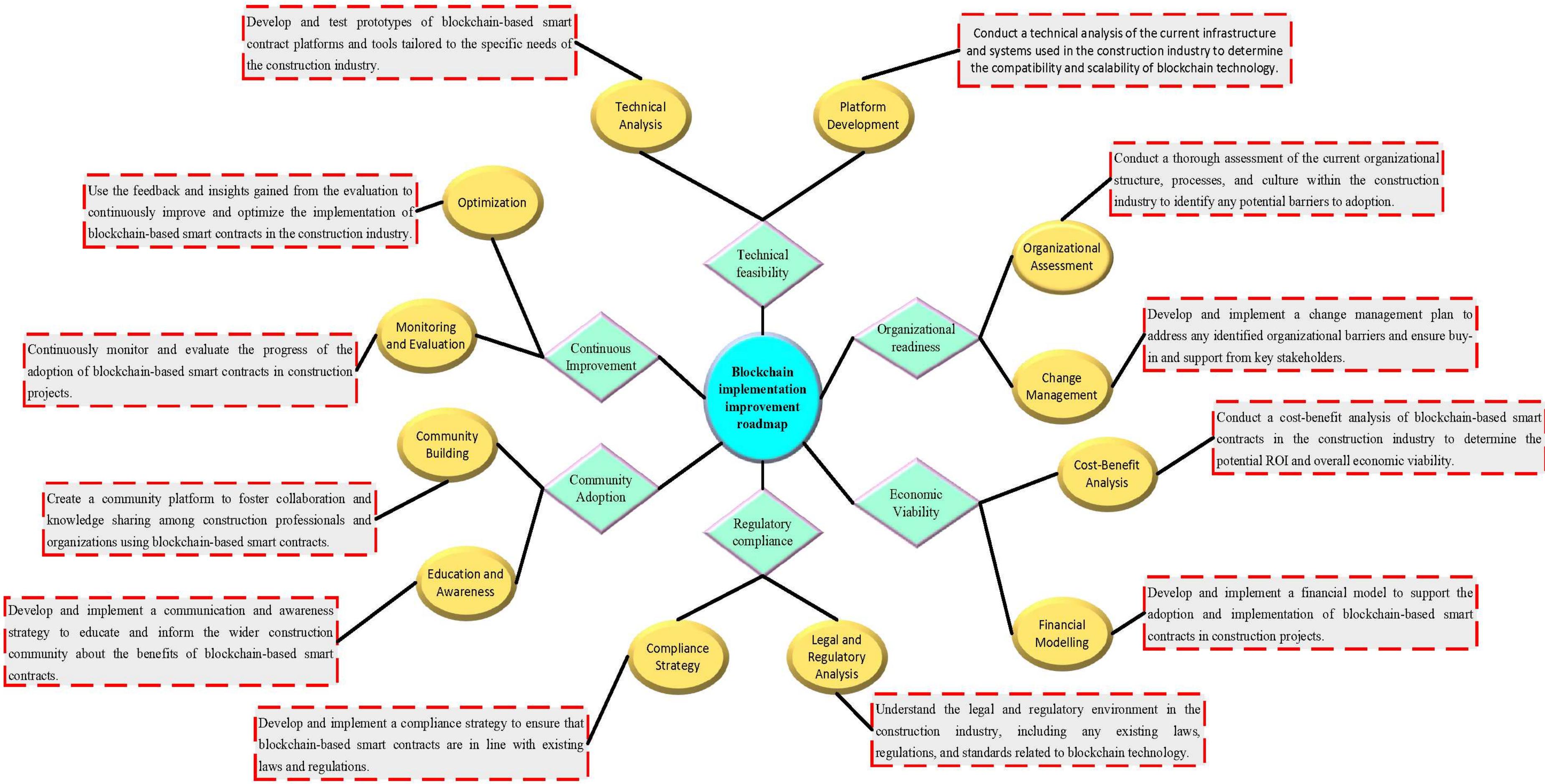

Figure 5: Roadmap to improve the implementation of BT

Table 1: Barriers to implementing Blockchain-enabled smart contract.

<table>
<tr><th>Barriers</th><th>Code</th><th>Sub-barriers</th><th>Final mean</th><th>Status</th><th>References</th></tr>
<tr><td rowspan="10">Technological (T)</td><td>T1</td><td>Complexity of blockchain technology</td><td>0.634</td><td>Accepted</td><td rowspan="10">(Kouhizadeh et al., 2021); (Tripoli & Schmidhuber, 2018); (Roth et al., 2022); (Balci & Surucu-Balci, 2021); (Aslam et al., 2021); (J. Li et al., 2019); (Qian & Papadonikolaki, 2021); (Smith & O'rourke, 2019); (Espinoza Pérez et al., 2022); (R. Kumar et al., 2019); (Yadav & Singh, 2020); (Ronaghi & Mosakhani, 2022);(Orji et al., 2020); (Zhao et al., 2022); (Y. Wang et al., 2021)</td></tr>
<tr><td>T2</td><td>Lack of standardization and interoperability</td><td>0.554</td><td>Accepted</td></tr>
<tr><td>T3</td><td>Limited scalability and processing speed</td><td>0.697</td><td>Accepted</td></tr>
<tr><td>T4</td><td>Insufficient security and privacy</td><td>0.734</td><td>Accepted</td></tr>
<tr><td>T5</td><td>High initial investment and technical skills required</td><td>0.432</td><td>Rejected</td></tr>
<tr><td>T6</td><td>Integration challenges with existing systems</td><td>0.332</td><td>Rejected</td></tr>
<tr><td>T7</td><td>Technical limitations in integrating with legacy systems</td><td>0.232</td><td>Rejected</td></tr>
<tr><td>T8</td><td>Limited technical expertise among construction professionals</td><td>0.834</td><td>Accepted</td></tr>
<tr><td>T9</td><td>Lack of technical support and maintenance</td><td>0.192</td><td>Rejected</td></tr>
<tr><td>T10</td><td>Technical compatibility issues with other technologies used in construction</td><td>0.674</td><td>Accepted</td></tr>
<tr><td rowspan="8">Organization (O)</td><td>O1</td><td>Resistance to change among stakeholders</td><td>0.774</td><td>Accepted</td><td rowspan="8">(Wu et al., 2022); (Junejo et al., 2020); (Altay & Motawa, 2020)
(Turk & Klinc, 2017); (W. Li et al., 2021); (Kouhizadeh et al., 2021)
(Zhao et al., 2022); (Sadeghi et al., 2022); (J. Li et al., 2019)
(Apichart Boonpheng et al., 2020); (Sciarelli et al., 2021); (Balci & Surucu-Balci, 2021);</td></tr>
<tr><td>O2</td><td>Inadequate leadership and management support</td><td>0.894</td><td>Accepted</td></tr>
<tr><td>O3</td><td>Lack of understanding and awareness among stakeholders</td><td>0.69</td><td>Accepted</td></tr>
<tr><td>O4</td><td>Incompatible existing IT infrastructure</td><td>0.33</td><td>Rejected</td></tr>
<tr><td>O5</td><td>Limited resources and funding</td><td>0.664</td><td>Accepted</td></tr>
<tr><td>O6</td><td>Organizational culture and attitudes toward new technologies</td><td>0.232</td><td>Rejected</td></tr>
<tr><td>O7</td><td>Lack of incentives for implementation</td><td>0.784</td><td>Accepted</td></tr>
<tr><td>O8</td><td>Disagreements among stakeholders on implementation</td><td>0.282</td><td>Rejected</td></tr>
</table>

