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# Blockchain Technology Adoption for Sustainable Construction Procurement Management: A Multi-Pronged Artificial Intelligence-Based Approach

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## Abstract

While blockchain technology (BT) has gained attention in the construction industry, limited research has focused on its application in sustainable construction procurement management (SCPM). Addressing this gap, the present study investigates the key drivers influencing BT adoption in SCPM using a hybrid methodological approach. This study includes a systematic review of academic and grey literature, expert consultations, and quantitative analysis using advanced fuzzy-based algorithms, k-means clustering, and social network analysis (SNA). Data were collected through an online survey distributed to professionals experienced in SCPM and blockchain implementation. The Fuzzy DEMATEL results identify "high quality", "decentralization and data security", and "cost of the overall project" as the most critical drivers. Meanwhile, SNA highlights "stability of the system", "overall performance of the project", and "customer satisfaction" as the most influential nodes within the network. These insights provide actionable guidance for industry stakeholders aiming to advance SCPM through blockchain integration and contribute to theoretical advancements by proposing novel analytical frameworks.

**Keywords:** blockchain technology; sustainability; procurement management; industry 4.0; fuzzy logic; artificial intelligence

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## 1. Introduction

The construction industry (CI) has been recognized as one of the most environmentally unfriendly industries, with a substantial environmental footprint stemming from the extraction and processing of raw materials, transportation, and waste disposal [1]. These activities contribute significantly to greenhouse gas emissions, pollution, and ecosystem degradation. However, the integration of Industry 4.0 technologies such as 3D printing, robotics, drones, BIM, and IoT has created new opportunities for adopting more sustainable construction practices [2–4]. Among these, blockchain technology (BT) has emerged as a promising

solution to enhance transparency, accountability, and operational efficiency within construction supply chains. Its application enables better tracking of raw materials and logistics, helping to curb illegal or unsustainable practices such as mining in restricted areas and deforestation. Furthermore, BT can facilitate efficient resource management, minimize construction waste, and support environmentally responsible decision-making [5].

Past research has increasingly emphasized BT's potential to promote sustainability within the construction industry. For instance, studies by Zhong et al. [6] and Perera et al. [7] demonstrate how BT can improve traceability of sustainable materials, foster trust among stakeholders, and reduce procurement fraud. These findings support the argument that BT is not merely a digital tool but a strategic enabler of sustainable construction transformation. Despite such advances, the integration of sustainability goals into procurement practices remains underexplored.

Originally conceptualized by Satoshi Nakamoto in 2008 with the release of Bitcoin [8], BT has since expanded beyond financial systems into various sectors, including agriculture, logistics, healthcare, and construction. Recent studies have examined BT's potential to improve transparency, efficiency, and trust in construction procurement, particularly within the scope of sustainable construction procurement management (SCPM) [9–12]. SCPM refers to procurement processes that incorporate sustainability principles—such as environmental stewardship, social responsibility, and economic viability—into decision-making.

Unlike conventional procurement, SCPM introduces additional expectations such as environmental certifications, responsible sourcing, and lifecycle impact assessments. Although BT has been widely acknowledged for improving transparency and reducing transaction costs [13,14], prior studies have primarily focused on general procurement applications. Consequently, the literature offers limited insights into how BT can be strategically leveraged to meet the distinct sustainability objectives of SCPM, leaving a crucial research gap that this study aims to fill.

To address this gap, this study aims to explore and evaluate the key drivers influencing the adoption of blockchain technology in SCPM. Specifically, this study formulates the following research objectives (ROs), designed in a logical progression.

The novelty of this research lies in its comprehensive approach to addressing the identified research gap. To fill this gap, this study explores the following research objectives (RO):

(RO1): To conduct a comprehensive literature review to identify a set of potential drivers for adopting BT in SCPM.

(RO2): To identify the relative influence of these identified drivers using the modified Fuzzy Decision-Making Trial and Evaluation Laboratory (FDEMATEL) method, thereby determining which drivers have the most impact in the SCPM context.

(RO3): To analyze the relational structure and prominence of these influential drivers through Social Network Analysis (SNA), thereby identifying those with the greatest strategic potential for facilitating BT adoption.

These objectives are sequential: first, identifying a comprehensive list of drivers (RO1), then quantifying their influence (RO2), and finally mapping their interrelationships and strategic significance (RO3). This layered approach ensures that the analysis is both data-driven and context-specific to SCPM, providing a comprehensive understanding of the subject matter. The novelty of this study lies in its integrative methodology, which combines FDEMATEL and SNA. These two advanced analytical tools have not been extensively applied in this domain to unravel the interdependencies and centrality of BT adoption drivers in sustainable procurement. Moreover, by focusing on SCPM rather than general procurement, this study advances theoretical understanding and provides actionable insights for aligning emerging technologies with sustainability goals in the

construction sector. The findings are expected to support both academic inquiry and practical policy formulation by offering a framework for decision-makers and practitioners to prioritize interventions that foster BT-enabled sustainable procurement systems in the construction industry.

## 2. Literature Review

### 2.1. BT and SCPM

Blockchain Technology (BT) enhances transparency, efficiency, and trust in information sharing through its decentralized, encrypted ledger system. BT has four key characteristics. First, it allows businesses to share data seamlessly across networks, making it particularly valuable for multi-organizational settings, such as financial consortia and procurement systems, because it is distributed and synchronized among all participants [15]. Second, BT incorporates smart contracts, which are pre-defined agreements stored on the blockchain before execution. These contracts are automated computer protocols designed to facilitate, verify, and enforce terms digitally, enabling trustworthy transactions without the need for third-party intermediaries. Depending on the protocol, specific operations such as payments are automatically executed. Smart contracts can also define non-monetary conditions, providing stakeholders with assurance that all actions within the network adhere to agreed-upon rules [16]. Third, BT operates on a peer-to-peer (P2P) network where consensus among participants is required for validating transactions, thereby preventing inaccuracies or fraudulent records. Lastly, the immutability of blockchain data ensures that validated transactions cannot be altered [17].

Traditional construction procurement primarily focuses on the "iron triangle" of cost, time, and quality. In contrast, sustainable construction procurement management (SCPM) integrates environmental, social, and economic dimensions into procurement decisions. SCPM emphasizes reducing environmental impacts through practices such as lifecycle assessments, the use of low-carbon materials, and minimizing construction waste. It also promotes social equity (e.g., ensuring fair labor practices and supporting local employment) and long-term economic resilience. Unlike conventional procurement, which often prioritizes immediate project deliverables, SCPM demands transparency, traceability, and accountability across the entire supply chain. BT supports SCPM by enabling end-to-end material traceability, verification of sustainability claims, and real-time performance monitoring, which are essential for achieving SCPM's holistic objectives.

Any asset recorded on a blockchain can be traced to its origin, journey, and final status, offering complete provenance tracking. BT can operate as either public (e.g., Bitcoin) or private (permissioned) networks, with the key difference being who is allowed to participate in the network. Public blockchains are open to anyone and typically use incentive mechanisms to encourage participation, as seen with Bitcoin [18]. However, public blockchains require high computational power due to consensus mechanisms like proof-of-work (PoW). Alternatives such as Proof of Stake (PoS) or Proof of Authority (PoA) may be used depending on the network design. Private blockchains, on the other hand, require invitations and validation before participants can join, making them particularly suitable for business supply chains (SCs) where controlled access and confidentiality are critical [19]. The adoption of BT can significantly expand business horizons by enabling decentralized, "trustless" transactions, removing intermediaries, and facilitating coordination among diverse supply chain members. For example, Maersk, a global logistics leader, reported saving billions of dollars in maritime container management through its partnership with IBM on BT [20].

For BT to operate effectively in procurement or broader economic systems, trust must be established among participants in generating, storing, and sharing critical records. In

traditional settings, industries such as banking, healthcare, and education rely heavily on third-party entities for record-keeping and maintenance. In contrast, BT-based digital systems reduce the risk of human error or corruption by ensuring secure, tamper-proof record-keeping [21]. Within procurement, particularly SCPM—BT, enhances coordination and collaboration across various stakeholders engaged in planning, monitoring, and executing projects [22].

While BT offers multiple advantages, it also brings challenges. On the positive side, it enables procurement to achieve traditional objectives—such as cost reduction, risk mitigation, and quality control while improving sustainability. For example, logistics services that are critical for delivering customer value can be streamlined and authenticated using BT-supported quality assurance mechanisms. Although conventional quality audits remain necessary, BT accelerates processes and makes transactional records more robust and reliable [12,23]. BT also provides a solid foundation for resolving global procurement challenges through its ability to enhance transparency, traceability, and security. Its architecture, based on cryptographically timestamped and immutable records, ensures that every transaction event is verifiable [24]. These features not only improve the trustworthiness of smart contracts but also facilitate stronger stakeholder relationships. Despite these benefits, many SC networks have encountered technical, organizational, behavioral, and policy-related barriers during the adoption of BT [25].

Recent research has explored the intersection of BT and sustainability. Studies indicate that BT's tracking and tracing capabilities can support more sustainable procurement by improving resource monitoring, waste reduction, and compliance with environmental standards [26]. BT has applications in sustainable water management, agriculture procurement, and product decarbonization, reflecting its growing potential in industries committed to reducing their environmental footprint. Companies are becoming increasingly aware of the need for traceability and sustainability, not only for regulatory compliance but also to maintain public trust and build stronger relationships with environmentally conscious consumers. These considerations often take precedence over traditional cost-cutting measures. However, sustainability and cost efficiency are sometimes perceived as conflicting priorities, making SCPM a complex yet crucial focus area [27].

### *2.2. Past Studies on BT Adoption in SCPM*

The existing literature highlights the transformative potential of blockchain technology (BT) in addressing procurement challenges such as improving transparency, ensuring integrity and compliance, resolving disputes, and managing stakeholder expectations. By maintaining immutable records of product origins, procurement members, and operational processes on blockchain ledgers, BT can enhance traceability, authenticity, and chain-of-custody management [26]. Numerous studies emphasize the positive impact of BT procurement sustainability; however, research on the specific challenges of integrating BT into sustainable procurement programs—such as resource constraints, inter-organizational coordination, and technological limitations—remains limited [23]. This study aims to address these gaps by examining the drivers of BT adoption in SCPM, offering actionable insights to help organizations navigate the complexities of integration and enhance sustainability practices in construction procurement.

Much of the existing research explores firms' intentions to adopt BT rather than identifying the critical success factors (CSFs) influencing implementation. Transaction Cost Theory (TCT) is frequently employed to evaluate the impact of BT procurement, with studies highlighting its ability to reduce opportunistic behavior, minimize uncertainty, and lower transaction costs [28]. Several studies have employed Decision-Making Trial and Evaluation Laboratory (DEMATEL) techniques to investigate factors influencing the adop-

tion of BT in agriculture and other supply chains (SCs). These studies primarily assessed interrelationships among adoption barriers in industrial and service sectors. However, such research often focuses on cryptocurrency-related challenges in public blockchain contexts, with limited attention to private BT applications or SCPM-specific issues, reducing their relevance to construction procurement [29].

BT's potential to enhance supply chain performance by improving quality, reducing costs, and increasing transparency has been widely recognized. In manufacturing, BT combined with radio frequency identification (RFID) has been proposed for tracking agricultural goods during early adoption stages. Parmentola et al. [30] emphasized that BT can create accurate, tamper-proof, and secure systems that improve sustainability.

However, reviews of digital supply chain (SC) technologies often overlook BT entirely, suggesting a lack of academic focus on its role in procurement transformation. Studies on SC traceability have examined both the practical applications of blockchain and the challenges associated with its implementation in trade-related SCs [31].

BT has been extensively discussed as a tool for enhancing data security, access control, and records management. However, much of the literature overlooks the exploration of how blockchain-based structural frameworks and architectures can be implemented effectively. Research has highlighted the potential of BT in sustainable and innovative cities, considering environmental, economic, and social governance perspectives [29]. Popular platforms such as Ethereum and Hyperledger Fabric are widely cited for blockchain deployment. In supply chain contexts, BT is considered a critical technology for achieving efficient logistics operations through approaches such as mean-variance optimization [32].

Similarly, studies in the gem industry emphasize BT's ability to ensure ethical sourcing and sustainability, particularly in sectors facing reputational risks due to unethical practices. In agri-food supply chains (ASCs), blockchain-based traceability has been extensively studied. For instance, BT has been applied to Indian food-retail SCs to monitor product authenticity [33], while the integration of IoT, HACCP, and blockchain has been proposed to improve real-time food safety and transparency [34]. A blockchain-based quality management framework was also suggested to address issues of centralized trust, information asymmetry, and inspection costs in SCs [35].

Sharma et al. [36] developed a blockchain-enabled IoT supply chain management system to monitor environmental parameters, including humidity, soil moisture, and air temperature, in real-time, thereby achieving high levels of transparency and security in procurement operations. Their system also leveraged barcodes and QR codes to enhance traceability in the mango and pork value chains [23]. Moreover, BT's potential to contribute to the United Nations Sustainable Development Goals (SDGs) has been explored, with experts emphasizing its ability to improve transparency, build trust, and ensure secure information sharing in procurement [37]. Some studies even propose that BT could allow firms to develop proprietary cryptocurrencies and protect sensitive data [38].

Despite its promise, BT adoption in construction and SCPM faces significant barriers. The absence of clear norms and regulatory guidelines is a major impediment, preventing seamless integration into existing systems in the highly regulated construction industry [39,40]. Establishing standardized protocols is necessary to boost organizational confidence and avoid legal or governmental conflicts [41]. From a technical perspective, construction projects necessitate complex, multi-party data exchanges, which raises concerns about trust in decentralized systems and the protection of sensitive data [42]. Studies also emphasize the need for stronger security and privacy frameworks to ensure effective adoption [43].

