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The Causal Architecture of Blockchain-Enabled Performance in Humanitarian Supply Chains

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ABSTRACT

Objective: To identify and prioritize blockchain technology (BT) facilitators for humanitarian supply chains and to develop a causal relationship model linking these facilitators to SCOR-based humanitarian supply chain performance attributes using a multi-objective intuitionistic fuzzy cognitive map (MOIFFCM).

Methodology: The study adopts a sequential mixed-method design within a single case study. A systematic literature review first identifies candidate BT facilitators and structures humanitarian supply chain processes and performance dimensions according to the SCOR model. Subsequently, semi-structured interviews with eight experts from academia and practice provide judgements on the influence and interdependence of these facilitators on key operations and performance attributes. These judgements are encoded in an intuitionistic fuzzy cognitive map and extended to a multi-objective IFCM framework to analyze complex and feedback-rich causal relationships.

Results: Thirteen BT facilitators relevant to humanitarian supply chains are validated. The MOIFFCM analysis shows that secure, shared, decentralized databases and smart contracts are the most influential facilitators for blockchain adoption in humanitarian supply chains. These enablers strongly affect SCOR-derived performance dimensions such as reliability, flexibility, responsiveness, cost performance, and aid management efficiency, and exhibit significant interdependencies with other facilitators.

Conclusion: Prioritizing and strengthening key BT facilitators—particularly secure decentralized data infrastructures and smart contracts—can improve visibility, traceability, and integrity of humanitarian supply chains while reducing administrative burden and transaction costs. Nonetheless, realizing these benefits requires addressing regulatory, legal, technical and infrastructural constraints. The proposed MOIFFCM-based model offers a decision-support tool for humanitarian managers to test adoption scenarios, prioritize facilitators under resource limitations and better align blockchain investments with targeted performance improvements.

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Introduction

As a result of having to rely on central authorities or intermediaries, several major corporations have developed their unique identification and procedures to sustain worldwide coverage of activities (Zhang, 2026). Absent accessibility generates several issues with the supply chain process concerning security systems, traceability, correctness, and validation (Drozdibob et al., 2022; Masoomi et al., 2022). Blockchain is among the promising methods in supply-chain management for chain-wide supervision (Viriyasitavat et al., 2020). Following the financial crisis of 2008, cryptocurrencies like Bitcoin led to the development of BT (Nakamoto, 2008). Even though the primary emphasis of this innovation is on financial applications, its distinctive characteristics have increased usage in several industries and even for non-financial business objectives.

Blockchain is built on distributed ledger technology, meaning electronic records are shared and maintained across a network rather than stored in one central location (Negi, 2025). This approach is increasingly transforming routine payment activities through digital platforms (Lim et al., 2021; Sahebi et al., 2022). It has also enabled new developments such as smart contracts and cryptocurrencies. As a result, a new era of electronic payments is emerging, even though challenges remain, including high energy consumption and ongoing privacy risks (Dolgui et al., 2020; Zhao et al., 2019). These issues have also had a notable effect on the humanitarian supply chain (HSC). Key Blockchain characteristics, such as decentralized, trustless peer-to-peer ledgers, can reduce fraudulent behavior by improving transparency and strengthening accountability, with implications for smart contracts, supply chain operations, digital identity systems, and financial services. In response, HSC initiatives seek to enhance transparency, responsibility, and efficiency by encouraging the integration of both public and private funding mechanisms through Blockchain-based solutions (Baharmand et al., 2021). In humanitarian contexts, Blockchain can function as a strategic tool for monitoring and distributing aid funds, managing and issuing identities in refugee camps, and establishing reliable land registries within HSC settings (Maina et al., 2025; Sahebi et al., 2020).

Blockchain is an innovative technology that, although still immature, represents a major technological breakthrough (Kshetri, 2018) because it seeks to transform how humanitarian supply chain stakeholders share supply chain data through a reliable, secure, and distributed decentralized platform (Natarajan & Swaminathan, 2014). In addition, humanitarian supply chain management (HSCM) depends on enabling tools such as electronic data interchange (EDI) and the Internet of Things (IoT), along with broader information and communication technologies, to improve overall effectiveness. Although the benefits of these facilitators for HSC performance are clear, their interrelationships are still not well understood (Argumedo-García et al., 2021; Fosso Wamba, 2020). Therefore, blockchain technology (BT) can be considered an enabler that enhances supply chain efficiency and competitiveness (Saberi et al., 2019). Moreover, because only a limited number of studies have examined the effects of integrating this technology into supply chains (Nandi et al., 2020; Tseng et al., 2011), it is important to identify the key facilitators of BT adoption in the HSC to improve efficiency and competitiveness. This study aims to develop a conceptual framework that explains the causal relationships between these facilitators and HSC performance indicators in Iran. Since BT is still relatively new in Iran, HSC stakeholders need to determine the main drivers of adoption, understand how these drivers are connected, and evaluate how they can help address the challenges noted above. Finally, the findings can provide practical and evidence-based recommendations for humanitarian organization stakeholders to strengthen the effectiveness of HSCM.

The study uses a hybrid Intuitive Fuzzy Cognitive Map (IFCM) method. In phase one, it identifies blockchain technology (BT) facilitators by reviewing prior literature and earlier studies. In phase two, the IFCM is applied to map how these BT facilitators relate to humanitarian supply chain performance measures. FCM is a symbolic modeling technique for representing complex systems. It is particularly useful for capturing dense causal and interdependent relationships among system elements, which can support more effective decision-making within that system (Axelrod, 2015). In this way, an FCM can reveal how different functions influence one another through their interdependencies. According to the stated materials, the following are the aims of this study:

- Discover and evaluate blockchain technology facilitators in the humanitarian supply chain.
- Map the causal model between blockchain technology facilitators and humanitarian supply chain performance attributes.

The rest of this paper is structured as follows. Section 2 reviews the literature on BT in HSC, BT facilitators, and HSC performance measures. Section 3 outlines the research methodology and explains the IFCM procedures and methodological steps. Section 4 reports the detailed data analysis and results. Finally, Sections 5 and 6 discuss the main findings and present the overall conclusions.

Literature Background

Blockchain in HSC

Recent studies highlighted the growing importance of advanced analytical approaches and emerging technologies in improving humanitarian supply chain performance. (Toufighi et al., 2026) developed optimization models for post-earthquake relief logistics network design and demonstrated how facility location and flow allocation decisions can substantially improve the responsiveness and effectiveness of humanitarian operations. Similarly, (Sadeghi Moghadam, Noferesti, et al., 2022) examined the capability and attractiveness of emerging technologies in Iran's humanitarian supply chain and identified technologies such as artificial intelligence, smart advisors, smart robots, and 3D printing as critical enablers of future humanitarian operations. Furthermore, (Sadeghi Moghadam, Taghizadeh Yazdi, et al., 2022) employed agent-based simulation to investigate coordination mechanisms in post-flood housing reconstruction and emphasized the importance of interaction and coordination among humanitarian actors for improving recovery outcomes. Collectively, these studies indicate that technological capabilities, coordination mechanisms, and analytical decision-support tools play a fundamental role in enhancing humanitarian supply chain performance. Nevertheless, despite these valuable contributions, limited attention has been devoted to understanding the complex causal interactions among blockchain technology facilitators and their simultaneous effects on multiple humanitarian supply chain performance dimensions.