	O9	Poor project management and coordination	0.499	Rejected	(Bai et al., 2022) (Kulkarni & Patil, 2020); (Saberi et al., 2019); (Rane & Thakker, 2020)
Environmental (E)	E1	Uncertainty and lack of trust in the technology	0.689	Accepted	(Rane & Thakker, 2020); (Hughes et al., 2019); (Azmi et al., 2022); (Spychiger et al., 2021) (Dakhli et al., 2019); (Ronaghi & Mosakhani, 2022); (Qian & Papadonikolaki, 2021); (Smith & O'rourke, 2019) (Kouhizadeh et al., 2021); (Tezel et al., 2021); (Biswas & Gupta, 2019)
	E2	Government regulations and legal barriers	0.799	Accepted	
	E3	Uncertainty and lack of trust in the technology	0.389	Rejected	
	E4	Competition from traditional systems	0.032	Rejected	
	E5	Cultural and societal resistance to new technologies	0.112	Rejected	
	E6	Economic and market conditions	0.594	Accepted	
	E7	Limited global acceptance and implementation of blockchain technology	0.442	Rejected	
	E8	Lack of industry-wide consensus on implementation and use	0.669	Accepted	
	E9	Lack of readily available information and educational resources	0.33	Rejected	
	E10	Lack of demonstrated success stories in construction	0.697	Accepted	
	E11	Market dynamics and lack of commercial implementation	0.435	Rejected	
Social (S)	S1	Lack of awareness and education about blockchain technology among stakeholders.	0.767	Accepted	(Badi et al., 2021; Ding et al., 2023; A. Kumar et al., 2023; J. Li & Kassem, 2021; A. J. McNamara & Sepasgozar, 2021; A. McNamara & Sepasgozar, 2018; Rathnayake et al., 2022; Sadeghi et al., 2022; Ye et al., 2022)
	S2	Limited implementation of digital technology in some cultures and societies.	0.667	Accepted	
	S3	Perceived risks associated with BESC, such as the potential for fraud, error, and hacking.	0.477	Rejected	
	S4	Concerns about the impact of blockchain technology on	0.738	Accepted	

		employment and job security.			
	S5	Limited understanding of the social and cultural implications of blockchain technology.	0.689	Accepted	
	S6	Challenges related to data ownership, sharing, and access on blockchain networks.	0.491	Rejected	
	S7	Ethical concerns regarding data privacy and security on blockchain networks.	0.638	Accepted	

Table 2. Net cause and the net effect of the barriers

Barriers	Ri	Ci	Ri + Ci	Ri-Ci
T1	8.672	7.967	16.638	0.705
T2	6.368	7.605	13.973	-1.237
T3	8.101	7.992	16.093	0.109
T4	7.615	7.933	15.547	-0.318
T8	6.801	7.599	14.401	-0.798
T10	8.107	7.692	15.800	0.415
O1	7.725	7.569	15.294	0.156
O2	8.230	8.077	16.307	0.153
O3	7.949	7.746	15.695	0.202
O5	7.329	7.949	15.279	-0.620
O7	7.589	7.378	14.967	0.210
E1	7.765	7.781	15.545	-0.016
E2	7.939	7.235	15.174	0.704
E6	6.883	7.552	14.435	-0.668
E8	7.953	7.145	15.098	0.808
E10	7.743	7.880	15.623	-0.138
S1	7.169	7.832	15.000	-0.663
S2	8.379	7.760	16.139	0.618
S4	7.296	7.782	15.078	-0.486
S5	8.034	7.825	15.858	0.209
S7	8.238	7.585	15.823	0.653

Appendix A

Appendix A

IF-Delphi

Step 1: Calculations for the first round

Following this, the average opinion from each expert and their deviation from the mean are calculated. This is done using equations 1 to 5. The results are subsequently shared with the experts for their evaluation, facilitating potential adjustments to be considered in pursuit of reaching a consensus.

$$\widetilde{A^{(i)}} = (\mu_A^i \cdot \nu_A^i) \qquad (1)$$

$$\widetilde{A^{(m)}} = IFWA_W(A^{(1)} \cdot A^{(2)} \cdot \dots \cdot A^{(S)}) = \left(\left[1 - \prod_{j=1}^{n}(1-\mu_j)^{w_j}\right] \cdot \left[\prod_{j=1}^{n}(\nu_j)^{w_j}\right]\right) \qquad (2)$$

$$S(A^{(m)}) = \mu_A^{(m)} - \nu_A^{(m)} \qquad (3)$$

$$S(A^{(i)}) = \mu_A^{(i)} - \nu_A^{(i)} \qquad (4)$$

$$d_A = \left|S(A^{(m)}) - S(A^{(i)})\right| \qquad (5)$$

This equation involves the notation A˜(i) denoting the viewpoint of the i-th expert, while A˜(m) signifies the collective average of all experts' opinions during the initial round. This is articulated using the S(A) representation and encapsulated by dA, which captures the disparity between individual expert opinions and their mean.