Furthermore, the high implementation costs of BT pose challenges for small- and medium-sized enterprises (SMEs). There is also a widespread lack of understanding of BT's

operational and strategic potential, combined with the absence of well-defined technical standards [11]. Therefore, further research is needed to address these gaps, particularly in identifying SCPM-specific drivers, barriers, and success strategies to enable widespread adoption and maximize BT's potential to enhance transparency, sustainability, and cost efficiency [44].

### *2.3. Research Gaps*

The existing literature highlights the transformative potential of BT in enhancing transparency, traceability, and operational efficiency across various sectors, including supply chain management, agriculture, and logistics [45,46]. In the construction domain, studies suggest that BT can reduce transactional friction, mitigate information asymmetry, and ensure the immutability of records [7,46]. These capabilities are particularly relevant to construction procurement, which often suffers from fragmented processes and a lack of trust among stakeholders.

However, several important gaps remain in the scholarly discourse:

- While BT has been widely discussed in general supply chains [47], there have been limited empirical studies specifically addressing its application within SCPM. Existing research often centers around public blockchains or cryptocurrency-focused systems, with insufficient emphasis on the potential of private or consortium blockchains tailored for construction procurement with sustainability mandates [6,48].
- Although studies have examined BT adoption in construction [49,50], many focus on perceived benefits or general intentions. Few have systematically identified and evaluated the critical drivers that influence adoption in sustainability-driven procurement environments, where environmental, social, and governance (ESG) goals play a central role [51,52].
- The current literature lacks robust analytical models that employ Multi-Criteria Decision-Making (MCDM) techniques, such as Fuzzy Delphi, AHP, or DEMATEL, to prioritize BT adoption factors in SCPM. Most contributions remain at a conceptual level or offer generalized roadmaps, without presenting structured frameworks that can support practical implementation and policymaking [53,54].

Based on these observed gaps, this study aims to provide a grounded and methodologically robust framework for identifying and evaluating key drivers of BT adoption in SCPM. By combining expert input with integrated MCDM techniques, this research aspires to inform both theoretical understanding and practical decision-making in sustainable construction procurement contexts.

## 3. Research Methodology

The research methodology for this study is structured into three sequential phases, as illustrated in the research flow chart (Figure 1). The first phase involves identifying the drivers for the adoption of BT in SCPM through a comprehensive literature review and expert consultations. The second phase focuses on data collection to validate and refine the identified drivers. The third phase involves data analysis using a hybrid approach combining fuzzy DEMATEL, k-means clustering, and social network analysis (SNA) to evaluate the drivers and their interrelationships. This phased approach ensures a systematic pathway from conceptualization to empirical analysis.

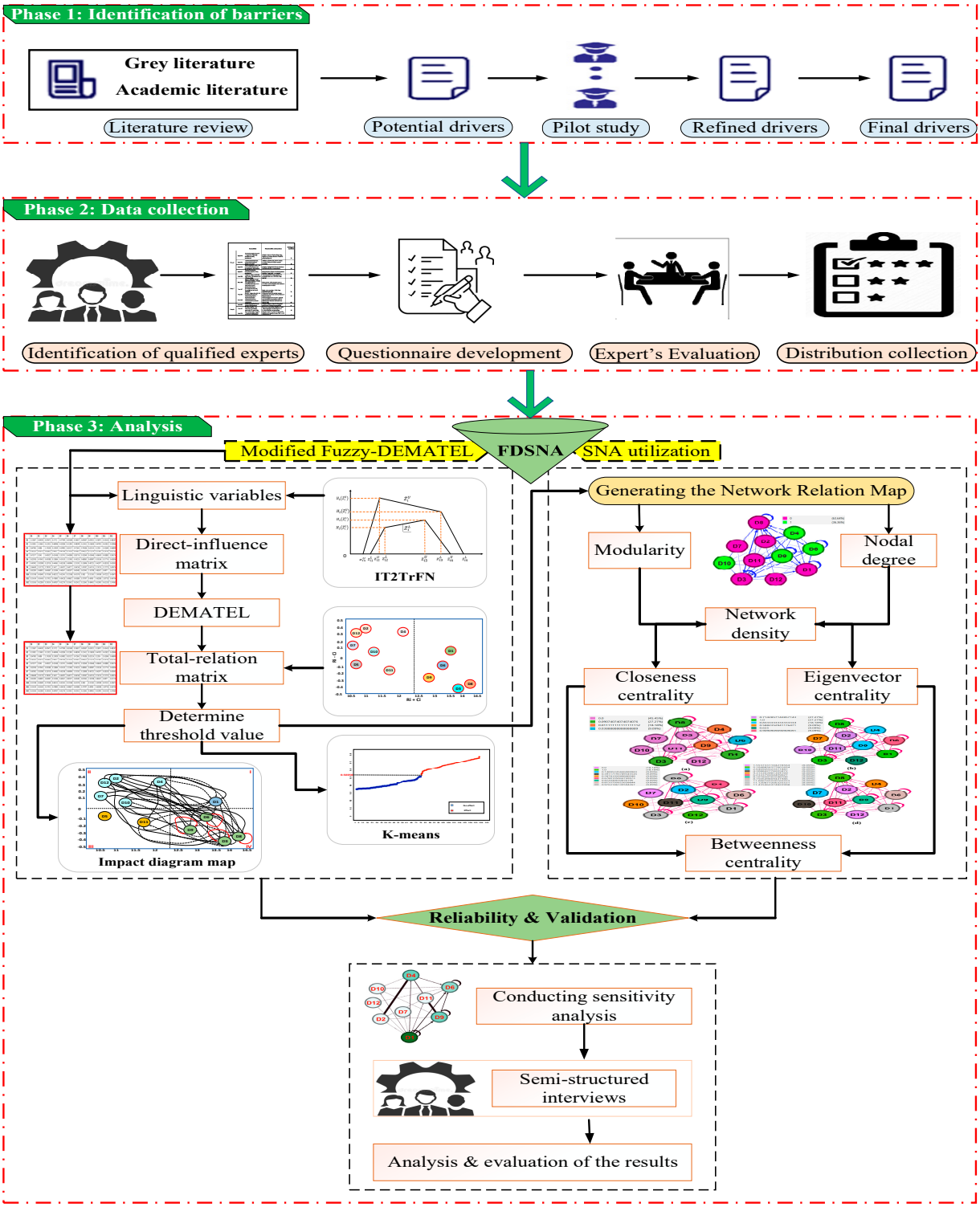



**Figure 1.** Research framework.

### *3.1. Phase 1: Identification of Drivers*

This section outlines the process of identifying and validating the drivers for BT adoption in SCPM. Initially, a comprehensive review of academic literature and grey literature (including government, industry, and project reports) was conducted to extract a preliminary list of 32 potential drivers [55]. To ensure robust validation, a panel of 13 experts was formed, with selection criteria requiring each expert to have at least 3 years of direct experience in construction procurement and a professional background in the construction

industry or academia [56]. The number 13 was chosen following recommendations from expert elicitation studies, which suggest that panels of 10–15 participants are sufficient to ensure diversity and reliable feedback while maintaining feasibility for in-depth discussions. An expert discussion was conducted via Zoom Meeting to evaluate and refine the identified drivers [9]. During the session, experts assessed the relevance and clarity of the 32 drivers and proposed organizing them into broader thematic categories. For example, the driver "Stability of the system" was expanded to include related elements such as transparency, security, elimination of intermediaries, and trustworthiness [11,57]. Based on iterative consensus, the 32 drivers were consolidated into 12 overarching categories to enhance clarity and usability. This refined set of 12 drivers forms the foundation for subsequent analysis in this study (Table 1).

**Table 1.** List of drivers with description.

| Drivers | Code | Description | References |
| --- | --- | --- | --- |
| Stability of the system | D1 | The four variables in assessing system robustness are transparency, security, removing intermediaries, and trustworthiness. After integrating BT into the SCPM, all of these characteristics made the SCPM and system more robust and sustainable, due to the transparency in information flow, stability of data, and peer-to-peer transactions that did not involve a third party. | [2–5,58] |
| Cost of the overall project | D2 | Three variables are combined to form the overall cost, energy, and project costs. The overall SCPM cost encompasses all financial investments, including documentation fees, stationery expenses, human resources costs, electricity costs, facility costs, and documentation incurred during production, among other expenses. | [15–18] |
| The overall performance of the project | D3 | The project's overall performance is measured by the efficiency, effectiveness, and speed with which the job is performed, characterized by low response times, high standardization, and reduced complexity of the work. A composite of five variables is built by examining the correlations between efficiency, speed, automation, simplification of current paradigms, and sharing demand in SCPM. | [9,37,59–62] |
| Decentralization and data security | D4 | By experts under the name data safety and decentralization, a group of four variables is grouped. All people involved directly or indirectly in the system need records and information regarding standardization, production, and supply. It is only on BT-integrated SCPM that it is possible to hack, change, control, or lose data for any reason. | [12,21,63–65] |
| Adaptability | D5 | Regarding adaptability, three variables—traceability, visibility, and identifying issues—form an ordinary driver. Using IoT/Industry 4.0, adaptability means tracking causes, goods location, accidents, and fraud between a SCPM's manufacturing and end-use processes. | [24–27] |

**Table 1.** *Cont.*

| Drivers | Code | Description | References |
|---|---|---|---|
| Policies and laws | D6 | A significant amount of time and effort is required to document laws and policies. Documentation plays a crucial role in all contracts, but public ledger technology provides transparency, speeds up work, checks for corruption in government, and also helps identify scams within any organization. The importance of data records for any legal action cannot be overstated. This technology does not allow for the deletion or modification of data, ensuring that there can be no fraud. Laws and government policies have been taken into account in the design to ensure accessibility. | [23,26,28,29,61] |
| The system with innovative features | D7 | With the intelligent system, smart contracts are implemented, invoicing is simplified, and inventory levels are improved. By eliminating fraud in documentation, ensuring timely tax payments, and ensuring the timely delivery of goods from the shipyard area, the system eliminates documentation fraud. | [29–32] |
| Satisfaction of customers | D8 | Feedback and customer centricity are the basis of customer satisfaction. The customer is satisfied when they provide positive feedback and respond positively. To achieve this, it is necessary to deliver the right product with the correct information at the right time, place, and in the right hands and commit to providing periodic service after the sale. | [23,33,34,36–38] |
| The system with high reliability | D9 | Four key drivers determine the Reliability of Systems: Scalability, Reliability, Durability, and the ability to withstand data loss. A record of the raw, semi-finished, and finished material is kept at every BT location. By maintaining accurate information about goods, IT saves time and money. | [19,20,23,34,59] |
| Detailed documentation | D10 | Auditable, accounting, and ecosystem documentation are part of the documentation. In BT, integration is preferred for several reasons, including smooth auditing processes, simplified financial systems, and seamless currency flow. | [3,12,23,33,34] |
| A data management system | D11 | A data management system controls access to data from end-users, simultaneously manipulates transactions from a single account, eliminates human error in documentation and other tasks, and enables real-time information flow. Three variables are considered in data management: data quality, flow and control of information, and access control. | [4,5,37,38,58] |
| High-quality | D12 | Quality assurance and quality fairness are drivers that affect quality. Any irregularity in the process, transportation, raw material specification, or the final product is considered a quality issue. The availability of complete information and the elimination of human error are key. | [2,23,66,67] |

### *3.2. Phase 2: Data Collection*

The second phase involved a broader expert group to evaluate and assign weights to the 12 drivers. The study population consisted of professionals with substantial expertise in BT and SCPM. While the Phase 1 panel (13 experts) refined the driver list, Phase 2 relied on a separate, larger group of 27 experts to assess the relative importance of each driver. This clarification directly addresses the reviewer's query: the same 13 experts were not reused but were complemented by a more diverse pool of academics and practitioners for this phase. The sampling method began with a pilot study involving four SCPM specialists to refine the questionnaire and ensure its relevance to the local context (see Appendix C). Following this, 40 experts were invited to participate in the survey, from which 27 were selected [57,68]. This group comprised 16 academics actively involved in blockchain and SCPM research, as well as 11 practitioners with management or technical roles in the construction and procurement industries (see Table 2). The selected experts had over 3 years of experience in their respective fields, with academics averaging 16.14 years of experience (standard deviation: 9.11 years) and practitioners averaging 19.08 years (standard deviation: 7.12 years). Before the survey, all participants underwent a briefing session on BT and SCPM concepts to ensure a uniform understanding of the study's objectives and criteria. The weights assigned by experts reflect the perceived significance of each driver relative to SCPM goals such as cost efficiency, transparency, and sustainability. To ensure all participants had a solid understanding of the study's context, they received training on BT and SCPM before completing the questionnaires. This approach aimed to enhance the reliability of the data and ensure a thorough understanding of the research objectives [69–72].