In recent years, the significance of BT has been found in numerous domains. The innovation indicates that implementing decentralization (replacing intermediaries with BT) may disrupt practically every sector (Riani, 2018b). Also, BT is the next industrial disruptor in the humanitarian assistance sector, according to several blockchain enthusiasts (Purvis, 2017). Cash payments are one possible use of BT to provide financial and humanitarian relief. Before, it evaluated the combination of in-kind help and monetary transactions, but since Blockchain is a digital ledger, it cannot send in-kind assistance (Javaid et al., 2021). As a result, BT in the humanitarian supply chain can be applied specifically to transferring funds. It can reshape the aid sector by supporting a more digital and future-oriented approach, mainly by enabling monetary transfers and reducing reliance on in-kind donations. This aligns with aid organizations' efforts to deliver assistance more directly to beneficiaries (Rodríguez-Espíndola et al., 2020). Through national banks or government authorities, blockchain can offer an alternative to cash-based transactions. It can also reduce fraud because transaction records are difficult to alter, and it may help prevent financial aid from being diverted by corrupt officials (Riani, 2018b). Earlier research also shows that relief organizations are often reluctant to shift toward cash transfers due to low trust. They worry that funds may not reach the intended recipients and could end up with the wrong parties (Upadhyay, 2020).

A permissioned Blockchain's lack of volatility may provide a remedy to this concern. It also implies that the money can be tracked, and the transaction would be entirely transparent. If Blockchain could be enabled, more impacted individuals would get the support they need, fewer in-kind contributions might be wasted, more excellent aid organizations would move to cash, and aid distribution may become more effective. It is hardly surprising that Blockchain has been applauded for the ideas it promotes. In principle, the advantage of Blockchain is that it is a decentralized distrust network with permissionless blockchain service. A centralized authority does not own the BT (Dutta et al., 2020). Thus, removing difficulties is essential to the humanitarian assistance supply chain. Figure 1 illustrates the key application domains of BT in humanitarian supply chains, including enhancing transparency and traceability of relief flows, reducing fraud in aid distribution, and supporting cash-based transfer programs for beneficiaries.

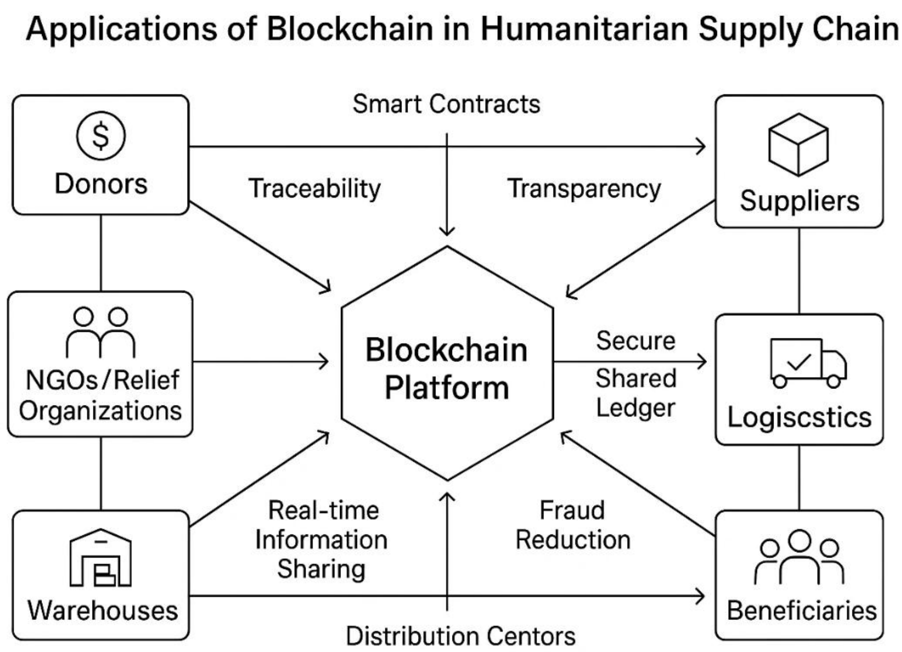


Figure 1. Key applications of BT in humanitarian supply chains

Blockchain facilitators

The BT facilitators (BTFs) found via existing literature are shown in Table 1. These elements are crucial BTFs that promote blockchain application in enterprises' supply chains. The BT system helps protect confidentiality and improves data security (Ourahou et al., 2020). Its cryptographic private key mechanism supports data privacy and confidentiality. BT also applies ring signatures to strengthen user confidentiality. These signatures use signer-verifying encryption, where each recipient holds a private key linked to a unique and undisclosed public key. This approach helps protect recipient privacy and supports the security of BT data (Yue et al., 2016). Blockchains are also self-managed, resistant to tampering, reliable, and auditable platforms (Bodkhe et al., 2020). Traceability is one of their key features. Because blockchain relies on decentralized databases, it can reduce errors and maintain audit trails (Wijaya et al., 2017). Transparency in blockchain transactions can further strengthen user trust (Fanning & Centers, 2016). Applying BT across supply chains can improve accountability by preserving process integrity and integrating information (Y. Wang et al., 2018a).

BT communication metadata is distributed across the network boundary rather than stored in one place. Because blockchain relies on distributed databases, it is difficult to consolidate this information in a single central location. Instead of keeping data on one server, information is continuously shared among multiple nodes, or computers. By using open databases, blockchain technology creates a distributed and decentralized environment (Wright & De Filippi, 2015; Zheng et al., 2017a). This structure can strengthen mutual trust among blockchain participants. In addition, records stored on the blockchain are difficult, and often practically impossible, to alter over time. This supports a complete audit trail of all prior on-ledger actions, which helps ensure reliable information tracking. For this reason, blockchains inherently produce immutable audit trails (Weber et al., 2016).

Blockchain's decentralized architecture lowers the likelihood that data can be forged, altered, or manipulated through cyberattacks (Kshetri, 2018). Many business risks stem from weak capital management, data exposure, and delayed or missed payments. With distributed databases, trade settlement confirmations can occur immediately, so participants have fewer concerns about late settlements or payment disruptions. Lower loss risk can reduce margin or collateral requirements, which releases capital for other investment opportunities. As a result, BT can enable faster collateral setup and investment decisions compared with traditional long-term processes (Priyan, 2025; Risso et al., 2024). Blockchain technology also strengthens supply chain provenance, or origin visibility (Kim & Laskowski, 2018). In many industries, a product's value is closely tied to where it comes from. BT can generate unique identifiers for each product, allowing its history to be tracked across the supply chain (S. Wang et al., 2019a). In this context, data integrity depends on secure data origination (Masoomi et al., 2025).