Step 2: Collect information on the second round

During this phase, the questionnaires are returned to the experts, and they are apprised of their peers' perspectives. Subsequently, the experts are invited to reevaluate their opinions and implement any requisite adjustments.

Step 3: Calculations for the second round

The determination of updated expert opinions involves computing an average using equations 6 to 9.

$$\widetilde{B^{(i)}} = \left(\mu_B^i \cdot \nu_B^i\right) \qquad (6)$$

$$\widetilde{B^{(m)}} = IFWA_W\left(B^{(1)} \cdot B^{(2)} \cdot \dots \cdot B^{(S)}\right) = \left(\left[1 - \prod_{j=1}^{n}(1-\mu_j)^{w_j}\right] \cdot \left[\prod_{j=1}^{n}(\nu_j)^{w_j}\right]\right) \qquad (7)$$

$$S\left(B^{(m)}\right) = \mu_B^{(m)} - \nu_B^{(m)} \qquad (8)$$

$$D_{A.B} = \left|S\left(B^{(m)}\right) - S\left(A^{(m)}\right)\right| \qquad (9)$$

In this context, $\tilde{B}(i)$ symbolizes the revised viewpoint of the i-th expert, while $\tilde{B}(m)$ denotes the collective average of all experts' revised opinions during the second round. The symbol S(B) stands for the score value, and D_{AB} refers to the difference between the average of experts' opinions in the two rounds.

Step 4: To obtain the final result, repeat the Delphi cycle.

The IF-Delphi process is iterated until the difference between the outcomes of two successive rounds reduces significantly to 0.2 (DAB $\leq$ 0.2), following the methodology suggested by Luthra et al. (2022). The IF-Delphi process is concluded after reaching a consensus on the opinions, and the critical criteria are chosen.

Evaluate the direct relationship between the factors

An IF-Delphi process questionnaire is designed as a pairwise comparison tool to identify factors that relate directly to each other. Experts are asked to evaluate the direct relationships between the barriers using a binary comparison format and the values specified in Table A1. The final step involves converting the linguistic statements into numerical values using the IF method. Appendix A provides a detailed explanation of Hesitant Fuzzy Sets.

Hesitant fuzzy sets

Two linguistic variables are used in the proposed framework: (1) pairwise interaction between barriers and (2) performance of alternatives to barriers. Torra (2010) introduces hesitant fuzzy sets (HFS) to measure linguistic variables (Erol et al., 2022). As a general overview, HFS consists of the following concepts.

Defining 1. Assume that X represents the reference set. X is a set A in which hA(x) represents each object x's membership within set A. Therefore, the HFS on X is a function whose value indicates which object x belongs to set A. A hesitant fuzzy element (HFE) is an hA(x) function.

We can consider three HFEs as h, h1, and h2. Torra, 2010; Xia, and Xu, 2011 outline the operation rules in the following way.

$$h' = \bigcup_{\beta \in h} \{1 - \beta\}$$

$$h_1 \cup h_2 = \overset{\cup}{\bigcup_{\beta_1 \in h_1, \beta_2 \in h_2}} max\{\beta_1, \beta_2\}$$

$$h_1 \cap h_2 = {}_{\beta_1 \in h_1, \beta_2 \in h_2} min\{\beta_1, \beta_2\}$$

$$h^\lambda = \bigcup_{\beta \in h} \{\beta^\lambda\}$$

$$\lambda h = \{1 - (1 - \beta)^\lambda\}$$

$$h_1 \oplus h_2 = \underset{\beta_1 \in h_1, \beta_2 \in h_2}{\cup} \{\beta_1 + \beta_2 - \beta_1 \beta_2\}$$

$$h_1 \otimes h_2 - {}_{\beta_1 \in h_1, \beta_2 \in h_2} \{\beta_1 \beta_2\}$$

Torra (2010) states that HFE can be ranked using a score function (Erol et al., 2022). (Bai et al., 2020) propose a modified score function to address some of the shortcomings of this function (Leong et al., 2020).

Table A1. A list of the corresponding HFEs.

Linguistic variables	Hesitant preference degrees	Corresponding HFE
EL (extremely low)	[0,0.2]	(0,0.1,0.2)
VL (very low)	[0.2,0.35]	(0.2,0.275,0.35)
L (low)	[0.35,0.5]	(0.35,0.425,0.5)
M (medium)	[0.5,0.65]	(0.5,0.575,0.625)
H (high)	[0.65,0.8]	(0.65,0.725,0.8)

VH (very high)	[0.8,0.9]	(0.8,0.85,0.9)
EH (extremely high)	[0.9,1]	(0.9,0.95,1)

Defining 2. Let h = ∪β∈h {β} = {βs |s = 1, 2, l] be the HFE with l being the number of elements in h. Eq (1) defines SF as the score function of h.

$$S_F(h) = \frac{\sum_{s=1}^{l} \rho(s)\beta_s}{\sum_{s=1}^{l} \rho(s)} \qquad (10)$$

A positive valued monotonic increasing sequence of s is defined as [p(s) |s = 1, 2,….., l]. Based on this assumption, we define p(s) as s, with s = 1, 2, …, l. Hence, Eq (2) relates h1 to h2 according to the Euclidean distance between them.

$$d(h_1,h_2) = \sqrt{\frac{1}{l}\sum_{s=1}^{l}\left(\beta_1^s - \beta_2^s\right)^2} \qquad (11)$$

Since experts collect the input data, an expert panel must be established. Following that, experts provide linguistic variables as assessment information. Table A1 provides the transformation rules used to transform linguistic variables into HFEs after collecting them (Yu et al., 2020). The numbers in the corresponding HFE represent pessimists, neutrals, and optimist.