**Table 2.** Details of the experts participating in this study.

| Categories | Size of the Company | Occupations | Degree | Years of Experience | |
|---|---|---|---|---|---|
| | | | | Construction | Procurement |
| Practitioner | More than 3000 employees | Technical specialist | M.Eng | More than 15 | Between 6 and 10 |
| | More than 5000 employees | Project Manager | M.Eng | More than 15 | Between 6 and 10 |
| | More than 5000 employees | Technical specialist | M.Eng | More than 15 | Between 6 and 10 |
| | More than 4000 employees | Legal Manager | M.Eng | More than 15 | Between 6 and 10 |
| | More than 5000 employees | Senior engineer | M.Eng | More than 15 | Between 6 and 10 |
| | More than 10,000 employees | Quality Manager | B.Eng | More than 15 | Between 1 and 5 |
| | More than 5000 employees | Project Supervisor | B.Eng | Between 6 and 10 | Between 6 and 10 |
| | More than 5000 employees | Technical specialist | B.Eng | Between 11 and 15 | Between 6 and 10 |
| | More than 10,000 employees | Project Supervisor | M.Eng | More than 15 | Between 6 and 10 |
| | More than 5000 employees | Project Supervisor | M.Eng | Between 11 and 15 | Between 6 and 10 |
| | More than 5000 employees | Technical specialist | B.Eng | More than 15 | Between 6 and 10 |
| | More than 5000 employees | Project Manager | M.Eng | Beween 11 and 15 | Between 6 and 10 |
| | More than 5000 employees | Consultant | M.Eng | Between 11 and 15 | Between 6 and 10 |
| Academic | More than 1000 employees | Professor | PhD | More than 15 | Between 1 and 5 |
| | More than 5000 employees | Professor | PhD | More than 15 | Between 6 and 10 |
| | More than 2000 employees | Professor | PhD | More than 15 | Between 6 and 10 |
| | More than 5000 employees | Professor | PhD | More than 15 | Between 6 and 10 |

**Table 2.** *Cont.*

| Categories | Size of the Company | Occupations | Degree | Years of Experience | |
|---|---|---|---|---|---|
| | | | | Construction | Procurement |
| Academic | More than 1000 employees | Professor | PhD | More than 15 | Between 6 and 10 |
| | More than 7000 employees | Assistant Professor | PhD | Between 6 and 10 | Between 1 and 5 |
| | More than 6000 employees | Associate Professor | PhD | Between 11 and 15 | Between 1 and 5 |
| | More than 5000 employees | Professor | PhD | More than 15 | Between 6 and 10 |
| | More than 5000 employees | Associate Professor | PhD | Between 11 and 15 | Between 1 and 5 |
| | More than 2000 employees | Assistant Professor | PhD | Between 6 and 10 | Between 1 and 5 |
| | More than 2000 employees | Assistant Professor | PhD | Between 6 and 10 | Between 1 and 5 |
| | More than 5000 employees | Associate Professor | PhD | Between 11 and 15 | More than 10 |
| | More than 5000 employees | Assistant Professor | PhD | Between 6 and 10 | Between 1 and 5 |
| | More than 7000 employees | Assistant Professor | PhD | Between 6 and 10 | Between 1 and 5 |

The research was conducted in Tamil Nadu, a large state located in the southern part of India. In recent years, people from rural areas have migrated to cities due to their moderate climate. Many construction projects have been launched to meet this increased demand. In this study, this region is an ideal case study since it has a high number of construction projects, and there are several reported fatalities. The researchers conducted additional interviews with several experts who had not been previously selected to validate the findings obtained through the advanced fuzzy-based algorithm, k-means clustering, and social network analysis technique. To enhance the reliability of findings, this study was conducted in Tamil Nadu, a region with high construction activity and reported procurement challenges. Nine additional experts (distinct from the earlier groups) were interviewed in a semi-structured format to validate the identified drivers and assigned weights using advanced fuzzy-based algorithms, k-means clustering, and social network analysis. Their profiles, which include experience levels exceeding 15 years in civil engineering and procurement, are provided in Table 3.

**Table 3.** Description of the experts for validation.

| Interviewees | Degree | Years of Experience | Occupations |
|---|---|---|---|
| 1 | M.Eng | 21 | Civil Engineering |
| 2 | B.Eng | 26 | Civil Engineering |
| 3 | B.Eng | 18 | Civil Engineering |
| 4 | M.Eng | 24 | Civil Engineering |
| 5 | B.Eng | 19 | Civil Engineering |
| 6 | B.Eng | 17 | Civil Engineering |
| 7 | M.Eng | 20 | Civil Engineering |
| 8 | M.Eng | 25 | Civil Engineering |
| 9 | B.Eng | 16 | Civil Engineering |

### *3.3. Phase 3: Data Analysis*

#### 3.3.1. Modified Fuzzy DEMATEL Method

Traditional DEMATEL cannot directly convert qualitative judgments in the linguistic variables into crisp numbers due to the inherent vagueness of human thought. This makes assigning an accurate and reasonable threshold value challenging because experts' experiences determine it. Two aspects of the DEMATEL method are improved using IT2TrFNs: (1) Experts' evaluations are represented through IT2TrFNs, allowing for more efficient information transfer. (2) K-means clustering is used instead of subjective judgment to optimize the threshold value. The modification of the DEMATEL technique is derived from the IT2TrFN theory. A detailed explanation of the modified fuzzy DEMATEL approach (proposed by [73]) and the use of Trapezoidal Fuzzy Number Type-II Interval is provided in Appendix C, along with the complete computational framework. The following steps are involved in the modified fuzzy DEMATEL.

Step 1. Establishing expert-driven matrices of direct impact.

To make impact judgments, decision-makers should conceptualize drivers as semantic values. Assuming they are responsible for analyzing the relationship between drivers [73], decision-makers can provide the impact matrix directly as semantic values [74]:

$$D^k = \begin{bmatrix} d_{11} & d_{12} & \cdots & d_{1n} \\ d_{21} & d_{22} & \cdots & d_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ d_{n1} & d_{n2} & \cdots & d_{nn} \end{bmatrix} \quad (1)$$

The mapping between semantic values and IT2TrFN is complete when $aij = LVij\ Pij$ describes the effect of driver $i$ on driver $j$, where $LVij$ represents the semantic value and $Pij$ represents the decision-maker's membership. Celik et al. [75] present the mapping relations in Table 4. The following is the matrix of direct influence:

$$\overset{\approx}{D}^k = \begin{bmatrix} e_{11} & e_{12} & \cdots & e_{1n} \\ e_{21} & e_{22} & \cdots & e_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ e_{n1} & e_{n2} & \cdots & e_{nn} \end{bmatrix} \quad (2)$$

**Table 4.** Linguistic variables are presented along with their corresponding IT2TrFNs.

| Linguistic Terms | IT2TrFNs |
|---|---|
| No influence (NI) | (0.1,0.1,0.1,0.1;1,1,0.1,0.1,0.1,0.1;1,1) |
| Very low influence (VL) | (0.1,0.2,0.4,0.5;1,1,0.12,0.22,0.38,0.48;0.8,0.8) |
| Low influence (L) | (0.3,0.4,0.6,0.7;1,1,0.32,0.42,0.58,0.68;0.8,0.8) |
| High influence (H) | (0.5,0.6,0.8,0.9;1,1,0.52,0.62,0.78,0.88;0.8,0.8) |
| Very high influence (VH) | (0.7,0.8,0.9,0.9;1,1,0.72,0.82,0.8,0.9;0.8,0.8) |

The overall averaged matrix should be calculated based on a determined weight for each expert. Due to the varying backgrounds of each expert, including their professional titles and job experience, this is more challenging in practice. The ordered weighted averaging operation (OWD) [76] was considered for this study. A fuzzy number of interval type-II can be expressed in the following manner with the OWA operator [77]:

$$OWD\left(e_{ij}^{1}, e_{ij}^{2}, \cdots, e_{ij}^{k}\right) = \bigoplus_{k=1}^{K}\left(\omega_k e_{ij}^{k}\right) \tag{3}$$

An expert k decides to weigh the weight of driver i based on their decision; bk ij represents the influence of driver i on driver j due to that expert's decision.

Step 2. Creating the matrix of direct influences that are normalized.

Criteria are selected based on the maximum value:

$$\text{Maxvar} = max\left(\underset{1\le i\le n}{max}\sum_{i=1}^{n} e_{ij}, \underset{1\le j\le n}{max}\sum_{j=1}^{n} e_{ij}\right) \tag{4}$$

As a result, let us look at the normative matrix directly:

$$M = \left(\frac{y_{ij}}{Maxvar}\right)_{n\times n} \tag{5}$$

Step 3. The total-relation matrix can be calculated by using the formula below.

$$T = \left(M + M^2 + M^3 + \cdots + M^k\right) = \sum_{k=1}^{\infty} M^k = M(I - M)^{-1} \tag{6}$$

$$T - \left[c_{ij}\right]_{n\times n} i, j \in \{1, 2, 3, \cdots, n\} \tag{7}$$

When there are n units in I, IT2TrFN is used to express $C_{ij}$.

Step 4. Estimating influence severity and prominence.

The total-relation matrix shows the degree of influence for each row and column. Calculations are based on the following formulas:

$$D_i - \sum_{j=1}^{n} c_{ij}, (i = 1, 2, 3, \cdots, n) \tag{8}$$

$$R_i = \sum_{j=1}^{n} c_{ji}, (i = 1, 2, 3, \cdots, n) \tag{9}$$

Step 5. By using K-Means clustering, confirm thresholds.

Using the k-means clustering algorithm, CIJ is determined. The clustering of all $C_{ij}$ is set to 2 when the parameter of cluster number is set to 2. The objective function is then calculated by using Equation (1). Once both center point sets are equal, the algorithm terminates, which means $|SSEn - SSEn - 1| < \varepsilon$ ($\varepsilon$ is selected). If this is not the case, the distance calculation should be repeated with the updated centroids.

Step 6. A map of impact digraphs is constructed.

Follow step 4 to calculate $Di + Ri$ to determine the centrality of the evaluation driver list, which indicates the importance of each factor; $Di - Ri$ for determining the cause importance of an element. Obstacle elements with a positive cause degree are classified as cause elements. Classification will be made if the result element group does not meet the criteria. The weight of a driver indicates its importance within the driver system. To calculate the results, follow the formula below.

$$W_i = \frac{\sqrt{D_i^2 + R_i^2}}{\sum_{i=1}^{n}\sqrt{D_i^2 + R_i^2}} \tag{10}$$

The selection of the modified fuzzy DEMATEL approach using IT2TrFN was motivated by its ability to handle higher-order uncertainties and capture the vagueness inherent in expert judgments, which traditional Type-I fuzzy sets cannot adequately represent. IT2TrFN effectively models both primary and secondary uncertainties, providing a more reliable

representation of subjective evaluations [78–81]. Furthermore, k-means clustering was integrated to objectively determine the threshold for constructing the NRM, replacing the conventional reliance on subjective expert opinion. By grouping influence values (Cij) into statistically distinct clusters, k-means ensures that the threshold reflects the natural separation within the data. To validate the robustness of this selection, a sensitivity analysis was conducted by testing alternative cluster numbers (K = 2, 3), which yielded consistent results. Additional diagnostics, such as within-cluster sum of squares (WCSS) and silhouette scores, confirmed the quality of the clustering. This hybrid approach thus enhances both the precision and objectivity of the causal mapping process.

#### 3.3.2. Social Network Analysis

The analysis of social networks using network and graph theory, known as social network analysis (SNA), examines various social networks that impact their actors differently [82]. As reported by Sodhro et al. [83], the nodes and edges within social networks have predefined content. Depending on how the edges interact, actors can have "directed" or "undirected" relationships. Through several metrics, SNA reveals complex relationships between nodes. SNA is used in this study in the following way:

Step 1: NRM (Network Relation Map) generation: This diagram provides a clear understanding of the problem by simplifying a complex system into manageable segments. A threshold is established during the development of the NRM to reduce complexity and identify significant obstacles. Thus, only relationships with a threshold value greater than the T-relation matrix must be mapped to the graph. There are two options to determine the threshold for creating the NRM. In the total relationship matrix, the average can be calculated based on the opinions of expert consultants [84]. If a relationship was more significant than the threshold, the relationship between the main drivers was filtered. The network and the critical links between the drivers are then imported into Gephi (version 0.10) for examination and visualization.

Step 2. Analysis: The complex interrelationships among potential drivers are explored using several metrics:

(1) Network density: Divide the total number of connections by the maximum number of connections to obtain the network density. The potential density of drivers can vary from 0 (no connections) to 1 (all possible connections), depending on the number of connections. Node networks become denser and more cohesive as the motus value increases. A dense network allows for better communication than a sparse network.

(2) Modularity: Groups, clusters, or communities are defined as modules by their modularity [85]. Modularity is used to optimize network methods for detecting community structures. Internal components are complex in clusters with high modularity, and there are dense connections between potential drivers. In a network with high modularity, there is a significant degree of connectivity between potential drivers.

(3) Nodal weighted degree: Drivers are sized according to how many connections (edges) they have with other drivers, forming the 12 potential drivers. Adding the weights of all the edges of the drivers determines their weighted degree. A network's weighted degree of nodes can give more significance to inward edges than outward edges. Specifically, the inward edges are weighted based on their total weight. A net weighted degree is calculated by subtracting an in-degree score from an out-degree score. Weighed edges show that a driver with the greatest impact on its neighbor has a greater likelihood of having a negative effect on it than a driver with a smaller impact.

(4) Betweenness centrality: As a driver appears on the shortest path between other drivers, it is said to have betweenness centrality. As indicated by this indicator, some of the 12 potential drivers in the network function as "bridges". A driver in a network with

high betweenness centrality holds significant power and control over the network, as more information passes through it, assuming that data is transmitted along the shortest path.

(5) Closeness centrality: Measurement of the closeness centrality of the network can be conducted using the distance centrality indicator. Based on this measure, one can compute the average distance between all drivers in the network. When two drivers are located close to each other, they can easily communicate and influence one another without involving multiple intermediaries.

(6) Eigenvector centrality: Using the number of connections within the network, one can determine an eigenvector driver's centrality. High-scoring drivers require higher scores on the eigen centrality analysis than those that do not.

## 4. Results

### *4.1. Analysis Results*

Table 5 presents the results of the fuzzy DEMATEL analysis, which utilizes the following Equations (6)–(10) to compute each driver's prominence ($Ri + Ci$), net influence ($Ri - Ci$), and relative importance (weight). Here, $Ri$ represents the total influence a driver exerts on others, while $Ci$ represents the total influence it receives from others. The values of $Ri + Ci$ indicate the centrality of each driver in the system, whereas $Ri - Ci$ distinguishes cause factors (positive values) from effect factors (negative values). The weight column reflects the normalized importance of each driver within the network, derived through the defuzzification process applied to the fuzzy influence matrix.