Table 1. List of BTFs

BTF	Details	References
Anonymity and privacy (BTF1)	In humanitarian supply chains, blockchain enables secure handling of sensitive beneficiary and donor information through cryptographic encryption and private key mechanisms. This ensures confidentiality, protects vulnerable populations' identities, and complies with data protection regulations during disaster response operations.	(Ying et al., 2018a)
Auditability (BTF2)	Blockchain enhances auditability by creating an immutable and time-stamped record of all humanitarian transactions. This allows donors, NGOs, and oversight bodies to verify fund allocation, procurement processes, and aid distribution activities, thereby strengthening accountability and reducing corruption risks.	(Hofmann et al., 2018b)

Decentralized database (BTF3)	In HSCs, a decentralized ledger distributes data across multiple nodes (e.g., NGOs, agencies, donors), eliminating reliance on a single central authority. This improves resilience in crisis zones where centralized systems may fail or become inaccessible.	(Izadi et al., 2023; Masoomi et al., 2025)(MacDonald et al., 2016; Zheng et al., 2017b)
Immutability (BTF4)	Once humanitarian transactions (e.g., procurement orders, shipment confirmations, beneficiary transfers) are recorded, they cannot be altered or manipulated. This ensures integrity of aid records and prevents fraudulent modifications.	(Kshetri, 2018; Sahebi et al., 2020; Tran et al., 2017)
Improved risk management (BTF5)	Blockchain reduces operational and financial risks by enabling near real-time validation of transactions, automated payment releases, and transparent monitoring of goods flows. This minimizes settlement failures, diversion of supplies, and contractual disputes in volatile environments.	(Gokhale, 2016; Y. Wang et al., 2018b)
Provenance (BTF6)	Blockchain assigns unique digital identifiers to relief items (e.g., medicine, food kits, medical equipment), enabling tracking from donors to final beneficiaries. This prevents counterfeit products and ensures authenticity and compliance with humanitarian standards.	(S. Wang et al., 2019b)
Reduced transaction costs (BTF7)	By eliminating intermediaries and automating verification processes, blockchain lowers administrative and coordination costs in humanitarian procurement and fund transfers, enabling more resources to be directed toward aid delivery.	(Hofmann et al., 2018b; Ying et al., 2018a)
Reduced settlement lead times (BTF8)	Smart validation mechanisms reduce delays in financial settlements and procurement approvals. Faster transaction execution is critical in humanitarian crises where time-sensitive deliveries can save lives.	(Kamble et al., 2021a; Ying et al., 2018a)
Secured database (BTF9)	Blockchain provides tamper-resistant and encrypted data storage, protecting sensitive humanitarian logistics data from cyberattacks, unauthorized access, and manipulation.	(Chen et al., 2018b; Ølnes et al., 2017b)
Shared database (BTF10)	Authorized stakeholders (NGOs, donors, UN agencies, logistics providers) can access synchronized and real-time information, improving coordination, reducing duplication of efforts, and minimizing information asymmetry.	(Gokhale, 2016; Y. Wang et al., 2018b)
Traceability (BTF11)	End-to-end traceability ensures that relief goods can be monitored across all supply chain stages—from procurement and warehousing to last-mile distribution—enhancing visibility and reducing losses or diversion.	(Abeyratne & Monfared, 2016; Tian, 2016)
Smart Contract (BTF12)	Smart contracts automate predefined humanitarian processes such as conditional fund release, supplier payments upon delivery confirmation, or milestone-based project disbursement, increasing efficiency and trust among stakeholders.	(Sahebi et al., 2022)
Transparency (BTF13)	Blockchain improves transparency by allowing authorized parties to observe real-time transactions governed by consensus mechanisms. This strengthens donor confidence and enhances public trust in humanitarian operations.	(Abeyratne & Monfared, 2016; Kshetri, 2018)

Because of key BT features such as fewer intermediaries, secure cryptographic signatures, and a decentralized database, BT can reduce transaction fees (Gaggioli, 2018; Kshetri, 2018). It can also lower overhead costs compared with traditional business models (Sikorski et al., 2017). Smart contract-based transactions can support the development of multi-supplier networks, which further decreases transaction expenses (Hofmann et al., 2018b). In addition, blockchain can shorten settlement processes and reduce transaction lead time by consolidating or removing unnecessary post-trade settlement steps (Gokhale, 2016). By embedding data within transactions, organizations can automate conditional process execution, reduce delays, and improve operational productivity (Kamble et al., 2021b; Shrier et al., 2016; Ying et al., 2018b). The distributed ledger structure can also enhance security because transactions are verified through cryptographic methods, and the data recorded in blocks is difficult to change. As a result, secure databases can serve as a strong foundation for implementing intelligent organizations (Chen et al., 2018b; Ølnes et al., 2017b; Ying et al., 2018a). Participants share ledger-based information and maintain replicated copies, while access and visibility are supported through an open tracking mechanism (Bumblauskas et al., 2020). Since blockchain networks are decentralized by design, failures or attacks that target a single central point are less likely to disrupt transactions (Gokhale, 2016; Y. Wang et al., 2018b). By enabling accurate data collection and exchange across sourcing, processing, storage, distribution, and sales, BT supports transparent and reliable information flows (Jeppsson & Olsson, 2017). All records can be traced back to blockchain blocks (Domingues et al., 2015). Overall, BT strengthens transparency and traceability in the exchange of financial resources, information, and products through decentralized databases and secure collaboration, which can increase public trust (Sahebi et al., 2022).

Through each node, a network duplicate is made in the Blockchain. This enables real-time data audits and inspection, enhancing accessibility. Recipients may have high transparency inside the blockchain network due to open network processes. Consequently, no or fewer trustworthy intermediaries are needed (Abeyratne & Monfared, 2016). The clarity BT provides enhances the credibility and reputation of a supply chain (Kshetri, 2018). In terms of the architecture of network reputation, BT introduces new possibilities. Moreover, fraud might be prevented (Cai & Zhu, 2016). With blockchain agreement, more credibility and transparency may be achieved. Blockchains are much more transparent and efficient than centralized supply networks (Kamble et al., 2021a).

HSC performance criteria based on the SCOR model

The score model evaluates supply chain performance using a set of performance attributes and related indicators (Ahmed et al., 2025). In this reference framework, key supply chain attributes such as reliability and agility are identified first, and the humanitarian supply chain is then assessed based on these defined attributes. Various performance measures are applied to evaluate each attribute (Abidi et al., 2020; Lockamy & McCormack, 2004). In actuality, a functional characteristic comprises a collection of signs that represent a method. The SCOR model contains the following five core elements:

Reliability

Capability to fulfill anticipated duties. This aspect of HSC concentrates on anticipating performance results. In the case of a calamity, this attribute is characterized primarily by prompt preparation, proper placement, and adequate quality. The sole stage one indication of this operational characteristic is the fulfillment of all assigned tasks to reduce the number of damaged individuals (Abidi et al., 2020).

Accountability

Key accountability elements after a disaster focus on saving lives and property, supporting the wellbeing of affected people, and limiting the overall impact of damage. These elements include relief and rescue, health and medical care, protection, communication, and early warning systems. During the crisis stage, the most critical response components must be identified and prioritized so that, when an incident occurs, responders can act more effectively, quickly, and accurately with less time and effort (Patil et al., 2020). This operational aspect, which reflects the value delivered by the effort, is measured using a level one indicator called the cycle time for completing relief operations.