Utilization of Hesitant fuzzy DEMATEL

The subjective weights of barriers are determined using hesitant fuzzy DEMATEL to analyze the interrelationships among barriers. This method allows experts to provide their knowledge and construct a structural model that illustrates the complex connections between causal barriers (H. Wu et al., 2022). The hesitant fuzzy DEMATEL process results in the following outcome.

Step 1. Compute direct-relation matrixes and make pairwise comparisons.

Assume there are m alternatives and n barriers. Suppose D = E1, E2, ..., Ep is a group of experts who offer their opinions on the relationship between the barriers. A direct-relation matrix is derived from linguistic variables after they have been transformed into HFEs. This matrix shows the direct relations between Ek and the expert.

$$Z^k = \begin{bmatrix} z_{11}^k & z_{12}^k & \cdots & z_{1n}^k \\ z_{21}^k & z_{22}^k & \cdots & z_{2n}^k \\ \vdots & \vdots & \vdots & \vdots \\ z_{n1}^k & z_{n2}^k & \cdots & z_{nn}^k \end{bmatrix}$$

Z k ij represents what happens when a barrier hits the jth barrier and is expressed as an HFE.

Step 2. Calculate the aggregated direct-relation matrix.

For aggregating the information given by experts, a hesitant fuzzy weighted averaging operator (HFWA) is presented (Xia and Xu, 2011).

$$\text{HFWA}\left(z_{ij}^1, z_{ij}^2, \ldots, z_{ij}^p\right) = {}_{\beta_1 \in z_{ij}^1, \beta_2 \in z_{ij}^2, \ldots, \beta_p \in z_{ij}^p}\left\{1 - \prod_{j=1}^{p}(1-\beta_j)^{\lambda_j}\right\} \qquad (12)$$

Its weight is defined as a jth expert, where j = [0, 1], and pj = 1λj = 1.

Zij = HFWA(z 1 ij, z 2 ij, .., z p ij) then yields the aggregated direct-relation matrix Z.

Step 3. Analyze the matrix of normalized direct-relations.

Using Eq (4), the score function is used to defuzzify HFEs in the aggregated direct-relation matrix.

$$a_{ij} = S_F(z_{ij}) = \frac{\sum_{s=1}^{l} s\beta_s}{\sum_{s=1}^{l} s} \qquad (13)$$

In zij, l represents the number of elements.

Then the normalized matrix A = [aij]n×n is obtained using Eq. (5).

$$\bar{\mathbf{a}}_{ij} = \frac{a_{ij}}{\max_i \sum_{j=1}^{n} a_{ij}} \qquad (14)$$

Step 4. Create a matrix of all the relationships.

According to Eq. (6), the total relation matrix T = [tij]n×n can be obtained to include the direct and indirect relations among factors.

$$T = \overline{A} + \overline{A}^2 + \cdots = \sum_{i=1}^{\infty} \overline{A}^i = \overline{A}(I - \overline{A})^{-1} \qquad (15)$$

I represent a matrix of identity.

Step 5. Develop a cause-and-effect diagram based on the calculated cause–effect relations.

Compute the sum of rows and columns representing the degrees of influence and influence based on the total relation matrix.

$$D = \sum_{j=1}^{n} t_{ij}, i = 1,2,\ldots,n \quad (16)$$

$$R = \sum_{i=1}^{n} t_{ij}, j = 1,2,\ldots,n \quad (17)$$

Using D+R, you can express the importance of each barrier. A barrier's importance increases as D+R increases. D-R indicates the net effect by dividing barriers according to their causes and effects. It is considered a causal barrier if D-R > 0. As opposed to that, if the barrier has the opposite effect, it is classified as an effect barrier. Assign a horizontal axis of D+R and a vertical axis of D-R to the cause-effect diagram. This diagram illustrates how barriers relate to one another.

In this study, visual representations such as diagrams and graphics can be created after obtaining information on the impact of different factors. To further hone in on the most critical relationships between the factors, it is possible to eliminate the values in the matrix that fall below a certain threshold (α). It is crucial to remember that choosing a low threshold value would mean disregarding only a few relationships and leaving us with complex diagrams. By setting the threshold value too high, significant relationships may be excluded. To balance the different considerations, we adopted a threshold value higher than the mean of the elements in the total relation matrix (T) by one standard deviation, as determined by using equation (9).

$$\alpha = \text{Mean}\ (t_{ij}) + \text{SD}\ (t_{ij}); i,j \in [1,n] \quad (18)$$

Utilisation of IFISM

Step 1: Calculate the aggregated expert opinions.

The next stage involves generating a matrix that combines the viewpoints of the experts by utilizing the pairwise comparison results obtained in the previous step. This can be done by applying equation (23).

$$\text{IFWA}_W\ (A^{(1)} \cdot A^{(2)} \cdots A^{(S)}) = \left(\left[1 - \prod_{j=1}^{n} (1 - \mu_j)^{w_j} \cdot \right] \cdot \left[\prod_{j=1}^{n} (\nu_j)^{w_j} \right] \right) \quad (19)$$

According to Attanassov's (1986) framework, the matrix incorporates three key factors: the degree of membership (μj), the degree of non-membership (νj), and the weighting of expert opinions (wj).