**Table 5.** Values of $Ri$, $Ci$, $Ri + Ci$, and $Ri - Ci$ for the driver.

| | ***Ri*** | ***Ci*** | ***Ri + Ci*** | ***Ri − Ci*** | **Weight** |
|---|---|---|---|---|---|
| D1 | 6.801543 | 6.720673 | 13.52222 | 0.08087 | 0.093236 |
| D2 | 5.631987 | 5.284317 | 10.9163 | 0.347671 | 0.083007 |
| D3 | 6.707044 | 7.107573 | 13.81462 | −0.40053 | 0.114555 |
| D4 | 6.315886 | 5.939657 | 12.25554 | 0.376229 | 0.114775 |
| D5 | 5.093696 | 5.136026 | 10.22972 | −0.04233 | 0.108224 |
| D6 | 6.459117 | 6.58895 | 13.04807 | −0.12983 | 0.154793 |
| D7 | 5.358921 | 5.22465 | 10.58357 | 0.134271 | 0.14855 |
| D8 | 6.87887 | 7.254008 | 14.13288 | −0.37514 | 0.232977 |
| D9 | 6.344795 | 6.570017 | 12.91481 | −0.22522 | 0.277563 |
| D10 | 5.745256 | 5.714912 | 11.46017 | 0.030344 | 0.34093 |
| D11 | 5.595075 | 5.77906 | 11.37413 | −0.18398 | 0.513407 |
| D12 | 5.583879 | 5.196229 | 10.78011 | 0.38765 | 1.00000 |

The comprehensive influence factors obtained from the fuzzy DEMATEL total-relation matrix were further classified using the k-means clustering algorithm to differentiate between significant and negligible influences. This step refines the fuzzy DEMATEL output by objectively determining the thresholds for "effect" and "no effect" relationships, rather than relying on subjective expert judgment. The clustering analysis identified the upper and lower bounds of the "no impact" range as [0.0729, 0.1719] and [0.1745, 0.3035], as illustrated in Figure A1. Based on this analysis, a threshold value of 0.50358 (Figure 2) was derived, where 88 total-relation indices below this threshold were classified as "no effect", and 63 indices above this value were classified as "effect". This threshold-based classification provides the foundation for constructing the Network Relation Map (NRM),

which is subsequently analyzed through Social Network Analysis (SNA) to uncover the interrelationships and centrality of drivers.

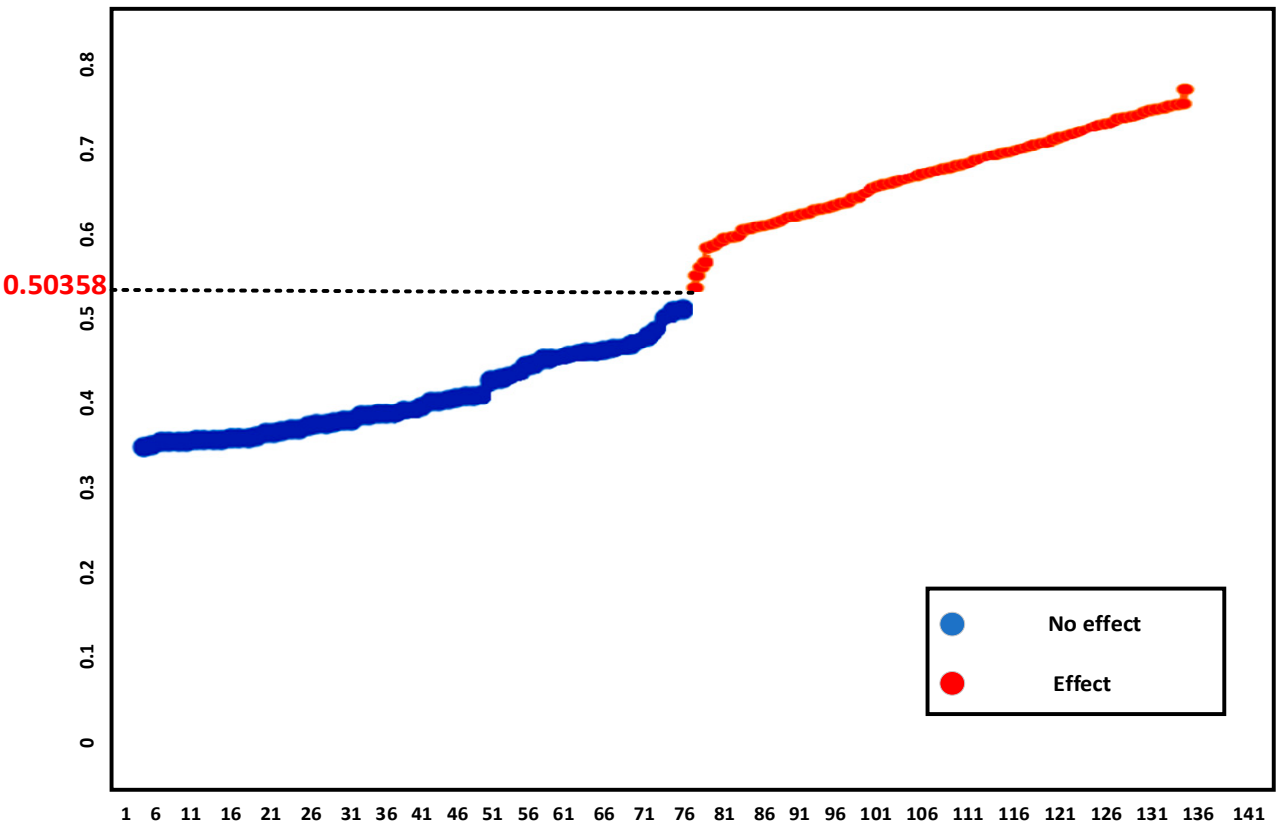



**Figure 2.** Total-relation index classification by the k-means clustering algorithm.

Figure A2 illustrates how the investment drivers interact with one another intuitively. A digraph map is presented in Figure 3, where the horizontal axis represents the centrality degree (i.e., the overall importance of each driver in the network), and the vertical axis represents the cause degree (i.e., the extent to which a driver influences others). Drivers located in Quadrant I are considered cause factors, meaning they exert a strong influence on the system and should be prioritized for intervention. Conversely, drivers in Quadrants III and IV are effect factors, which are more reactive and influenced by others. The priority for strategic focus follows the order: Quadrant I (most important), then Quadrant II, Quadrant IV, and finally Quadrant III.

To further explore these relationships, the Network Relationship Map (NRM) is constructed using Gephi, as shown in Figure 4, based on a threshold value of 0.50358, derived from the average total influence score. This filtering ensures that only the most meaningful interactions are included. The network consists of 12 drivers and 213 connections, with each node representing a driver and arrows indicating influence pathways. The network's density is calculated to be 0.818, suggesting that most drivers are directly connected. The average path length of 1.27 and a network diameter of 2 imply that communication or influence flows easily between drivers, which is ideal for coordinated implementation strategies in firms.

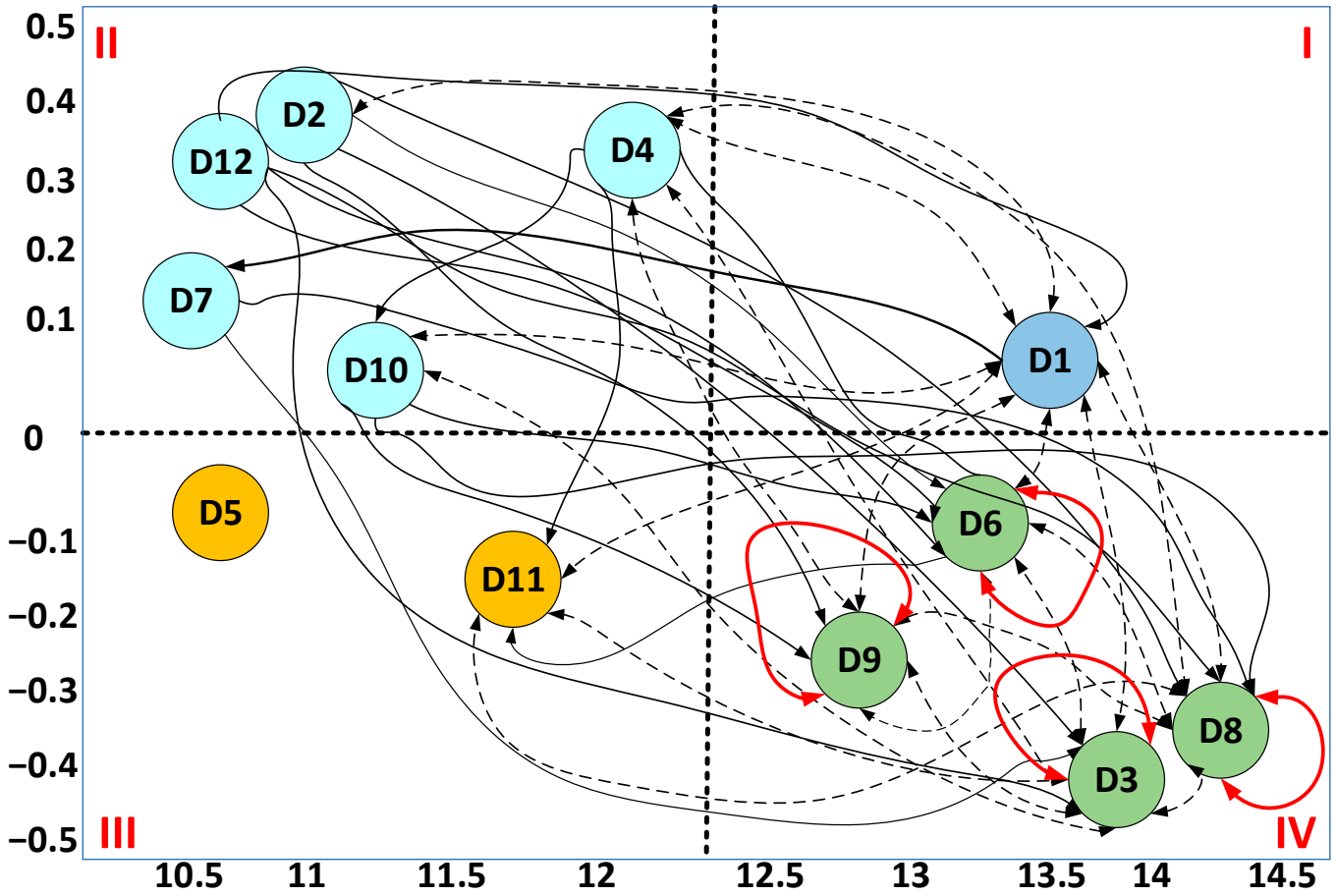



**Figure 3.** Diagraph map of impact (note: dashed-line arrows indicate two-way relations; solid-line arrows indicate one-way relations).

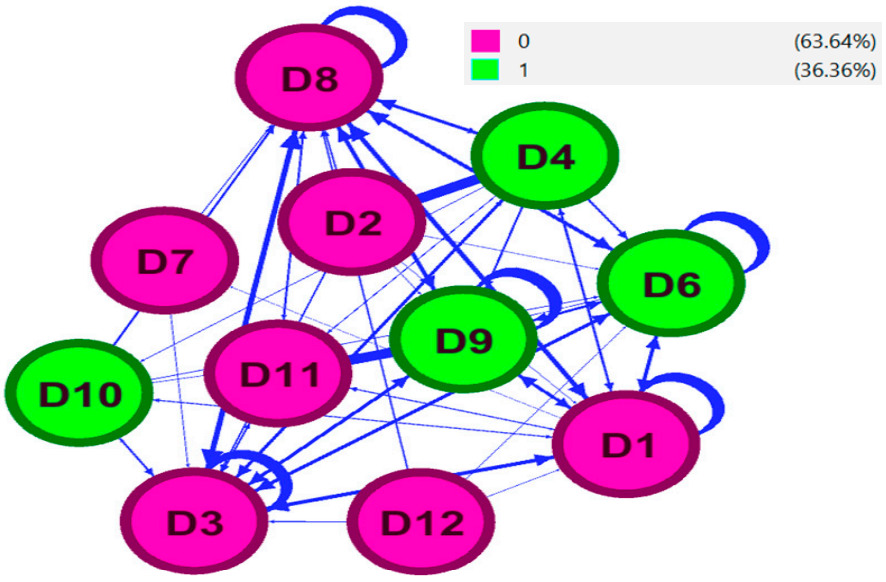



**Figure 4.** Clusters of the 12 drivers.

Furthermore, the modularity value of 0.013, derived from community detection algorithms, suggests low clustering, indicating that the drivers form a highly integrated network rather than fragmented subgroups. In practice, this suggests that Indian construction firms adopting blockchain may encounter challenges in forming cohesive implementation teams

or silos. However, the low modularity also implies strong communication and alignment across various drivers, which could be leveraged to implement blockchain in a more unified and strategic manner across departments and functions.

Several measures can be used to analyze the impact of each driver on the entire NRM, including betweenness centrality, closeness centrality, and eigenvector centrality. The scores for these measures are listed in Table 5, while the driver network maps for each measure are displayed in Figure 5a–d. As indicated by their highest closeness centrality scores, the drivers with the shortest path to other drivers are D1, D3, and D8. These drivers are at the center of the network, as demonstrated in Figure 5b, with the highest betweenness centrality scores indicating their control over the relationships among drivers. In addition, D3, D8, and D1 had the highest eigenvector centrality scores, as shown in Table 6 and Figure 5c, due to their connections with highly influential nodes. It is essential to note that although D5 does not directly impact other drivers, its connections and susceptibility to the impact of other drivers make it crucial to the entire network map. Indian construction firms have utilized BT to hinder the development of clusters within their networks, as illustrated in Figure 5, where colors denote groups of clusters.