Agility

Human resources and institutional infrastructure are vital to aid organizations because they enhance agility and constitute some of an organization's most valuable resources (Singh, 2025). As external circumstances shift continuously, unexpected disasters can arise and generate significant operational pressure. Consequently, managers need to be ready to respond efficiently to evolving situations (Abidi et al., 2020). This capability reflects how well an organization can handle external demands and adjust rapidly to change. It is assessed through measures such as upstream and downstream HSC adaptability, as well as the overall importance of this capability during disaster response.

Costs

This attribute reflects the operational costs related to humanitarian supply chain procedures. Common cost components include labor, materials, relief items, and transportation expenses. (Boxy et al., 2020).

Aid management efficiency

This attribute indicates how effectively an organization utilizes its resources. In supply chain operations, strong asset management practices can help reduce inventory levels and limit reliance on outsourcing. It is evaluated through measures such as cash-to-cash cycle time, return on supply chain fixed assets, and return on working capital. Overall, this attribute is primarily internally focused (Birdoğan & Abuasad, 2020; Patil et al., 2020).

Performance assessment in a HSC involves evaluating how goods, materials, and information are stored and transported from their source to the end beneficiary. To meet the supply chain objective of reducing disaster-related hardships for affected populations, operations must be both efficient and cost-conscious (Patil et al., 2020).

Research gap

Because BT studies have thus far been predominantly concentrated on technical issues of features and design, whereas neglecting implementations, wealth generation, and management, there is little practical guidance for experts in adjusting this innovation to the supply chain (Risius & Spohrer, 2017). On the other hand, few analyses of the efficacy of BT implementation in supply chains have been conducted (Francisco & Swanson, 2018; Kamble et al., 2021a; Queiroz & Wamba, 2019). To cover this gap in the research, a conceptual model of the influence of BT facilitators (one of the developing facilitators in the supply chain) on the functional properties of the HSC is offered. According to the study literature, hardly any of the studies on this subject have examined the impact of this technology's facilitators on the features and performance metrics of the supply chain employing cognitive mapping. Furthermore, there is relatively little research on Blockchain in the HSC. In addition, this study employs cognitive mapping in an intuitive fuzzy environment to address the uncertainty space, which has not been done before in the area of the supply chain. On the other hand, the relationship among the technology's facilitators has been established by proposing a combined strategy of a multi-objective intuitive FCM. In addition, Blockchain is discussed in the emerging trends segment of the new version of the SCOR model (SCOR v12); In this respect, the procedures and functional properties of the HSC relative to the reference model of supply chain operations, as well as the emergence and implementation of BT in the created procedures with an emphasis on the derived facilitators, are described.

Materials and Methods

This study adopts a mixed-method research design, integrating both qualitative and quantitative approaches within a single case study setting. From a methodological standpoint, the research is descriptive in terms of data collection, while concept development is grounded in an in-depth case analysis. A sequential exploratory strategy is employed, where qualitative insights are first generated and subsequently structured into a quantitative analytical framework. The proposed analytical framework for examining the impact of BTFs on HSCs' performance is developed through two main stages. In the initial stage, a systematic review of the literature is conducted to identify potential BTFs. In the subsequent stage, semi-structured interviews were conducted with experts to evaluate how BTs influence the identified supply chain processes. Particular attention is given to assessing the mutual interactions among the selected facilitators, recognizing that technological enablers often exert interdependent and reinforcing effects. Experts also evaluate the relative strength and strategic importance of each facilitator in enhancing SC performance. Building upon these insights, cognitive mapping principles are applied to explore the causal structure among facilitators and performance measures. The study then develops a conceptual model based on a multi-objective IFCM approach, which enables the analysis of complex, uncertain, and feedback-driven relationships within the system.

Table 2. Research expert panel

Experts	Field	Job Title	Experience
1	Academics	Supply chain professor	13
2	Academics	Computer science professor	21
3	Academics	Crisis management professor	19
4	System integration	Blockchain-related computer engineering	13
5	System integration	Computer science degrees	11
6	Humanitarian organization managers	Military aids coordinator	13
7	Humanitarian organization managers	Procurement manager	21
8	Banking system managers	Cybersecurity manager	16

In this study, 11 experts were initially selected for participation in the panel through a structured screening process based on predefined expertise criteria. However, 3 individuals withdrew before the first session due to personal circumstances. As a result, data collection and subsequent IFCM analysis were conducted using the evaluations of eight qualified experts (see Table 2). Although the final panel consisted of 8 participants, this number remains methodologically acceptable for expert-based decision modeling approaches such as IFCM, where depth of expertise is prioritized over sample size. The reliability of the results is supported by the high level of domain knowledge and professional experience of the selected specialists. Among the eight participants, five were academic scholars with research backgrounds in SCM and emerging technologies, while three were practitioners specializing in crisis and disaster management. The overall research framework was depicted in Figure 2. The study begins with a systematic literature review to identify potential BTFs and humanitarian supply chain performance attributes. In the next step, an expert panel comprising eight academics and practitioners with extensive experience in humanitarian aid and emergency response validates and refines these constructs. Subsequently, causal relationships between facilitators and performance dimensions were elicited and quantified using intuitionistic fuzzy cognitive mapping. Finally, a multi-objective analysis was employed to derive the relative importance of each facilitator under different performance-oriented scenarios.

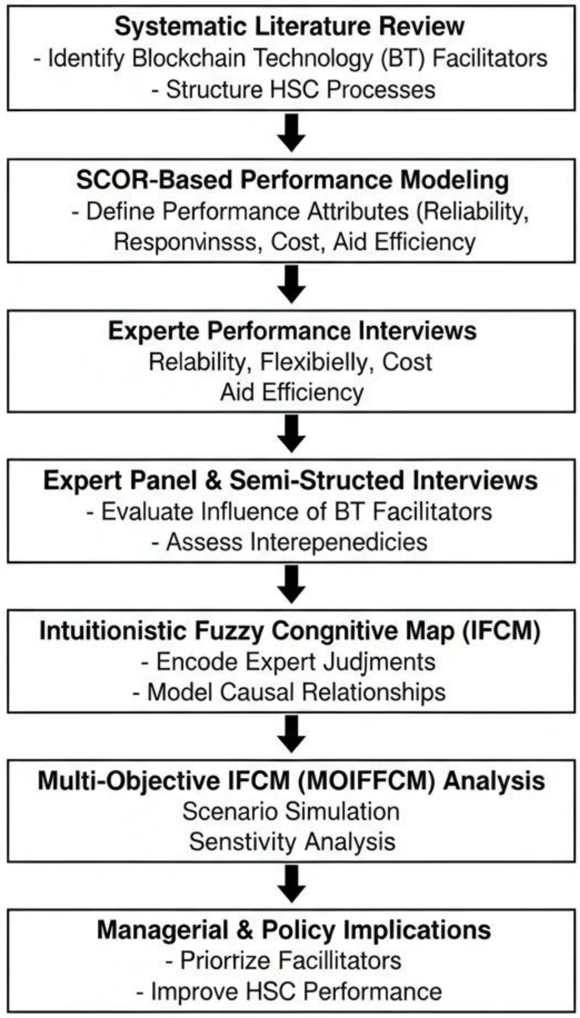


Figure 2. Research framework and methodological steps

Intuitionistic fuzzy cognitive map

Axelrod introduced the cognitive map in 1976 as a method for modeling complex systems and identifying causal relationships (Axelrod, 2015). Later (Kosko, 1986) extended Axelrod's approach and developed the FCM, describing it as a fuzzy directed graph that allows feedback. Similar to conventional cognitive maps, FCM comprises a set of nodes representing changeable ideas. An $n \times n$ framework depicts an FCM containing n ideas. In principle, the causal link between two ideas is represented by the nonlinear function e (c_i, c_j), which represents the magnitude of $ci's$ impact on cj. (Schneider et al., 1998) created a technique for the automated development of FCMs. (Rodriguez-Repiso et al., 2007) created an enhanced FCM consisting of four matrices: the starting matrix of success, the fuzzified matrix of success, the intensity of relationship matrix of success, and the ultimate matrix of success.