Step 2: Expert opinion matrix on defuzzification

To convert the fuzzified matrix of each criterion into a defuzzified form, the following equation (24) is utilized, which subtracts the degree of non-membership (νj) from the degree of membership (μj).

$S(A) = \mu_A - \nu_A$ (20)

Step 3: Create the initial matrix of reachability

To generate the initial reachability matrix, the first step is to set a threshold limit, which can be achieved by applying the following equation:

If $\pi_{ij} \geq t \rightarrow \pi_{ij} = 1.\pi_{ji} = 0$

If $\pi_{ij} < t \rightarrow \pi_{ij} = 0.\pi_{ji} = 1$ (21)

Step 4: Create a matrix of final reachability

The initial matrix is raised to the power of K + 1 using equation (26) to achieve stability.

$M^* = M^k = M^{k+1} k > 1$ (22)

The final reachability matrix (M*) and a positive integer (k) result from this process.

Step 5: Calculate the levels of each variable and draw a network of interactions

We use the antecedent (A) and reachability (R) sets to generate the ISM diagram to determine the criteria levels. The information obtained from the previous total relation matrix is used to visualize the interactions and relationships between variables at various levels.

Step 6: MICMAC analysis

MICMAC analysis is conducted by multiplying cross-impact matrixes to form four quadrants: autonomous, dependent, linked, and independent (Nandal et al., 2019). The final reachability matrix is partitioned by measuring each factor's drive and dependence power. Unlike autonomous variables, dependent variables possess strong dependence power compared to other criteria, whereas autonomous variables function nearly independently from the system. Linkage variables are strongly influenced by and dependent on other factors and can influence other factors. Dependence is weak between independent variables and strong between dependent variables (Avinash et al., 2018).

Appendix B

Table B1. Total relation matrix

	T1	T2	T3	T4	T8	T10	O1	O2	O3	O5	O7	E1	E2	E6	E8	E10	S1	S2	S4	S5	S7
T1	0.380	0.408	0.433	0.428	0.407	0.413	0.407	0.436	0.418	0.431	0.392	0.421	0.387	0.409	0.384	0.425	0.420	0.418	0.416	0.426	0.413
T2	0.304	0.266	0.309	0.317	0.303	0.309	0.302	0.321	0.310	0.312	0.290	0.307	0.289	0.304	0.283	0.310	0.311	0.304	0.308	0.312	0.297
T3	0.404	0.383	0.356	0.398	0.380	0.391	0.376	0.400	0.382	0.402	0.378	0.391	0.368	0.380	0.368	0.398	0.393	0.389	0.389	0.388	0.386
T4	0.374	0.358	0.380	0.332	0.365	0.365	0.365	0.386	0.363	0.368	0.349	0.367	0.341	0.358	0.336	0.371	0.371	0.367	0.368	0.369	0.361
T8	0.344	0.322	0.342	0.333	0.284	0.323	0.310	0.338	0.332	0.341	0.312	0.328	0.305	0.315	0.295	0.332	0.331	0.336	0.324	0.333	0.322
T10	0.404	0.381	0.405	0.399	0.384	0.343	0.381	0.407	0.385	0.397	0.370	0.394	0.359	0.380	0.364	0.395	0.393	0.397	0.393	0.394	0.381
O1	0.398	0.368	0.384	0.379	0.360	0.365	0.322	0.384	0.379	0.380	0.355	0.363	0.343	0.354	0.347	0.375	0.380	0.372	0.381	0.376	0.360
O2	0.399	0.387	0.409	0.407	0.386	0.397	0.385	0.365	0.390	0.412	0.380	0.398	0.377	0.388	0.365	0.405	0.401	0.395	0.397	0.403	0.385
O3	0.395	0.377	0.393	0.388	0.379	0.377	0.371	0.403	0.339	0.390	0.365	0.394	0.352	0.374	0.346	0.390	0.389	0.386	0.386	0.386	0.369
O5	0.355	0.344	0.363	0.362	0.343	0.353	0.350	0.369	0.353	0.320	0.335	0.352	0.334	0.349	0.334	0.357	0.350	0.348	0.352	0.355	0.351
O7	0.370	0.355	0.372	0.369	0.359	0.353	0.359	0.377	0.365	0.372	0.308	0.370	0.354	0.356	0.342	0.372	0.376	0.364	0.369	0.369	0.358
E1	0.389	0.371	0.388	0.379	0.365	0.373	0.368	0.392	0.377	0.383	0.350	0.332	0.342	0.358	0.341	0.381	0.376	0.378	0.376	0.377	0.370
E2	0.385	0.374	0.392	0.391	0.369	0.381	0.374	0.395	0.384	0.397	0.361	0.383	0.316	0.379	0.351	0.391	0.384	0.384	0.383	0.390	0.376
E6	0.336	0.323	0.337	0.339	0.327	0.328	0.325	0.348	0.331	0.341	0.321	0.333	0.311	0.286	0.309	0.333	0.336	0.332	0.331	0.334	0.324
E8	0.396	0.372	0.395	0.396	0.373	0.380	0.365	0.398	0.379	0.394	0.370	0.385	0.362	0.371	0.312	0.392	0.392	0.382	0.380	0.386	0.374
E10	0.388	0.366	0.390	0.376	0.369	0.374	0.371	0.392	0.372	0.373	0.352	0.371	0.346	0.359	0.338	0.336	0.371	0.377	0.380	0.376	0.364
S1	0.359	0.340	0.364	0.353	0.334	0.339	0.337	0.348	0.352	0.356	0.328	0.347	0.321	0.334	0.315	0.353	0.309	0.347	0.343	0.351	0.338
S2	0.418	0.394	0.415	0.412	0.396	0.396	0.393	0.426	0.399	0.419	0.386	0.406	0.371	0.395	0.376	0.411	0.407	0.357	0.407	0.405	0.388
S4	0.367	0.351	0.365	0.365	0.349	0.353	0.348	0.371	0.353	0.356	0.333	0.351	0.326	0.338	0.325	0.353	0.353	0.342	0.312	0.346	0.340
S5	0.392	0.375	0.394	0.398	0.374	0.381	0.374	0.405	0.385	0.396	0.370	0.387	0.364	0.381	0.357	0.398	0.392	0.387	0.393	0.346	0.386
S7	0.409	0.390	0.407	0.411	0.393	0.396	0.387	0.416	0.398	0.409	0.373	0.401	0.369	0.382	0.358	0.403	0.398	0.399	0.393	0.402	0.344