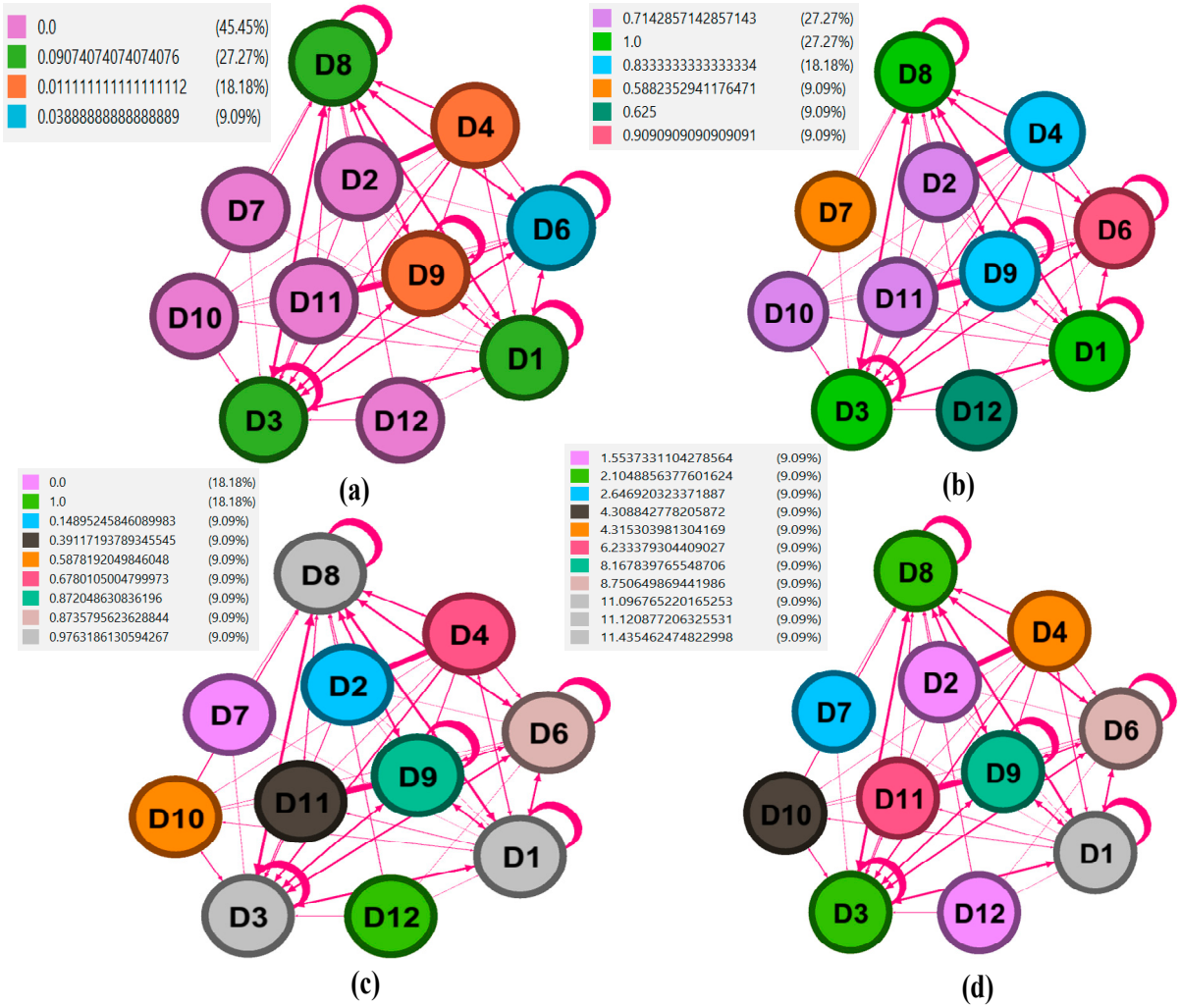



**Figure 5.** The NRM is created by considering the following drivers: (**a**) the betweenness centrality, (**b**) the closeness centrality, (**c**) the weighted degree, and (**d**) the eigenvector centrality status.

**Table 6.** Ranking of drivers based on different measures.

| Drivers | Closeness | Rank | Betweenness | Rank | Eigenvector | Rank |
|---|---|---|---|---|---|---|
| D1 | 1.0000 | 1 | 0.9074 | 1 | 0.97632 | 2 |
| D2 | 0.7143 | 4 | 0.0000 | 5 | 0.00000 | 8 |
| D3 | 1.0000 | 1 | 0.0907 | 2 | 1.00000 | 1 |
| D4 | 0.8333 | 3 | 0.0111 | 4 | 0.58782 | 5 |
| D5 | 0.0000 | 7 | 0.0000 | 5 | 0.00000 | 8 |
| D6 | 0.9091 | 2 | 0.0389 | 3 | 0.87358 | 3 |
| D7 | 0.5882 | 6 | 0.0000 | 5 | 0.14895 | 7 |
| D8 | 1.0000 | 1 | 0.0907 | 2 | 1.00000 | 1 |
| D9 | 0.8333 | 3 | 0.0111 | 4 | 0.87205 | 3 |
| D10 | 0.7143 | 4 | 0.0000 | 5 | 0.39117 | 6 |
| D11 | 0.7143 | 4 | 0.0000 | 5 | 0.67801 | 4 |
| D12 | 0.6250 | 5 | 0.0000 | 5 | 0.00000 | 8 |

The nodal degree has traditionally been measured by measuring the number of direct ties between nodes in social network analysis (SNA) [10]. However, these studies did not consider the relative weight of each node's influence on the entire network. To address this limitation, FDSNA was developed, which leverages the driver's influence weight calculated by DEMATEL in SNA analysis. By doing so, FDSNA can compute both the nodal and the weighted nodal degrees.

A weighted nodal degree is derived by summing up the weighted in-degrees and weighted out-degrees of the nodal drivers in Figure 5d. Those drivers with stronger connections, such as D1, D3, and D8, are centrally placed, while those with weaker ones are located at the sides of the graph. The thickness of the arrows represents the influence of the interconnections between the drivers. A net weight degree and a net degree value are also presented in Table 7. The effect factor D3, however, is considered to have a high net degree value despite its high net degree value. The net weight degrees of D3, D8, and D1 are the highest in Table 7, whereas the three nodal degrees are D3, D8, and D1. Accordingly, higher net nodal degrees are not necessarily associated with more significant net influences on others. Therefore, the FDSNA approach is given preference over the SNA approach.

**Table 7.** A description of the net weight degree status.

| Label | Weight Degree | Rank | Weighted Out-Degree | Net Weight | Rank | Out-Degree | Degree | Net Degree | Rank |
|---|---|---|---|---|---|---|---|---|---|
| D1 | 5.7553 | 3 | 5.34147 | 11.0968 | 3 | 9 | 19 | 10 | 2 |
| D2 | 0.0000 | 10 | 2.64692 | 2.6469 | 9 | 5 | 5 | 0 | 9 |
| D3 | 6.6165 | 2 | 4.81892 | 11.4355 | 1 | 8 | 19 | 11 | 1 |
| D4 | 2.1848 | 7 | 4.04860 | 6.2334 | 6 | 7 | 11 | 4 | 4 |
| D5 | 0.0000 | 10 | 0.00000 | 0.0000 | 12 | 0 | 0 | 0 | 9 |
| D6 | 5.1674 | 4 | 3.58322 | 8.7507 | 4 | 6 | 15 | 9 | 3 |
| D7 | 0.5060 | 9 | 1.04772 | 1.5537 | 11 | 2 | 3 | 1 | 8 |
| D8 | 6.7520 | 1 | 4.36891 | 11.1209 | 2 | 7 | 18 | 11 | 1 |
| D9 | 4.6335 | 5 | 3.53429 | 8.1678 | 5 | 6 | 14 | 8 | 4 |

**Table 7.** *Cont.*

| Label | Weight Degree | Rank | Weighted Out-Degree | Net Weight | Rank | Out-Degree | Degree | Net Degree | Rank |
|---|---|---|---|---|---|---|---|---|---|
| D10 | 1.5858 | 8 | 2.72950 | 4.3153 | 7 | 5 | 8 | 3 | 7 |
| D11 | 2.6659 | 6 | 1.64290 | 4.3088 | 8 | 3 | 8 | 5 | 5 |
| D12 | 0.0000 | 10 | 2.10489 | 2.1049 | 10 | 4 | 4 | 0 | 9 |

A network can be analyzed using SNA metrics and statistics to identify key influencers. The SNA metrics closeness and betweenness centrality, eigenvector centrality, and weighted degree give more weight to drivers scoring high in these metrics. Based on the results of SNA metrics, Table 8 displays the top three drivers for five SNA indicators. Five times more frequently than the remaining top three SNA metrics, D3 and D8 are the most critical.

**Table 8.** Key drivers for the five SNA indicators.

| Driver ID | Key Drivers | SNA Indicator |
|---|---|---|
| D1 | Stability of the system | Betweenness centrality |
| D3 | The overall performance of the project | Betweenness centrality |
| D8 | Satisfaction of customers | Betweenness centrality |
| D1 | Stability of the system | Closeness centrality |
| D3 | The overall performance of the project | Closeness centrality |
| D8 | Satisfaction of customers | Closeness centrality |
| D3 | The overall performance of the project | Eigenvector centrality |
| D8 | Satisfaction of customers | Eigenvector centrality |
| D1 | Stability of the system | Eigenvector centrality |
| D8 | Satisfaction of customers | Weighted degree |
| D3 | The overall performance of the project | Weighted degree |
| D1 | Stability of the system | Weighted degree |
| D3 | The overall performance of the project | Net weighted degree |
| D8 | Satisfaction of customers | Net weighted degree |
| D1 | Stability of the system | Net weighted degree |

### *4.2. Sensitivity Analysis*

A sensitivity analysis was conducted to test the proposed NRM's strength. To assess the network's sensitivity to the removal of crucial drivers, D3 and D8 were excluded as the main drivers, resulting in a new network consisting of nine nodes and 29 edges, as depicted in Figure 6. After thoroughly analyzing the new network, three notable observations emerged. Firstly, the new network exhibits a reduced level of complexity, boasting a density of 0.403, considerably lower than the original network's density of 0.818. Secondly, there was an increase in the network diameter and average path length, which now stand at 2 and 1.17, respectively, in contrast to the original network's 2 and 1.27. Table 9 illustrates the significant impact on the SNA metrics for the entire network resulting from the exclusion of D3 and D8. Consequently, several nodes can have a negative impact on the new network. Based on the results of this research, it appears that removing D3 and D8, which displayed the strongest interconnections with other drivers, led to reduced network complexity and more significant challenges when sharing information.

This underscores the effectiveness and robustness of the proposed FDSNA approach in visualizing the intricate interrelationships between drivers and identifying key drivers.

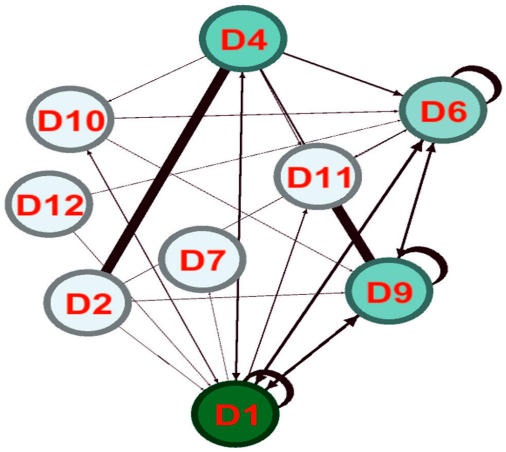



**Figure 6.** Results of the sensitivity analysis.

**Table 9.** Sensitivity analysis of the SNA new metrics score.

| Drivers | Closeness New | Original | Betweenness Centrality New | Original | Net Weighted Degree New | Original | Eigenvector Centrality New | Original |
|---|---|---|---|---|---|---|---|---|
| D1 | 1.000000 | 1.0000 | 0.345238 | 0.9074 | 8.41425 | 11.0968 | 1.000000 | 0.97632 |
| D2 | 0.636364 | 0.7143 | 0.000000 | 0.0000 | 1.54058 | 2.6469 | 0.000000 | 0.00000 |
| D4 | 0.857143 | 0.8333 | 0.014881 | 0.0111 | 3.84807 | 6.2334 | 0.452504 | 0.58782 |
| D5 | 0.000000 | 0.0000 | 0.000000 | 0.0000 | 0.00000 | 0.0000 | 0.000000 | 0.00000 |
| D6 | 0.666667 | 0.9091 | 0.041667 | 0.0389 | 6.14765 | 8.7507 | 0.863759 | 0.87358 |
| D7 | 0.000000 | 0.5882 | 0.000000 | 0.0000 | 0.50602 | 1.5537 | 0.243604 | 0.14895 |
| D9 | 0.666667 | 0.8333 | 0.026786 | 0.0111 | 5.59116 | 8.1678 | 0.861323 | 0.87205 |
| D10 | 0.666667 | 0.7143 | 0.000000 | 0.0000 | 2.63279 | 4.3153 | 0.352672 | 0.39117 |
| D11 | 0.545455 | 0.7143 | 0.000000 | 0.0000 | 2.10011 | 4.3088 | 0.564159 | 0.67801 |
| D12 | 0.583333 | 0.6250 | 0.000000 | 0.0000 | 1.02211 | 2.1049 | 0.000000 | 0.00000 |

### *4.3. Reliability and Validity*

Several measures were employed to assess the reliability of the responses. To determine the dependability of the FDSNA results, raw numerical data were used, following the suggestion of Durdyev et al. [86], rather than relying on linguistic factors provided by specialists. The consistency of responses was deemed acceptable if the calculated value exceeded 0.70 for all experts. The experts were requested to re-evaluate their responses if this threshold was not met. On average, the selected experts achieved a consistency value of 0.7479, indicating that the results were reliable. The CR value of each pairwise evaluation had to be greater than 0.1 to guarantee the reliability of the FDSNA findings. In cases where the added CR value was less than 0.1, the expert was required to complete a new survey. The average CR values for all experts who evaluated the FDSNA results were above the threshold value of 0.093, indicating significant differences between their responses.