An intuitionistic fuzzy set (IFS) is one of the fuzzy set theory's extensions (Zadeh, 1965). IFS, established by(Atanassov, 2000), has been proven more consistent with ambiguity than other excellent fuzzy sets. When the known evidence is insufficient to characterize the imprecision using the standard fuzzy set, the IFS idea might be seen as an excellent or alternative technique. IFS is defined by a membership function and a non-membership function such that the total of both values is below one. Fuzzy sets solely assess the degree of acceptability (Atanassov, 1999). IFSs are now being explored and utilized in numerous scientific disciplines. (Atanassov, 1999, 2000; Ban, 2006; Deschrijver & Kerre, 2002) are some of the researchers who have conducted studies on IFS (2002). Definition 1 - Assume reference set = {x_1, x_2, x_3…}. In this case, set A, which is a subset of X, is an intuitionistic fuzzy set defined as below:

$$A = \{\prec x, u_A(x), v_A(x) \succ \forall x \in X\} \tag{1}$$

In the above definition, $u_A(x), v_A(x)$ are the degrees of membership and non-membership, respectively, which are defined as $u_A(x): x \rightarrow [0,1], v_A(x): x \rightarrow [0,1]$ and satisfy $0 \leq u_{ij}(x) + u_{ij}(x) \leq 1$. In addition, for each $x \in X$, the intuitionistic index π_x is defined as $\pi_x = 1 - u_x - v_x$ (Atanassov, 1999).

$\left(u_{ij}(X), u_{ij}(X), \pi_{ij}(X)\right) \leq 1$ is an intuitionistic fuzzy number that satisfies the following conditions:

$$u_{ij}(x) \epsilon [0,1], v_{ij}(x) \epsilon [0,1], \pi_{ij}(x) \epsilon [0,1], 0 \leq u_{ij}(x) + v_{ij}(x) \leq 1, \pi_{ij}(x) = 1 - u_{ij}(x) - v_{ij}(x) \tag{2}$$

It must be noted that although the intuitionistic fuzzy number is similar (in appearance) to the triangular fuzzy number (a, b, c), it is quite different. A triangular fuzzy number is a convex normal fuzzy set with a membership function in which (a ≺ b ≺ c); while an intuitionistic fuzzy number is a point in three-dimensional space constructed by axes. $u_{ij}(X), v_{ij}(X), \pi_{ij}(X)$ (Szmidt & Kacprzyk, 2000). Atanassov and Gargov (1999) have described intuitionistic fuzzy numbers (0.50, 0.20, 0.30) as a scenario where votes in favor of adoption are 0.5, votes against it are 0.2, and abstained votes are 0.30. In this context, the following relationship holds:

$$\mu_{ij}^{\beta}(x) + v_{ij}^{\beta}(x) \leq 1, \;\; 0 \leq \mu_{ij}^{\alpha}(x) \leq \mu_{ij}^{\beta}(x) \leq 1, \;\; 0 \leq v_{ij}^{\alpha}(x) \leq \mu_{ij}^{\beta}(x) \leq 1 \tag{3}$$

These numbers are better suited to deal with uncertainty and provide a more logical-mathematical framework to deal with inexact facts and incomplete information (Glykas, 2010). Some of the operators and relationships between these numbers are provided in the following. For simplicity's sake, these numbers are expressed as $[u_{ij}(x), v_{ij}(x), \pi_{ij}(x)]$ where $\pi_{ij}(x)$, $v_{ij}(x)$ and $\pi_{ij}(x)$ are numbers in the range [0, 1]. Assume intuitionistic fuzzy numbers $A = \{\langle x, \mu_A(x), v_A(x) | x \in X\rangle\}$ and $A_1 = \{\langle x, \mu_{A1}(x), v_{A1}(x) | x \in X\rangle\}$ and $A_2 = \{\langle x, \mu_{A2}(x), v_{A2}(x) | x \in X\rangle\}$ and the real number n. According to Xu and Cai (2012), the following relationships are defined:

$$\bar{A} = \{\langle x, v_A(x), \mu_A(x) | x \in X\rangle\} \tag{4}$$

$$A_1 \cap A_2 = \left\{\langle x, \min\left\{\mu_{A_1}(x), \mu_{A_2}(x)\right\}, \max\left\{v_{A_1}(x), v_{A_2}(x)\right\} \mid x \in X\rangle\right\} \tag{5}$$

$$A_1 \cup A_2 = \left\{\langle x, \max\left\{\mu_{A_1}(x), \mu_{A_2}(x)\right\}, \min\left\{v_{A_1}(x), v_{A_2}(x)\right\} \mid x \in X\rangle\right\} \tag{6}$$

$$A_1 + A_2 = \left\{\langle x, \mu_{A_1}(x) + \mu_{A_2}(x) - \mu_{A_1}(x)\, \mu_{A_2}(x), v_{A_1}(x), v_{A_2}(x) \mid x \in X\rangle\right\} \tag{7}$$

$$A_1 . A_2 = \left\{\langle x, \mu_{A_1}(x) . \mu_{A_2}(x) . v_{A_1}(x) + v_{A_2}(x) - v_{A_1}(x) . v_{A_2}(x) \mid x \in X\rangle\right\} \tag{8}$$

$$nA = \left\{\langle x, 1 - \left(1 - \mu_A(x)\right)^n, \left(v_A(x)\right)^n\rangle\right\} \tag{9}$$

$$A^n = \left\{\langle x, \left(\mu_A(x)\right)^n, 1 - \left(1 - v_A(x)\right)^n\rangle\right\} \tag{10}$$

Multi-Objective Intuitionistic Fuzzy Cognitive Mapping (MOIFFCM) was employed to simultaneously evaluate the influence of blockchain facilitators on multiple humanitarian supply chain performance objectives. After constructing the intuitionistic fuzzy adjacency matrix based on expert evaluations, the causal structure was analyzed through iterative propagation of direct and indirect influences. The intuitionistic fuzzy weights were aggregated using expert consensus operators and normalized to preserve consistency among membership, non-membership, and hesitation degrees. Subsequently, performance attributes derived from the SCOR framework were introduced as target concepts, enabling the assessment of facilitator impacts across multiple objectives, including reliability, accountability, agility, cost performance, and aid management efficiency. This approach allows the identification of dominant facilitators, feedback mechanisms, and influence pathways within a complex humanitarian supply chain environment characterized by uncertainty and interdependence. All quantitative IFCM and MOIFFCM computations were implemented in Python 3.11. The analysis was conducted using a combination of NumPy and SciPy libraries for matrix operations and intuitionistic fuzzy calculations, Pandas for data management and aggregation of expert judgments, and NetworkX for modeling and analyzing the cognitive network structure.