Table B2: Eminent and net effect of the categories of barriers

Categories	Average Eminent
Technological barriers	15.409
Organizational barriers	15.508
Environmental barriers	15.175
Social barriers	15.580

Table B3: Barriers' most significant relationship coefficients

	Impacted barriers																				
Impacting barriers	0.380	0.408	0.433	0.428	0.407	0.413	0.407	0.436	0.418	0.431	0.392	0.421	0.387	0.409	0.384	0.425	0.420	0.418	0.416	0.426	0.413
	0.404	0.383		0.398	0.380	0.391		0.400	0.382	0.402		0.391		0.380		0.398	0.393	0.389	0.389	0.388	0.386
			0.380					0.386													
	0.404	0.381	0.405	0.399	0.384		0.381	0.407	0.385	0.397		0.394		0.380		0.395	0.393	0.397	0.393	0.394	0.381
	0.398		0.384					0.384	0.379	0.380							0.380		0.381		
	0.399	0.387	0.409	0.407	0.386	0.397	0.385		0.390	0.412	0.380	0.398		0.388		0.405	0.401	0.395	0.397	0.403	0.385
	0.395		0.393	0.388			0.371	0.403		0.390		0.394				0.390	0.389	0.386	0.386	0.386	
	0.389		0.388					0.392	0.377	0.383						0.381		0.378	0.376	0.377	
	0.385		0.392	0.391		0.381	0.374	0.395	0.384	0.397		0.383		0.379			0.384	0.384	0.383	0.390	0.376
	0.396		0.395	0.396		0.380		0.398		0.394		0.385				0.392	0.392	0.382	0.380	0.386	0.374
	0.388		0.390			0.374		0.392										0.377	0.380		
	0.418	0.394	0.415	0.412	0.396	0.396	0.393	0.426	0.399	0.419		0.406		0.395		0.411	0.407		0.407	0.405	0.388
	0.367																				
	0.392		0.394	0.398		0.381		0.405	0.385	0.396				0.381		0.398	0.392	0.387	0.393		0.386
	0.409	0.390	0.407	0.411	0.393	0.396	0.387	0.416	0.398	0.409		0.401		0.382		0.403	0.398	0.399	0.393	0.402	

Table B4: Results of level partitioning the barriers to implementing BESC in construction projects.

Elements (Mi)	Reachability Set R (Mi)	Antecedent Set A (Ni)	Intersection Set R(Mi)∩A(Ni)	Level
T1	1,	1,	1,	7
T2	2, 3, 4, 5, 6,	1, 2, 3, 4, 5, 6, 7,	2, 3, 4, 5, 6,	6
T3	2, 3, 4, 5, 6,	1, 2, 3, 4, 5, 6, 7,	2, 3, 4, 5, 6,	6
T4	2, 3, 4, 5, 6,	1, 2, 3, 4, 5, 6, 7,	2, 3, 4, 5, 6,	6
T8	2, 3, 4, 5, 6,	1, 2, 3, 4, 5, 6, 7,	2, 3, 4, 5, 6,	6
T10	2, 3, 4, 5, 6,	1, 2, 3, 4, 5, 6, 7,	2, 3, 4, 5, 6,	6
O1	7,	7,	7,	7
O2	8,	1, 2, 3, 4, 5, 6, 7, 8,	8,	5
O3	9,	1, 2, 3, 4, 5, 6, 7, 9,	9,	3
O5	10,	1, 2, 3, 4, 5, 6, 7, 8, 10,	10,	2
O7	11,	1, 2, 3, 4, 5, 6, 7, 9, 11, 13, 20,	11,	2
E1	12,	1, 2, 3, 4, 5, 6, 7, 8, 12,	12,	4
E2	13,	1, 2, 3, 4, 5, 6, 7, 13, 20,	13,	3
E6	14,	1, 2, 3, 4, 5, 6, 7, 9, 11, 13, 14, 20,	14,	1
E8	15,	1, 2, 3, 4, 5, 6, 7, 8, 12, 15, 20,	15,	3
E10	16,	1, 2, 3, 4, 5, 6, 7, 8, 9, 12, 15, 16, 20,	16,	2
S1	17,	1, 2, 3, 4, 5, 6, 7, 8, 9, 12, 15, 16, 17, 20,	17,	1
S2	18,	1, 2, 3, 4, 5, 6, 7, 8, 9, 11, 12, 13, 15, 16, 18, 20,	18,	1
S4	19,	1, 2, 3, 4, 5, 6, 7, 8, 10, 19,	19,	1
S5	20,	1, 2, 3, 4, 5, 6, 7, 20,	20,	4
S7	21,	1, 2, 3, 4, 5, 6, 7, 9, 11, 13, 20, 21,	21,	1