This investigation aimed to verify construction engineering and management forecasts in line with Durdyev et al. [87]'s conclusions. Four validation techniques were employed to achieve this objective. Firstly, competent experts participated in identifying obstacles, as suggested by Mohandes et al. [70], to ensure excellent internal validity. Secondly, qualified specialists were involved throughout the research, resulting in robust face validity. Thirdly,

four expert panels reviewed and tested the survey questionnaires, enhancing the study's face validity. Lastly, the study objectives were assessed based on the framework provided to ensure the research goals were achieved.

A semi-structured interview was conducted with an experienced expert to obtain external validation for this study. According to Table 10, the validation process is viewed from the perspective of the selected specialists. As a result, the generalization of the findings to a broader context was enabled after comparing the results between the primary and validation studies.

**Table 10.** Validation of results based on expert interviews.

| Interviews | Experts' Involvement in Validation | | | | | | | | | Aggregation of Responses |
|---|---|---|---|---|---|---|---|---|---|---|
| **Drivers** | **Expert 1** | **Expert 2** | **Expert 3** | **Expert 4** | **Expert 5** | **Expert 6** | **Expert 7** | **Expert 8** | **Expert 9** | |
| D1 | 2 | 5 | 3 | 4 | 5 | 3 | 3 | 2 | 2 | 3.222 |
| D2 | 3 | 5 | 2 | 5 | 5 | 2 | 1 | 2 | 1 | 2.889 |
| D3 | 5 | 5 | 5 | 3 | 4 | 3 | 4 | 4 | 3 | 4.000 |
| D4 | 1 | 5 | 2 | 2 | 5 | 3 | 3 | 2 | 4 | 3.000 |
| D5 | 4 | 5 | 4 | 5 | 4 | 4 | 2 | 1 | 3 | 3.556 |
| D6 | 5 | 5 | 3 | 3 | 5 | 4 | 4 | 3 | 2 | 3.778 |
| D7 | 3 | 5 | 5 | 3 | 4 | 5 | 3 | 5 | 1 | 3.778 |
| D8 | 3 | 4 | 4 | 5 | 4 | 2 | 5 | 5 | 5 | 4.111 |
| D9 | 2 | 5 | 5 | 4 | 2 | 3 | 4 | 5 | 5 | 3.889 |
| D10 | 2 | 2 | 4 | 2 | 1 | 3 | 5 | 5 | 4 | 3.111 |
| D11 | 3 | 1 | 3 | 3 | 2 | 4 | 3 | 5 | 3 | 3.000 |
| D12 | 3 | 2 | 3 | 3 | 4 | 4 | 5 | 4 | 5 | 3.667 |

## 5. Discussion

A new technique, referred to as modified FDSNA, was proposed in this research to identify significant connections between drivers and establish an NRM. The findings indicate that not only did the SNA strategy corroborate the outcomes obtained from DEMATEL, but it also provided supplementary insights to decision-makers and managers to effectively identify potential drivers for the successful execution of BT in the Indian SCPM.

A DEMATEL analysis was conducted to measure the direct/indirect influence of drivers (Table 1) and categorize them as cause or effect factors (Figure 1). Based on the causal diagram, D3, D6, and D8 are the most likely drivers since they interact most with other drivers. In addition, they have a high rate and a positive value, making them net drivers of causation. Moreover, D12, D4, and D2 have the highest positive values and the greatest influence on other drivers, indicating that they are the most causal drivers. According to these results, CI experts in India believe that BT adoption requires attention to "the overall performance of the project", "customer satisfaction", and "stability of the system". The market is still in its infancy, and there is no straightforward recipe for success yet. Numerous companies fail to realize returns on their investments as they overlook the significance and feasibility of blockchain solutions, as there exists no methodical assessment of the value at stake [88–90].

In this context, what are the most effective ways for companies to evaluate if blockchain is a viable option for strategic purposes, warranting significant investments? Several blockchain functions must be utilized for SCPM to be more trustworthy, transparent, resource-efficient, and traceable. Several functions contribute to SCPM adoption. By integrating IoT, BDA, and cloud computing technologies, these blockchain technologies can

be remedied [22,66,91]. Moreover, governments have adopted oppressive policies towards Bitcoin, thereby hindering the development of other blockchain-based solutions [92].

SCPM/BT integration and procurement collaboration are the most prominent challenges related to specific procurement challenges. It is possible to overcome these obstacles by developing a collaborative ecosystem. To establish proficient governance frameworks for adopting blockchain, it is imperative to identify suitable collaborators [93]. The protection of sensitive and proprietary information requires clear disclosure policies. Promoting adoption by sharing less sensitive details on effective sustainability techniques is advisable, rather than disclosing negative or critical sustainability practices. Collaborating and exchanging information on social and environmental practices, progress, and developmental information may also prove beneficial. Positive experiences from sharing SCPM information can lead to more positive practices and collaborations between companies, ultimately bringing about greater competitive advantages.

The relationships between the drivers were revealed using the NRM constructed with SNA based on the recognition of influential correlations between them (Table A1). Analyzing the NRM using different SNA metrics revealed the following remarkable findings:

1. Strong relationships were found among the three clusters of identified drivers, facilitating the flow of information through the network. As a result, treating a single driver can have an immediate impact on the entire NRM. BT cannot be successfully used within Indian construction companies if one driver is selected and solved without considering the effect of other drivers on that driver.
2. The flow of information and communication in a network is influenced by drivers such as "stability of the system", "overall performance of the project", and "customer satisfaction". These factors are most influential on the flow of information in a network. Due to this, it is crucial to understand aspects with a high degree of closeness because they play an imperative role in facilitating the timely availability of competitive information [94]. This means that the three drivers mentioned above are crucial to the rapid transformation of the entire driver network.
3. There are several key drivers with the highest weighted degree, including "stability of the system", "the overall performance of the project", and "customer satisfaction". These drivers interact the most with other drivers and have the largest net weight and influence over them. It is evident from the causal diagram that these three drivers have the most significant impact on other drivers.
4. SNA analysis showed that although the "adaptability" and "high-quality" drivers scored the lowest among the four SNA static factors, they remain significant drivers with strong eigenvector centrality; therefore, they can influence the entire NRM. "Adaptability" and "quality" are key drivers since they are inextricably linked to decisive factors. As revealed by the NRM, addressing and treating all other drivers wisely can increase "adaptability" and "high-quality".
5. Table 8 summarizes the main drivers for the successful implementation of BT in Indian construction companies, including "stability of the system", "overall project performance", and "customer satisfaction".

Blockchain has been less prevalent in the CI due to its naive nature [90]. BT adoption in the construction industry is driven by three key success factors: system stability, overall project performance, and customer satisfaction. A survey conducted by Deloitte and PwC in 2018 also confirmed this study's findings. In addition to these drivers, blockchain can support SCPM by promoting the use of more environmentally friendly materials and practices [14]. In addition to enabling procurement teams to make informed decisions about which materials to purchase, blockchain can also be used to track the carbon footprint of various materials and products. It can also be used to create digital certificates of origin

and quality for materials, promoting the use of sustainably sourced materials and reducing the potential for fraud and misrepresentation [15].

Despite the many potential benefits of BT in SCPM, some challenges and barriers must be addressed. One of the key challenges is the need for interoperability between different blockchain platforms and systems. This can be a particular issue in the CI, where many different stakeholders and systems are involved in the procurement process [62]. Another challenge is the need for standardization and regulation of BT in the CI [23]. Ensuring that all parties use the technology consistently and responsibly without clear standards and regulations can be challenging. This raises concerns regarding data privacy and security issues.

Alternatively, all nations could sign a cooperative international agreement. International trade connects most procurements. Therefore, blockchain adoption can facilitate international adoption since most procurements are not geographically isolated [9]. Moreover, using blockchain will help construction stakeholders build trust, which can mitigate any uncertainty surrounding its use. India's Andhra Pradesh government acquired land for the state's new capital, Amaravati, to develop it. This is a great example. To increase the adoption rate of blockchain technology in the construction industry, the government can play a crucial role by implementing suitable measures. Along with addressing privacy, security, and interoperability concerns, blockchain systems must overcome stakeholder controversies. Addressing these issues can enhance the user experience, improving consumer satisfaction [59,61].

Lastly, it is worth noting that government agencies and their affiliated organizations actively endorse such endeavors. Public-private partnerships (PPPs) between the government and the private sector are expected to accelerate the adoption of blockchain in the construction industry [25]. Since several developing countries share comparable conditions with India, this study's findings may apply to other nations without requiring modifications based on their respective contexts and requirements.

Overall, the use of BT in SCPM can revolutionize the industry's operations. By promoting greater transparency, accountability, efficiency, and sustainability, blockchain can help to create a more responsible and environmentally friendly CI. However, it is essential that the challenges and barriers to adoption are addressed and that the technology is used responsibly and ethically.

*Implications for Practice and Policy*

The findings from fuzzy DEMATEL and SNA reveal that drivers such as overall project performance (D3), customer satisfaction (D6), and system stability (D8) hold central positions within the network, exerting significant influence on other factors. For firms, this highlights the importance of prioritizing performance-driven blockchain applications that enhance transparency, streamline processes, and facilitate real-time data exchange. These drivers should be treated as critical focus areas when integrating blockchain into construction procurement workflows.

This study offers actionable insights for construction project managers, procurement professionals, and policymakers seeking to implement blockchain in sustainable construction procurement management (SCPM). The ranked drivers allow organizations to allocate resources strategically, design targeted training programs, develop supportive regulatory frameworks, and adopt blockchain-based tools aligned with specific sustainability goals. For example, drivers such as system stability and data management emphasize the importance of secure and transparent procurement operations, while policies and laws highlight the role of governance in enabling smoother implementation. These findings bridge the gap between theory and practical applications of digital procurement transformation.

From a managerial standpoint, firms can optimize blockchain adoption by first focusing on system stabilization (D8), followed by enhancing performance (D3), and improving client engagement and satisfaction (D6). This structured approach fosters adaptability, cost efficiency, and long-term digital maturity. Additionally, training and capacity-building initiatives should align with these central drivers to maximize their effectiveness.

For policymakers, the findings suggest a targeted approach to regulation and incentives. Policy measures should prioritize transparent procurement protocols, support the development of digital infrastructure, and promote blockchain-based pilot projects with measurable performance outcomes. Furthermore, regulatory bodies could establish national digital standards and data-sharing frameworks to enhance systemic stability and facilitate the scalable implementation of blockchain technology in the construction sector.

## 6. Conclusions

This study investigates the drivers promoting the adoption of BT within SCPM using a hybrid methodological approach. Several methods were utilized in this study, including a systematic literature review, expert interviews, and a questionnaire survey. According to the data collected from the pool of qualified experts, the following conclusions can be drawn:

1. The drivers that act as stumbling blocks to adopting BT-based technologies were identified through a comprehensive literature review and expert interviews.
2. Analyzing the effect and intensity of interrelationships among drivers as a function of their causal interrelationships using the modified FDEMATEL method, the study results indicate that decision-makers must deal effectively with drivers by addressing potential "causal" drivers.
3. Created an NRM of potential drivers and determined their complex relationships using SNA. The most potential drivers for BT adoption in SCPM are "stability of the system", "overall project performance", and "customer satisfaction".

This study contributes to the body of knowledge and practice by providing detailed, novel insights that benefit stakeholders in the construction industry, policymakers, and those involved in sustainability practices. Examining the drivers of BT towards promoting SCPM can potentially revolutionize how the CI operates. By leveraging blockchain's unique features, such as transparency, immutability, and decentralization, sustainable procurement practices can be effectively implemented, reducing environmental impact and increasing social responsibility. While examining the potential drivers of BT in promoting SCPM, some limitations become evident. One such limitation is the lack of clear guidelines and standards for blockchain integration into construction procurement practices. Additionally, there is a need for further research into the financial implications and cost–benefit analysis of implementing BT in construction procurement. Also, comprehensive case studies will be conducted to assess real-world financial impacts, develop clear guidelines for seamless integration, and explore regulatory challenges to overcome legal barriers.

Furthermore, research should address barriers to blockchain adoption in SCPM by analyzing socio-economic, technical, and organizational hurdles. Developing blockchain-based tools tailored to construction procurement systems is crucial, as is exploring the broader potential of blockchain in project and supply chain management to optimize workflows and enhance transparency. By focusing on these areas, future research can provide actionable insights for industry stakeholders and policymakers, facilitating the adoption of blockchain technology and advancing sustainability practices in the construction sector.

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S.R.M. and M.A.; Resources, P.S. and C.K.; Software, P.S.; Supervision, S.R.M. and V.R.P.K.; Validation, S.R.M. and C.C.; Writing—original draft, A.K.S., S.R.M., P.S. and V.R.P.K.; Writing—review and editing, A.K.S., S.R.M., P.S., C.C., M.A. and C.K. All authors have read and agreed to the published version of the manuscript.

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## Appendix A

This appendix comprises three invaluable tables: Table A1 showcases a matrix that normalizes direct influences, while Table A2 presents a matrix of total relationships. Lastly, Table A3 elucidates the influence relationships for the construction network relation map.