Results

The values reported in Tables 6–8 were generated through a structured IFCM procedure. Initially, experts evaluated the pairwise influence among the thirteen blockchain facilitators using intuitionistic fuzzy numbers expressed as triplets (μij, νij, πij), where membership represents the strength of influence, non-membership reflects the degree of rejection of influence, and hesitation captures uncertainty, subject to the condition $\mu+\nu+\pi=1$. Individual expert judgments were aggregated using an averaging operator to construct a collective intuitionistic fuzzy adjacency matrix. Subsequently, the summation matrix of weights was computed by propagating direct and indirect influences across the facilitator network using IFCM arithmetic operations, including intuitionistic fuzzy multiplication and addition. A normalization step ensured that all computed values remained within the admissible interval while preserving the intuitionistic constraint. The final results were decomposed into three matrices representing membership, non-membership, and hesitation, with diagonal elements set to zero to exclude self-influence.

Table 3. Membership (μ) matrix of causal weights among BTFs

BTF	BTF1	BTF2	BTF3	BTF4	BTF5	BTF6	BTF7	BTF8	BTF9	BTF10	BTF11	BTF12	BTF13
BTF1	0	0.58	0.62	0.66	0.54	0.60	0.50	0.52	0.71	0.64	0.59	0.55	0.67
BTF2	0.61	0	0.65	0.74	0.63	0.68	0.57	0.59	0.73	0.70	0.76	0.62	0.82
BTF3	0.56	0.63	0	0.69	0.60	0.64	0.55	0.57	0.68	0.75	0.66	0.61	0.72
BTF4	0.65	0.79	0.70	0	0.67	0.73	0.59	0.61	0.81	0.74	0.77	0.69	0.84
BTF5	0.52	0.60	0.58	0.63	0	0.62	0.66	0.71	0.64	0.59	0.68	0.74	0.65
BTF6	0.57	0.67	0.64	0.72	0.61	0	0.60	0.63	0.69	0.66	0.83	0.70	0.78
BTF7	0.48	0.55	0.52	0.58	0.73	0.57	0	0.76	0.60	0.54	0.62	0.80	0.59
BTF8	0.50	0.57	0.54	0.60	0.75	0.59	0.79	0	0.63	0.56	0.65	0.82	0.61
BTF9	0.70	0.73	0.67	0.82	0.64	0.69	0.61	0.63	0	0.72	0.74	0.68	0.80
BTF10	0.63	0.71	0.78	0.75	0.58	0.65	0.55	0.57	0.73	0	0.70	0.64	0.77
BTF11	0.60	0.77	0.68	0.79	0.69	0.85	0.63	0.66	0.75	0.72	0	0.71	0.88
BTF12	0.54	0.62	0.60	0.70	0.76	0.72	0.83	0.84	0.67	0.66	0.73	0	0.81
BTF13	0.66	0.83	0.74	0.86	0.65	0.79	0.60	0.63	0.82	0.78	0.90	0.84	0

Table 4. Non-Membership (ν) matrix of causal weights among BTFs

BTF	BTF1	BTF2	BTF3	BTF4	BTF5	BTF6	BTF7	BTF8	BTF9	BTF10	BTF11	BTF12	BTF13
BTF1	0	0.24	0.22	0.20	0.28	0.25	0.32	0.30	0.15	0.21	0.23	0.27	0.19
BTF2	0.21	0	0.20	0.14	0.22	0.18	0.26	0.24	0.13	0.16	0.11	0.23	0.08
BTF3	0.26	0.21	0	0.17	0.24	0.22	0.29	0.27	0.18	0.12	0.21	0.25	0.16
BTF4	0.18	0.10	0.16	0	0.19	0.15	0.25	0.23	0.09	0.14	0.12	0.18	0.07
BTF5	0.30	0.25	0.27	0.23	0	0.24	0.18	0.14	0.22	0.28	0.19	0.13	0.21
BTF6	0.25	0.19	0.22	0.16	0.23	0	0.24	0.21	0.18	0.20	0.09	0.15	0.12
BTF7	0.33	0.29	0.31	0.27	0.12	0.28	0	0.10	0.24	0.30	0.22	0.07	0.26
BTF8	0.31	0.27	0.29	0.25	0.11	0.26	0.09	0	0.22	0.28	0.20	0.06	0.24
BTF9	0.16	0.13	0.19	0.08	0.23	0.18	0.24	0.22	0	0.15	0.14	0.20	0.09
BTF10	0.22	0.15	0.11	0.14	0.29	0.23	0.30	0.28	0.14	0	0.18	0.24	0.13
BTF11	0.23	0.12	0.19	0.10	0.18	0.07	0.22	0.20	0.13	0.15	0	0.17	0.05
BTF12	0.27	0.23	0.25	0.16	0.12	0.14	0.06	0.05	0.21	0.22	0.16	0	0.08
BTF13	0.19	0.08	0.14	0.06	0.21	0.12	0.26	0.24	0.09	0.11	0.04	0.07	0

The membership matrix (Table 3) reveals a structurally coherent influence network in which governance-oriented facilitators play a dominant role. Transparency exhibits the strongest outgoing and incoming influence relationships, particularly with Traceability, Immutability, and Auditability, indicating that visibility and information openness constitute the core drivers of blockchain effectiveness in HSCs. Traceability and Immutability also display high membership values in their mutual interactions, suggesting a reinforcing cycle between record integrity and end-to-end tracking capability. Smart contracts demonstrate strong influence on operational efficiency facilitators such as reduced settlement lead times and transaction costs, highlighting their practical contribution to accelerating humanitarian financial and procurement processes. Infrastructure-related facilitators, including Decentralized Database and Shared Database, show moderate yet widespread influence patterns, functioning as structural enablers rather than dominant drivers. Overall, the membership values indicate that trust-building mechanisms and information governance capabilities form the central backbone of blockchain integration within humanitarian logistics systems.

The non-membership matrix (Table 4) and hesitation matrix (Table 5) further validate the stability of this structure. Low non-membership values are observed in relationships involving Transparency, Traceability, and Immutability, reflecting strong expert agreement on their interdependence. In contrast, relatively higher non-membership values appear in indirect economic relationships, such as those linking anonymity or decentralization to cost reduction, suggesting that experts perceive these effects as less direct or more context-dependent. Hesitation values remain generally moderate to low across the matrix, indicating a high level of consensus while acknowledging some uncertainty in secondary or indirect relationships. The lowest hesitation levels correspond to governance and operational efficiency links, reinforcing their robustness within the network. Collectively, the three matrices demonstrate that blockchain facilitators in humanitarian supply chains are structured around a governance-centric core supported by infrastructural enablers and operational efficiency mechanisms, forming a coherent and strategically aligned causal system suitable for subsequent centrality and scenario analysis within the IFCM framework.