Table B5: Feedback from stakeholders for a roadmap

Statements	E1	E2	E3	E4	E5	E6	E7

The technical feasibility of using BESC in construction projects has been adequately addressed.	***	**	***	**	***	*	***
The organizational readiness for implementing BESC has been adequately addressed.	***	**	**	***	**	***	*
The economic viability of using BESC in construction projects has been adequately addressed.	***	*	***	***	***	**	***
The level of compliance with existing laws and regulations has been adequately addressed.	**	***	*	***	**	***	*
The level of community implementation and acceptance of BESC has been adequate.	***	**	**	***	***	*	**
The level of continuous improvement of BESC has been adequate.	***	**	***	**	***	*	***

where,

***	High effective
**	Moderate effective
*	Low effective

Appendix E

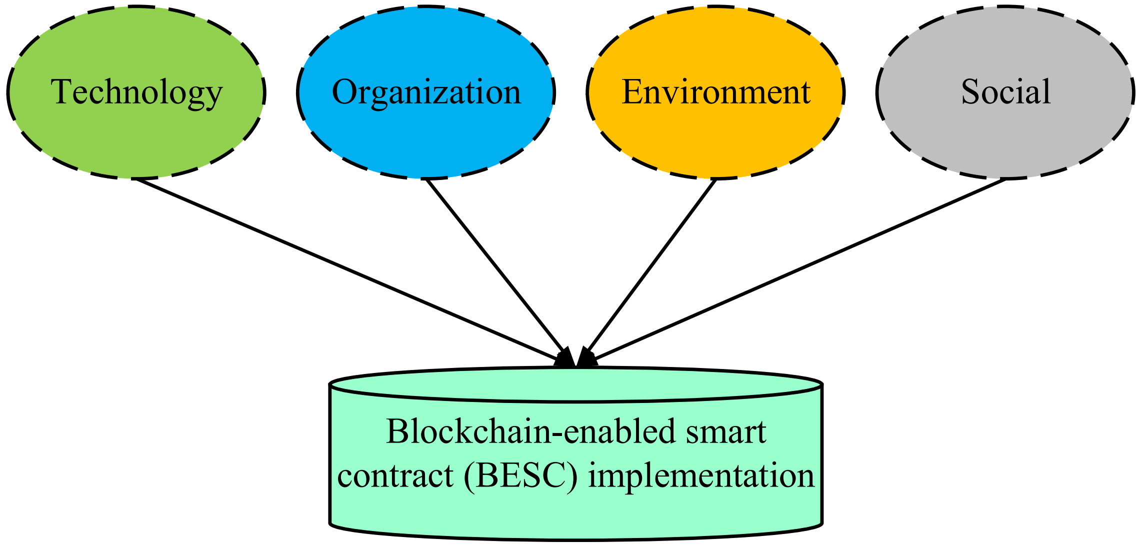

Figure C1. TOE +S (Technology, Organization, Environment and Social) framework for BESC implementation

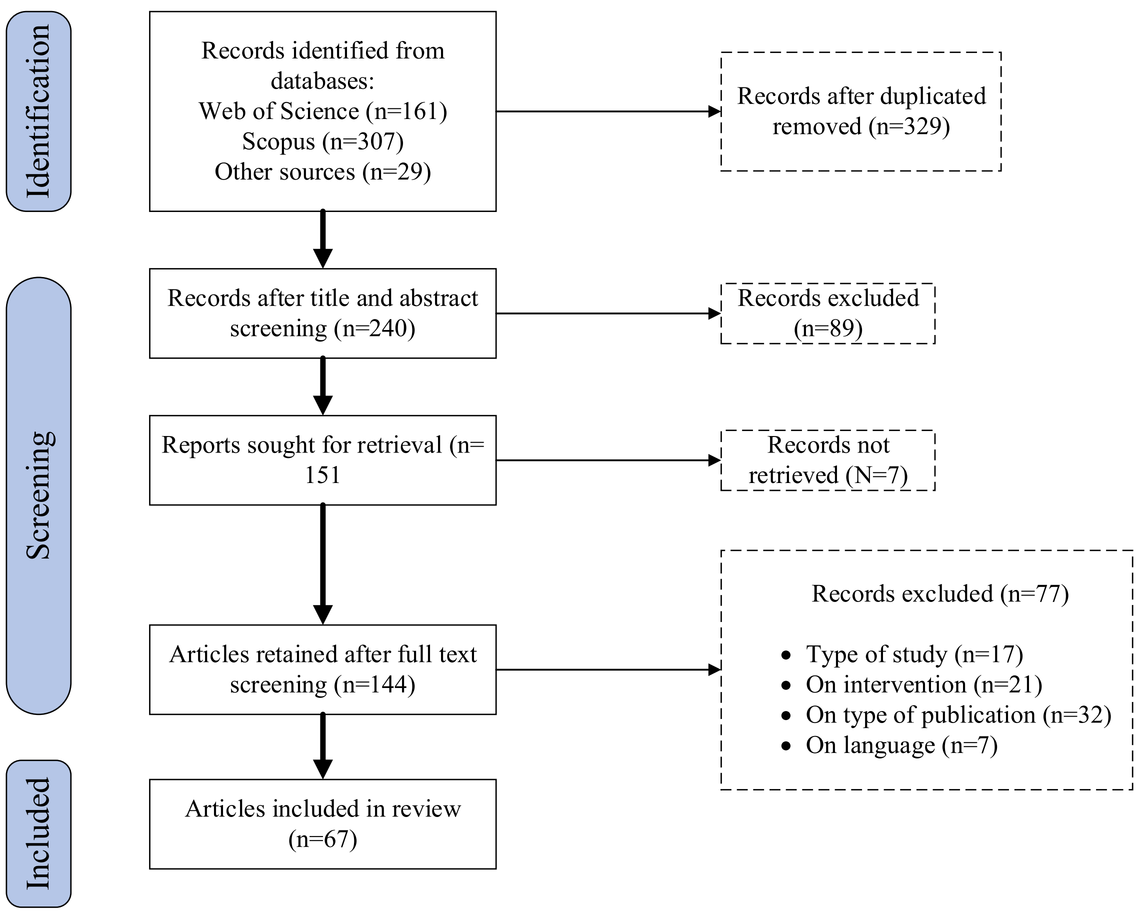

Figure C2: PRISMA flow diagram for study selection criteria.