**Table A1.** Matrix normalizing direct influences.

| Drivers | D1 | D2 | D3 | D4 | D5 | D6 | D7 | D8 | D9 | D10 | D11 | D12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| D1 | 1.550637 | 0.494392 | 0.676472 | 0.55752 | 0.477099 | 0.635608 | 0.506017 | 0.693607 | 0.639211 | 0.538975 | 0.543418 | 0.488587 |
| D2 | 0.510831 | 1.356655 | 0.552925 | 0.469006 | 0.420286 | 0.512895 | 0.408399 | 0.553412 | 0.516858 | 0.447933 | 0.453823 | 0.428966 |
| D4 | 0.647963 | 0.4886 | 0.576108 | 0.550039 | 0.459983 | 0.635327 | 0.472641 | 0.704186 | 0.633554 | 0.52914 | 0.542604 | 0.466899 |
| D5 | 0.583205 | 0.456752 | 0.626832 | 1.44955 | 0.447396 | 0.579505 | 0.459817 | 0.644215 | 0.572374 | 0.517687 | 0.524791 | 0.453763 |
| D6 | 0.471377 | 0.3941 | 0.491027 | 0.435406 | 1.313745 | 0.443896 | 0.381754 | 0.502049 | 0.450448 | 0.406439 | 0.418881 | 0.384574 |
| D7 | 0.623938 | 0.476413 | 0.650388 | 0.526864 | 0.451429 | 1.513981 | 0.456224 | 0.668061 | 0.609097 | 0.501166 | 0.517754 | 0.463804 |
| D9 | 0.493992 | 0.392909 | 0.520716 | 0.444065 | 0.402508 | 0.480994 | 1.335391 | 0.526996 | 0.487231 | 0.442977 | 0.428138 | 0.403003 |
| D10 | 0.664488 | 0.501779 | 0.708183 | 0.56422 | 0.494287 | 0.649222 | 0.494248 | 1.601897 | 0.643516 | 0.539576 | 0.537379 | 0.480074 |
| D11 | 0.612839 | 0.466955 | 0.643667 | 0.513004 | 0.440147 | 0.605077 | 0.465483 | 0.655943 | 1.503768 | 0.482427 | 0.49977 | 0.455716 |
| D12 | 0.535598 | 0.418495 | 0.573169 | 0.485252 | 0.412343 | 0.525368 | 0.415376 | 0.5802 | 0.515165 | 1.393589 | 0.472225 | 0.418475 |
| D1 | 0.514149 | 0.414434 | 0.557952 | 0.476893 | 0.404528 | 0.496627 | 0.405884 | 0.570797 | 0.49938 | 0.462008 | 1.387718 | 0.404704 |
| D2 | 0.511656 | 0.422834 | 0.530134 | 0.467837 | 0.412276 | 0.510451 | 0.423415 | 0.552645 | 0.499415 | 0.452995 | 0.452558 | 1.347663 |

**Table A2.** Matrix of total relationships.

| Drivers | D1 | D2 | D3 | D4 | D5 | D6 | D7 | D8 | D9 | D10 | D11 | D12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| D1 | 0.550637 | 0.494392 | 0.676472 | 0.55752 | 0.47710 | 0.635608 | 0.506017 | 0.693607 | 0.639211 | 0.538975 | 0.543418 | 0.488587 |
| D2 | 0.510831 | 0.356655 | 0.552925 | 0.469006 | 0.420286 | 0.512895 | 0.40840 | 0.553412 | 0.516858 | 0.447933 | 0.453823 | 0.428966 |
| D3 | 0.647963 | 0.48860 | 0.576108 | 0.550039 | 0.459983 | 0.635327 | 0.472641 | 0.704186 | 0.633554 | 0.52914 | 0.54260 | 0.46690 |
| D4 | 0.58320 | 0.456752 | 0.626832 | 0.44955 | 0.44740 | 0.57950 | 0.459817 | 0.644215 | 0.572374 | 0.517687 | 0.524791 | 0.453763 |
| D5 | 0.471377 | 0.39410 | 0.491027 | 0.435406 | 0.313745 | 0.44390 | 0.381754 | 0.502049 | 0.450448 | 0.406439 | 0.418881 | 0.384574 |
| D6 | 0.623938 | 0.476413 | 0.650388 | 0.526864 | 0.451429 | 0.513981 | 0.456224 | 0.668061 | 0.60910 | 0.501166 | 0.517754 | 0.46380 |
| D7 | 0.493992 | 0.392909 | 0.520716 | 0.444065 | 0.402508 | 0.480994 | 0.335391 | 0.52700 | 0.487231 | 0.442977 | 0.428138 | 0.40300 |
| D8 | 0.664488 | 0.501779 | 0.708183 | 0.56422 | 0.494287 | 0.649222 | 0.494248 | 0.60190 | 0.643516 | 0.539576 | 0.537379 | 0.480074 |
| D9 | 0.612839 | 0.466955 | 0.643667 | 0.51300 | 0.440147 | 0.605077 | 0.465483 | 0.655943 | 0.503768 | 0.482427 | 0.49977 | 0.455716 |
| D10 | 0.53560 | 0.418495 | 0.573169 | 0.485252 | 0.412343 | 0.525368 | 0.415376 | 0.58020 | 0.515165 | 0.393589 | 0.472225 | 0.418475 |
| D11 | 0.514149 | 0.414434 | 0.557952 | 0.476893 | 0.404528 | 0.496627 | 0.405884 | 0.57080 | 0.49938 | 0.462008 | 0.387718 | 0.40470 |
| D12 | 0.511656 | 0.422834 | 0.530134 | 0.467837 | 0.412276 | 0.510451 | 0.423415 | 0.552645 | 0.499415 | 0.45300 | 0.452558 | 0.347663 |

**Table A3.** Influence relationships for the construction network relation map.

| Drivers | D1 | D2 | D3 | D4 | D5 | D6 | D7 | D8 | D9 | D10 | D11 | D12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| D1 | 0.55064 | 0.00000 | 0.67647 | 0.55752 | 0.00000 | 0.63561 | 0.50602 | 0.69361 | 0.63921 | 0.53897 | 0.54342 | 0.00000 |
| D2 | 0.51083 | 0.00000 | 0.55293 | 0.00000 | 0.00000 | 0.51289 | 0.00000 | 0.55341 | 0.51686 | 0.00000 | 0.00000 | 0.00000 |
| D4 | 0.64796 | 0.00000 | 0.57611 | 0.55004 | 0.00000 | 0.63533 | 0.00000 | 0.70419 | 0.63355 | 0.52914 | 0.54260 | 0.00000 |
| D5 | 0.58320 | 0.00000 | 0.62683 | 0.00000 | 0.00000 | 0.57950 | 0.00000 | 0.64422 | 0.57237 | 0.51769 | 0.52479 | 0.00000 |
| D6 | 0.00000 | 0.00000 | 0.00000 | 0.00000 | 0.00000 | 0.00000 | 0.00000 | 0.00000 | 0.00000 | 0.00000 | 0.00000 | 0.00000 |
| D7 | 0.62394 | 0.00000 | 0.65039 | 0.00000 | 0.00000 | 0.51398 | 0.00000 | 0.66806 | 0.60910 | 0.00000 | 0.51775 | 0.00000 |
| D9 | 0.00000 | 0.00000 | 0.52072 | 0.00000 | 0.00000 | 0.00000 | 0.00000 | 0.52700 | 0.00000 | 0.00000 | 0.00000 | 0.00000 |
| D10 | 0.66449 | 0.00000 | 0.70818 | 0.56422 | 0.00000 | 0.64922 | 0.00000 | 0.60190 | 0.64352 | 0.00000 | 0.53738 | 0.00000 |
| D11 | 0.61284 | 0.00000 | 0.64367 | 0.51300 | 0.00000 | 0.60508 | 0.00000 | 0.65594 | 0.50377 | 0.00000 | 0.00000 | 0.00000 |
| D12 | 0.53560 | 0.00000 | 0.57317 | 0.00000 | 0.00000 | 0.52537 | 0.00000 | 0.58020 | 0.51516 | 0.00000 | 0.00000 | 0.00000 |
| D1 | 0.51415 | 0.00000 | 0.55795 | 0.00000 | 0.00000 | 0.00000 | 0.00000 | 0.57080 | 0.00000 | 0.00000 | 0.00000 | 0.00000 |
| D2 | 0.51166 | 0.00000 | 0.53013 | 0.00000 | 0.00000 | 0.51045 | 0.00000 | 0.55264 | 0.00000 | 0.00000 | 0.00000 | 0.00000 |

## Appendix B

This appendix comprises Figures A1 and A2, which provide a vivid depiction of both the degree of causation and centrality, as well as the intricate interplay between drivers and their corresponding levels of influence.

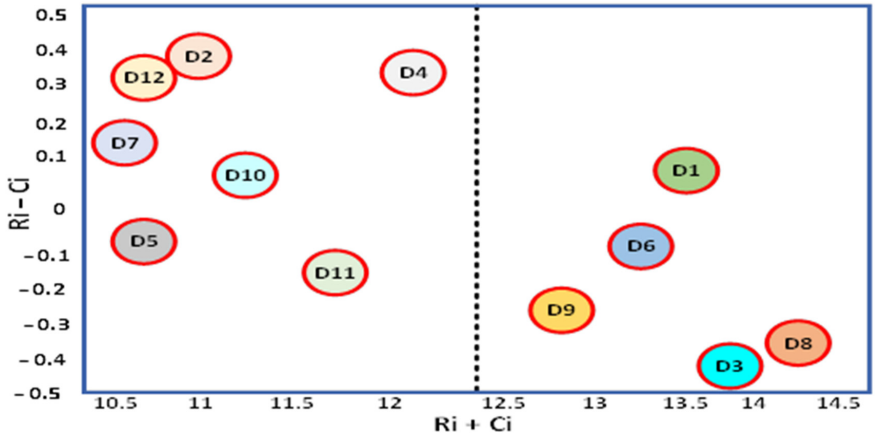



**Figure A1.** Visual representation of the cause degree and the center degree.

| | D1 | D2 | D3 | D4 | D5 | D6 | D7 | D8 | D9 | D10 | D11 | D12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| D1 | 0 | 1 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 1 |
| D2 | 0 | 1 | 0 | 1 | 1 | 0 | 1 | 0 | 0 | 1 | 1 | 1 |
| D3 | 0 | 1 | 0 | 0 | 1 | 0 | 1 | 0 | 0 | 0 | 0 | 1 |
| D4 | 0 | 1 | 0 | 1 | 1 | 0 | 1 | 0 | 0 | 0 | 0 | 1 |
| D5 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| D6 | 0 | 1 | 0 | 1 | 1 | 0 | 1 | 0 | 0 | 1 | 0 | 1 |
| D7 | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 |
| D8 | 0 | 1 | 0 | 0 | 1 | 0 | 1 | 0 | 0 | 0 | 0 | 1 |
| D9 | 0 | 1 | 0 | 0 | 1 | 0 | 1 | 0 | 0 | 1 | 1 | 1 |
| D10 | 0 | 1 | 0 | 1 | 1 | 0 | 1 | 0 | 0 | 1 | 1 | 1 |
| D11 | 0 | 1 | 0 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 |
| D12 | 0 | 1 | 0 | 1 | 1 | 0 | 1 | 0 | 1 | 1 | 1 | 1 |

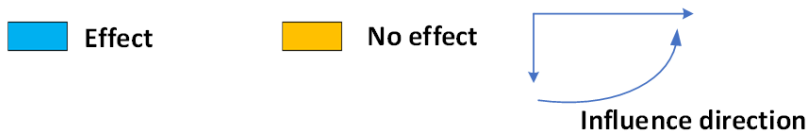



**Figure A2.** Relationship between drivers and their influence.

## Appendix C

"Development of Fuzzy-DEMATEL-based survey"

Section A: Experts need to answer the following questions:

| |
|---|
| How many construction projects are done using blockchain technology |
| Size of the company |
| Occupations |
| Degree |
| Years of experience |

Section B: Questionnaire survey:

**Table A4.** Variables and codes to be used.

| The Extent of the Impact | Code | Explanation |
|---|---|---|
| No influence | NI | There is no influence between the two drivers |
| Very low influence | VL | One driver has a very low influence on the other one |
| Low influence | L | One driver has a low influence on the other one |
| High influence | H | One driver has a high influence on the other one |
| Very high influence | VH | One driver has a very high influence on the other one |

Examples:

- Based on your expertise, if you believe that D1 has no effect on D2. Please fill in NI in the box.
- Based on your expertise, if you believe that D3 has a "very high impact" on D4. Please fill in VH in the box.

With the above in mind, please fill in the boxes highlighted in YELLOW using the CODE shown in Table A5 based on variables in Table A6.