Table 5. Hesitation (π) matrix of causal weights among BTFs

BTF	BTF1	BTF2	BTF3	BTF4	BTF5	BTF6	BTF7	BTF8	BTF9	BTF10	BTF11	BTF12	BTF13
BTF1	0	0.18	0.16	0.14	0.18	0.15	0.18	0.18	0.14	0.15	0.18	0.18	0.14
BTF2	0.18	0	0.15	0.12	0.15	0.14	0.17	0.17	0.14	0.14	0.13	0.15	0.10
BTF3	0.18	0.16	0	0.14	0.16	0.14	0.16	0.16	0.14	0.13	0.13	0.14	0.12
BTF4	0.17	0.11	0.14	0	0.14	0.12	0.16	0.16	0.10	0.12	0.11	0.13	0.09
BTF5	0.18	0.15	0.15	0.14	0	0.14	0.16	0.15	0.14	0.13	0.13	0.13	0.14
BTF6	0.18	0.14	0.14	0.12	0.16	0	0.16	0.16	0.13	0.14	0.08	0.15	0.10
BTF7	0.19	0.16	0.17	0.15	0.15	0.15	0	0.14	0.16	0.16	0.16	0.13	0.15
BTF8	0.19	0.16	0.17	0.15	0.14	0.15	0.12	0	0.15	0.16	0.15	0.12	0.15
BTF9	0.14	0.14	0.14	0.10	0.13	0.13	0.15	0.15	0	0.13	0.12	0.12	0.11
BTF10	0.15	0.14	0.11	0.11	0.13	0.12	0.15	0.15	0.13	0	0.12	0.12	0.10
BTF11	0.17	0.11	0.13	0.11	0.13	0.08	0.15	0.14	0.12	0.13	0	0.12	0.07
BTF12	0.19	0.15	0.15	0.14	0.12	0.14	0.11	0.11	0.12	0.12	0.11	0	0.11
BTF13	0.15	0.09	0.12	0.08	0.14	0.09	0.14	0.13	0.09	0.11	0.06	0.09	0

This section examines supply chain performance attributes based on the SCOR model and treats them as the target concepts in cognitive mapping (Table 6). Next, expert interviews are conducted to identify the causal relationships between BT facilitators and these performance attributes and to assign weights to the identified links. Each expert interview produces a cause and effect matrix. The weighting of experts for these causal relationships follows the same approach used in the earlier section that derived causal links among BT facilitators.

Table 6. Nomenclature for the performance characteristics

Performance characteristics of HSC	Symbol
Reliability	Goal 1 (C_1)
accountability	Goal 2 (C_2)
Agility	Goal 3 (C_3)
Cost	Goal 4 (C_4)
Aid management efficiency	Goal 5 (C_5)

Because the causal relationships are evaluated using an intuitionistic fuzzy approach, Table 7 presents the membership values for the weights assigned to the links between facilitators and performance characteristics. Table 8 reports the non-membership values for these assigned weights. Table 9 provides the uncertainty values associated with the weights assigned to the causal relationships between facilitators and performance characteristics.

Table 7. Membership (μ) matrix of causal weights among BTFs and performance characteristics

Goal/BTF	Goal 1	Goal 2	Goal 3	Goal 4	Goal 5
BTF1	0.3264	0.2749	0.3264	0.3064	0.3414
BTF2	0.4540	0.4312	0.4433	0.4185	0.5000
BTF3	0.5000	0.5783	0.5753	0.5382	0.5344
BTF4	0.5783	0.5545	0.5215	0.5188	0.5410
BTF5	0.5317	0.5753	0.5643	0.5000	0.5000
BTF6	0.5000	0.6810	0.5000	0.5000	0.6277
BTF7	0.6468	0.6608	0.5000	0.6810	0.5000
BTF8	0.5124	0.7124	0.5000	0.6810	0.5000
BTF9	0.6810	0.5124	0.5000	0.3264	0.3308
BTF10	0.6608	0.6608	0.6468	0.6277	0.4185
BTF11	0.6277	0.6277	0.6810	0.6277	0.5000
BTF12	0.7860	0.6767	0.7477	0.7477	0.7169
BTF13	0.9000	0.9000	0.9000	0.9000	0.9000

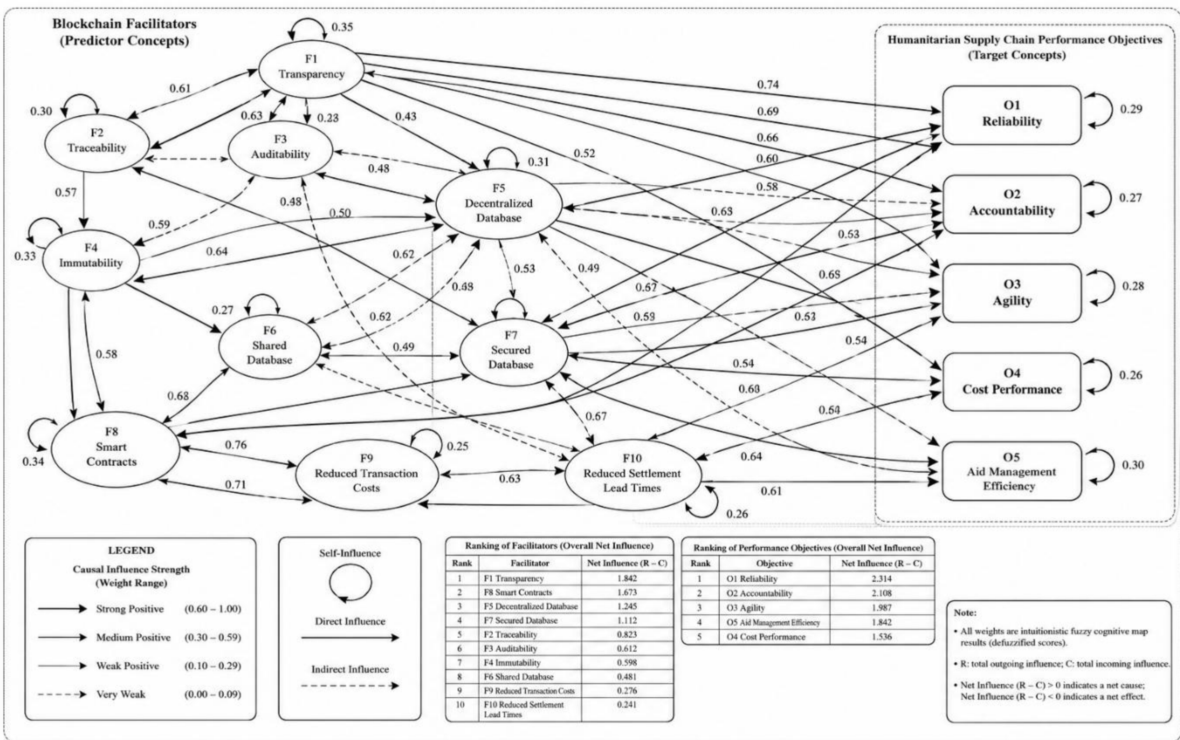
Table 8. Non-Membership (ν) matrix of causal weights among BTFs and performance characteristics