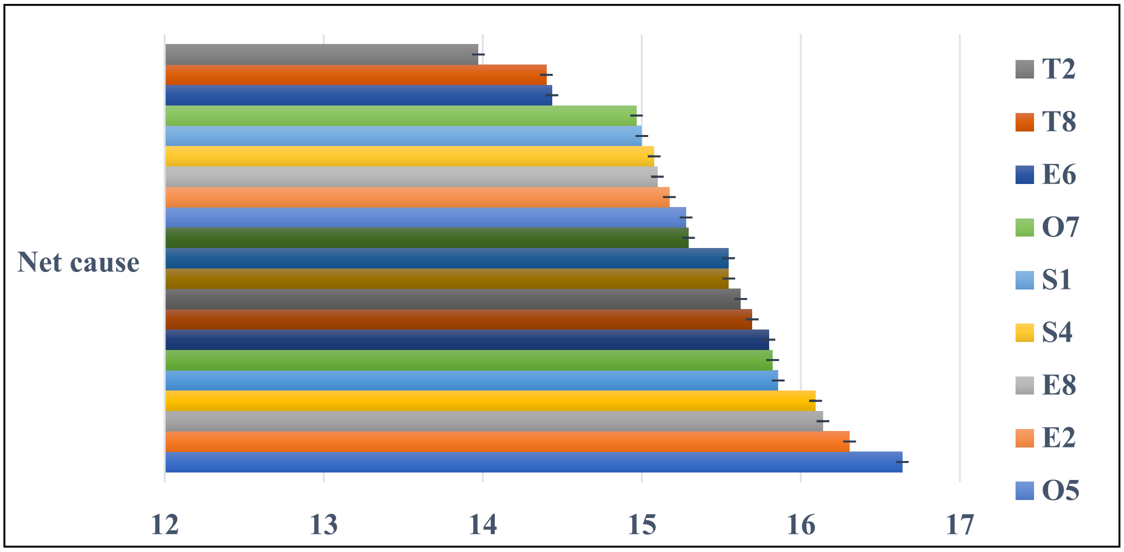

Figure C3: Net cause levels of the barriers

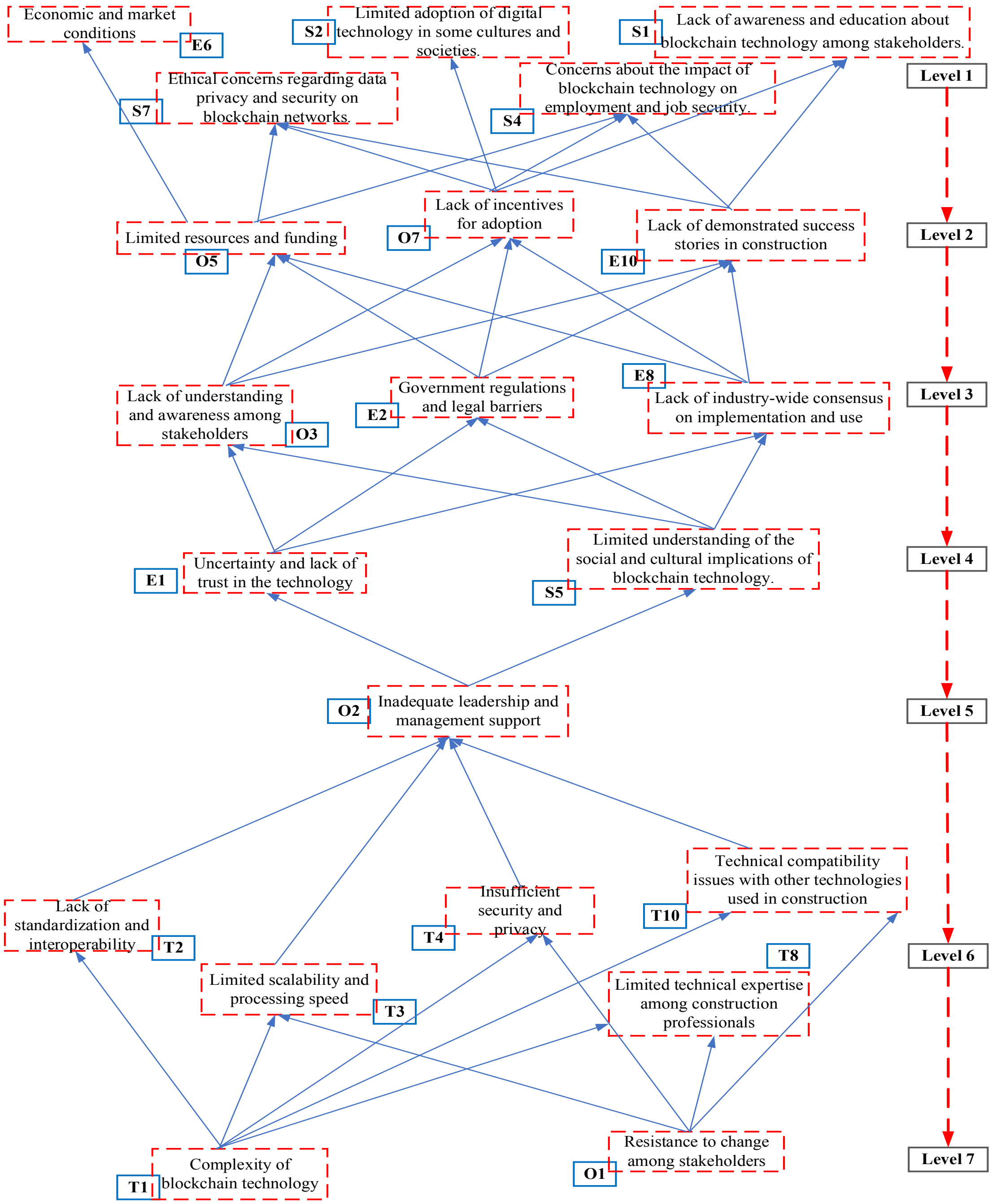

Figure C4: Hierarchal structure of the barriers to implementing BESC in construction projects.