**Table A5.** Sample of variables to fill in the questionnaire.

| Drivers | D1 | D2 | D3 | D4 | D5 | D6 | D7 | D8 | D9 | D10 | D11 | D12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| D1 | | | | | | | | | | | | |
| D2 | | | | | | | | | | | | |
| D3 | | | | | | | | | | | | |
| D4 | | | | | | | | | | | | |
| D5 | | | | | | | | | | | | |
| D6 | | | | | | | | | | | | |
| D7 | | | | | | | | | | | | |
| D8 | | | | | | | | | | | | |
| D9 | | | | | | | | | | | | |
| D10 | | | | | | | | | | | | |
| D11 | | | | | | | | | | | | |
| D12 | | | | | | | | | | | | |

**Table A6.** List of drivers with description.

| Drivers | Code | Description |
| --- | --- | --- |
| Stability of the system | D1 | Transparency, security, removing intermediaries, and trustworthiness are four variables considered in assessing system robustness. After the integration of BT into construction procurement management (CPM), all of these characteristics made the CPM and system more robust and sustainable due to the transparency in information flow, stability of data, and peer-to-peer transactions without involving a third party. |
| Cost of the overall project | D2 | Three variables are combined to form the overall cost: cost, energy, and overall project costs. The overall CPM cost includes all financial investments like documentation fees, stationery expenditures, human resources costs, electricity costs, facility costs, documentation incurred during production, etc. |
| The overall performance of the project | D3 | The overall performance of the project is the efficiency, effectiveness, and speed of doing the job effectively with low responses, high standardization, and reduced complexity of the work. A composite of five variables is built by examining the correlations between efficiency, speed, automation, simplification of current paradigms, and sharing demand in CPM. |
| Decentralization and data security | D4 | By experts under the name data safety and decentralization, a group of four variables is grouped. All people involved directly or indirectly in the system need records and information regarding standardization, production, and supply. It is only on BT-integrated CPM that it is possible to hack, change, control, or lose data for any reason. |
| Adaptability | D5 | Regarding adaptability, three variables, traceability, visibility, and identifying issues, form a common driver. Using IoT/Industry 4.0, adaptability means tracking causes, goods location, accidents, and fraud between a CPM's manufacturing and end-use processes. |
| Policies and laws | D6 | A lot of time and effort is involved in documenting laws and policies. Documentation plays a crucial role in all contracts, but public ledger technology gives us transparency, speeds up work, checks for corruption in government, and also helps to find out scams in any organization. The importance of data records for any legal action cannot be overstated. This technology does not allow the deletion or modification of data, so there can be no fraud; laws and government policies have been factored together to form accessibility. |
| The system with innovative features | D7 | With the smart system, smart contracts are implemented, invoicing is simplified, and inventory levels are improved. By eliminating any fraud in the documentation, paying taxes on time, and ensuring that goods are delivered on time from the shipyard area, the system removes any fraud in the documentation. |

**Table A6.** *Cont.*

| Drivers | Code | Description |
| --- | --- | --- |
| Satisfaction of customers | D8 | Feedback and customer centricity, based on expert opinion, is the basis of customer satisfaction. The customer is satisfied when they provide positive feedback and respond positively. In order to achieve this, it is necessary to deliver the right product with the correct information at the right time, at the right place, and in the right hands, and to commit to providing periodic service after the sale. |
| The system with high reliability | D9 | Reliable systems are determined by four drivers: Scalability, Reliability, Durability, and the ability to lose data. A record of raw, semi-finished, and finished material is kept at every BT location. By keeping the correct information about goods, IT saves not only time but also money. |
| Detailed documentation | D10 | Auditable, accounting, and ecosystem documentation are part of the documentation. In BT, integration is preferred for several reasons, such as smooth auditing processes, simplified financial systems, and smooth currency flow. |
| A data management system | D11 | A data management system controls access to data from the end-users, manipulates transactions from a single account simultaneously, eliminates human error in the documentation and other tasks, and allows real-time information flow. Three variables are considered in data management: data quality, flow and control of information, and access control. |
| High-quality | D12 | Quality assurance and quality fairness are drivers that affect quality. Any irregularity in the process, transportation, raw material specification, or the final product is considered poor quality, due to the lack of availability of complete information and the need to eliminate human error. |

Section C: Additional questions

From your perspective, what would be the ways/strategies/suggestions/solutions (in terms of policy, regulation, engineering, application, etc.) for promoting the adoption of blockchain in the construction industry?

| Suggestions/Strategies |
| --- |
| 1. |
| 2. |
| 3. |
| 4. |
| 5. |

## Appendix D

*Appendix D.1. Fuzzy-DEMATEL*

The modification of the DEMATEL technique is derived from the IT2TrFN theory. Within the next phase, we will introduce a modified fuzzy DEMATEL approach, which was proposed by [91,92]. This chapter concludes with a description of the analysis framework that has been constructed.

Appendix D.1.1. Trapezoidal Fuzzy Number Type-II Interval

Members of IT2TrFN describe a method in which personal information remains fuzzy, subjective, and uncertain despite the freedom and flexibility provided by the process.

**Defining 1.** *Fuzzy sets of type II can be expressed in two ways.*

$$\widetilde{Z} = \{((a,b), b_{\widetilde{Z}}(a,b)) \mid \forall x \in X, \forall b \in J_x \subseteq [0,1], 0 \le b_{\widetilde{Z}}(a,b) \le 1\} \tag{A1}$$

$$\approx\!\!\approx Z = \frac{\int_{a\in X} \int_{b\in J_a} b_{\sim}(a,b)}{(a,b)dbda} \tag{A2}$$

*where* $b_{\underset{A}{\approx}} Z$ *has a type-II affiliation function,* $J_a \subseteq [0,1]$.

**Defining 2.** *The fuzzy set Z (a,b) that is described as Z (a,b) is an interval type-II fuzzy set, which takes the form of*

$$\approx\!\!\approx Z = \frac{\int_{a\in X} \int_{b\in J_x} 1}{(a,b)dbda} \tag{A3}$$

*where Ja ⊆ [0, 1].*

**Defining 3.** *Since the upper and lower bounds of IT2TrFN are trapezoidal fuzzy numbers shown in Figure A3, it is a trapezoidal fuzzy number. The following is the result:*

$$\approx\!\!\approx Z = \left(\overset{\sim U}{Z_i}, \overset{\sim L}{Z_i}\right) = \begin{bmatrix} \left(z_{i1}^U, z_{i2}^U, z_{i3}^U, z_{i4}^U; H_1\left(\overset{\sim U}{Z_i}\right), H_2\left(\overset{\sim U}{Z_i}\right)\right), \\ \left(z_{i1}^L, z_{i2}^L, z_{i3}^L, z_{i4}^L; H_1\left(\overset{\sim L}{Z_i}\right), H_2\left(\overset{\sim L}{Z_i}\right)\right) \end{bmatrix} \tag{A4}$$

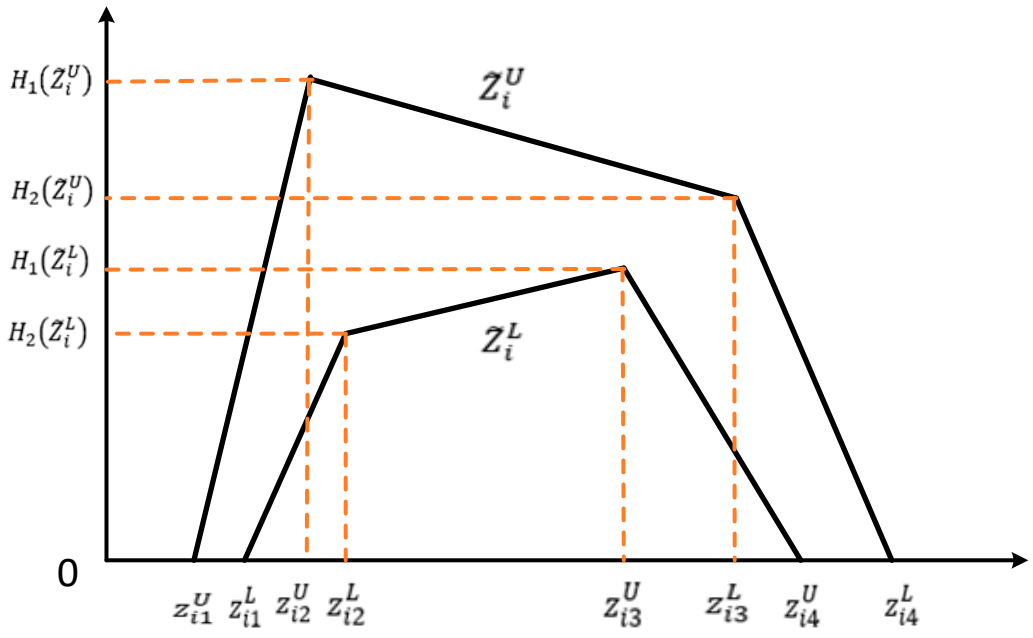



**Figure A3.** Schematic diagram of IT2TrFN.

The Hj(U i) becomes a member of the aU i(j + 1), and the Hj(Li) becomes a member of the aL i(j + 1), 1 + j + 2. $\overset{\sim U}{Z_i}\ \overset{\sim L}{Z_i}$.

Sets of interval trapezoids with constant k are interval trapezoidal type-II fuzzy sets:

$$\begin{aligned}\overset{\approx}{Z}_1 \oplus \overset{\approx}{Z}_2 &= \left(\overset{\sim U}{Z}_1, \overset{\sim L}{Z}_1\right) \oplus \left(\overset{\sim U}{Z}_2, \overset{\sim L}{Z}_2\right) \\ &= \left[\begin{array}{l}\left(z_{11}^U + z_{21}^U, z_{12}^U + z_{22}^U, z_{13}^U + z_{23}^U, z_{14}^U + z_{24}^U; min\left(H_1\left(\overset{\sim U}{Z}_1\right), H_1\left(\overset{\sim U}{Z}_2\right)\right), min\left(H_2\left(\overset{\sim U}{Z}_1\right), H_2\left(\overset{\sim U}{Z}_2\right)\right)\right), \\ \left(z_{11}^L + z_{21}^L, z_{12}^L + z_{22}^L, z_{13}^L + z_{23}^L, z_{14}^L + z_{24}^L; min\left(H_1\left(\overset{\sim L}{Z}_1\right), H_1\left(\overset{\sim L}{Z}_2\right)\right), min\left(H_2\left(\overset{\sim L}{Z}_1\right), H_2\left(\overset{\sim L}{Z}_2\right)\right)\right)\end{array}\right]\end{aligned} \tag{A5}$$

$$\begin{aligned}Z\overset{\approx}{Z'}X_1 \otimes \overset{\approx}{Z}_2 &= \left(\overset{\sim U}{Z}_1, \overset{\sim L}{Z}_1\right) \otimes \left(\overset{\sim U}{Z}_2, \overset{\sim L}{Z}_2\right) \\ &= \left[\begin{array}{l}\left(z_{11}^U \times z_{21}^U, z_{12}^U \times z_{22}^U, z_{13}^U \times z_{23}^U, z_{14}^U \times z_{24}^U; min\left(H_1\left(\overset{\sim U}{Z}_1\right), H_1\left(\overset{\sim U}{Z}_2\right)\right), min\left(H_2\left(\overset{\sim U}{Z}_1\right), H_2\left(\overset{\sim U}{Z}_2\right)\right)\right), \\ \left(z_{11}^L \times z_{21}^L, z_{12}^L \times z_{22}^L, z_{13}^L \times z_{23}^L, z_{14}^L \times z_{24}^L; min\left(H_1\left(\overset{\sim L}{Z}_1\right), H_1\left(\overset{\sim L}{Z}_2\right)\right), min\left(H_2\left(\overset{\sim L}{Z}_1\right), H_2\left(\overset{\sim L}{Z}_2\right)\right)\right)\end{array}\right]\end{aligned} \tag{A6}$$

$$k\overset{\approx}{Z}_1 = \left[\begin{array}{l}\left(kz_{11}^U, kz_{12}^U, kz_{13}^U, kz_{14}^U; H_1\left(\overset{\sim U}{Z}_1\right), H_2\left(\overset{\sim U}{Z}_1\right)\right), \\ \left(kz_{11}^L, kz_{12}^L, kz_{13}^L, kz_{14}^L; H_1\left(\overset{\sim L}{Z}_1\right), H_2\left(\overset{\sim L}{Z}_1\right)\right)\end{array}\right] \tag{A7}$$

According to Herrera-Viedma [74], IT2TrFN is defuzzed as follows:

$$\text{Defuzzified}\left(\overset{\approx}{Z}_i\right) = \begin{array}{l}\frac{\left(z_{i4}^U - z_{i1}^U\right) + \left(H_1\left(\overset{\sim U}{Z_i}\right) * z_{i2}^U - z_{i1}^U\right) + \left(H_2\left(\overset{\sim U}{Z_i}\right) * z_{i3}^U - z_{i1}^U\right)}{4} + z_{i1}^U \\ + \frac{\left(z_{i4}^L - z_{i1}^L\right) + \left(H_1\left(\overset{\sim L}{Z_i}\right) * z_{i2}^L - z_{i1}^L\right) + \left(H_2\left(\overset{\sim L}{Z_i}\right) * z_{i3}^L - z_{i1}^L\right)}{4} + z_{i1}^L \\ \hline 2\end{array} \tag{A8}$$

Appendix D.1.2. Algorithm for Clustering Using K-Means

K-means clusters data based on their mean values in a non-hierarchical manner. Clustering data into K categories is achieved by optimizing the mean distance values iteratively. Its unsupervised machine-learning algorithm can improve the objectivity of threshold values.

**Definition 1.** *A sample data set of $x_i$ would be compared to a cluster centroid set of $c_j$ [93,94]. The distance between the sample data and the centroid is calculated using the Euclidean distance formula, which is derived from the Pythagorean theorem:*

$$dis(x_i, c_j) = \sqrt{(x_{i1} - c_{j1})^2 + (x_{i2} - c_{j2})^2 + \cdots + (x_{im} - c_{jm})^2} \tag{A9}$$

*where $x_i = (x_{i1}, x_{i2}, \cdots, x_{im})$, $c_i = (c_{j1}, c_{j2}, \cdots, c_{jm})$ and M represents the dimension.*

**Definition 2.** *A sample cluster's centroid is determined in each iteration by following the steps below [93,94]:*

$$c_j = \frac{1}{N(\varphi_j)} - \left\{\sum_{x_i \in \varphi_j} x_{i1}, \sum_{x_i \in \varphi_j} x_{i2}, \cdots, \sum_{x_i \in \varphi_j} x_{im}\right\} \tag{A10}$$

*where* $N(_{\varphi j})$ *measures how many data points are within the cluster* $\varphi$j.

**Definition 3.** *Based on the definition of the clustering criterion function, when* $|SSEN + SSEN - 1| < \varepsilon$, *the clustering criterion function has converged [93,94]*

$$SSE = \sum_{j=1}^{K} \sum_{x_i \in \varphi_j} dis(x_i, c_j) \tag{A11}$$

*where n denotes the number of iterations, the discriminant condition, etc.*

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