Goal/BTF	Goal 1	Goal 2	Goal 3	Goal 4	Goal 5
BTF1	0.57	0.62	0.57	0.59	0.56
BTF2	0.45	0.47	0.46	0.48	0.40
BTF3	0.40	0.32	0.32	0.36	0.37
BTF4	0.32	0.35	0.38	0.38	0.36
BTF5	0.37	0.32	0.34	0.40	0.40
BTF6	0.40	0.22	0.40	0.40	0.27
BTF7	0.25	0.24	0.40	0.22	0.40
BTF8	0.39	0.19	0.40	0.22	0.40
BTF9	0.22	0.39	0.40	0.57	0.57
BTF10	0.24	0.24	0.25	0.27	0.48
BTF11	0.27	0.27	0.22	0.27	0.40
BTF12	0.14	0.22	0.16	0.16	0.18
BTF13	0.05	0.05	0.05	0.05	0.05

Table 9. Hesitation (π) matrix of causal weights among BTFs and performance characteristics

Goal/BTF	Goal 1	Goal 2	Goal 3	Goal 4	Goal 5
BTF1	0.10210	0.10125	0.10210	0.10203	0.10197
BTF2	0.10050	0.10044	0.10050	0.10032	0.10000
BTF3	0.10000	0.10023	0.10026	0.10034	0.10032
BTF4	0.10023	0.10035	0.10024	0.10022	0.10034
BTF5	0.10031	0.10026	0.10032	0.10000	0.10000
BTF6	0.10000	0.10054	0.10000	0.10000	0.10034
BTF7	0.10047	0.10053	0.10000	0.10054	0.10000
BTF8	0.10016	0.10040	0.10000	0.10054	0.10000
BTF9	0.10054	0.10016	0.10000	0.10210	0.10208
BTF10	0.10053	0.10053	0.10047	0.10034	0.10032
BTF11	0.10034	0.10034	0.10054	0.10034	0.10000
BTF12	0.07705	0.10054	0.09082	0.09082	0.10036
BTF13	0.05000	0.05000	0.05000	0.05000	0.05000

Using the causal relationships identified in earlier stages of the study, a multi-objective intuitionistic fuzzy map was constructed. In this map, the nodes represent the examined concepts, including the factors supporting BT and the supply chain performance dimensions. The directed arrows indicate the cause and effect relationships among these concepts. Figure 3 highlights the governance-centric backbone of transparency, traceability, immutability and accountability, and the central role of secure, shared and decentralized databases together with smart contracts in improving reliability, responsiveness, agility, cost efficiency and aid management efficiency.



Ranking of Facilitators (Overall Net Influence)

Rank	Facilitator	Net Influence (R – C)
1	F1 Transparency	1.842
2	F8 Smart Contracts	1.673
3	F5 Decentralized Database	1.245
4	F7 Secured Database	1.112
5	F2 Traceability	0.823
6	F3 Auditability	0.612
7	F4 Immutability	0.598
8	F6 Shared Database	0.481
9	F9 Reduced Transaction Costs	0.276
10	F10 Reduced Settlement Lead Times	0.241

Ranking of Performance Objectives (Overall Net Influence)

Rank	Objective	Net Influence (R – C)
1	O1 Reliability	2.314
2	O2 Accountability	2.108
3	O3 Agility	1.987
4	O5 Aid Management Efficiency	1.842
5	O4 Cost Performance	1.536

Figure 3. Final causal MOIFFCM model

The final multi-objective intuitionistic fuzzy cognitive map reveals a governance-centric causal structure in which information-related facilitators such as transparency, traceability, immutability and accountability form the backbone of blockchain adoption in humanitarian supply chains. These governance mechanisms, together with infrastructural enablers – namely decentralized, shared and secure databases – feed into smart contracts and efficiency-oriented facilitators such as reduced interaction costs, shorter payment settlement times and improved risk management. In particular, smart contracts and secure databases significantly enhance reliability and responsiveness while simultaneously improving cost efficiency, whereas shared and decentralized databases mainly strengthen reliability, agility, and aid management efficiency by providing a trusted, tamper-proof, and commonly accessible information base for humanitarian actors. The conceptual framework distinguishes three interconnected layers of influence. The first layer consists of governance-oriented facilitators, including transparency, traceability, auditability, and immutability, which establish trust and information integrity throughout the supply chain. The second layer comprises infrastructure-oriented facilitators such as decentralized databases, shared databases, and secured databases, which provide the technological foundation necessary for blockchain implementation. The third layer includes operational facilitators and performance outcomes, where smart contracts, reduced transaction costs, and reduced settlement lead times directly contribute to improvements in reliability, accountability, agility, cost efficiency, and aid management effectiveness. This layered structure provides a clearer explanation of how blockchain capabilities translate into operational and managerial performance improvements.

Several measures were adopted to enhance the validity and robustness of the results. First, the identified blockchain facilitators were derived from an extensive review of the literature and subsequently validated through expert evaluation, providing methodological triangulation. Second, the expert panel consisted of highly experienced academics and practitioners from complementary domains, ensuring diversity of perspectives and reducing individual bias. Third, intuitionistic fuzzy sets were employed to capture not only agreement and disagreement but also hesitation, thereby reflecting uncertainty inherent in expert judgments. Finally, the aggregation of multiple expert evaluations into a collective cognitive map reduced the influence of individual opinions and improved the overall stability and reliability of the resulting causal structure.

Discussion

BT remains in an early phase and must overcome numerous technical, regulatory, infrastructural, and organizational barriers before it can be fully developed and broadly adopted. Moreover, demands for significant computing capacity and reliable high-bandwidth internet access add to these constraints, limiting rapid implementation across global supply chains (Min, 2019). If the drivers of BT adoption are strengthened through well-designed supply chain policies and strategies, the technology could significantly enhance HSC operations and encourage supply chain stakeholders to implement BT to support greater sustainability. The results show that in this cognitive map, there is no causal relation between some of the facilitators, while some others have bilateral causal relations; that is, the effect is not unilateral in these facilitators, and they are affected by each other. In addition, according to the drawn multi-objective intuitionistic FCM, it can be seen that, for example, reducing the time of settling the payments and reducing the costs of interactions affect each other. Smart contracts affect the reduction of the costs of interactions. Invariability affects the accountability sequence, trackability, and origin. Decentralized databases affect safe databases and smart contracts. Safe databases affect decentralized databases, shared databases, and smart contracts. Transparency affects the improvement in risk management. The accountability sequence affects invariability and trackability. Shared databases affect safe databases and smart contracts. Finally, trackability affects the accountability sequence, invariability, and origin.

The field evidence also indicates that several preconditions must still be addressed before blockchain can be deployed effectively to improve humanitarian supply chain outcomes. The results further indicate that blockchain can deliver meaningful benefits for humanitarian supply chains; therefore, supply chain actors should invest in the capabilities required for effective implementation, encourage coordinated adoption, and prioritize operational arrangements that enable timely support and assistance for injured individuals (Sahebi et al., 2020). In addition, blockchain facilitators can support the measurement, monitoring, and control of HSC risks and contribute to sustained performance improvement. Technical benefits also need to be combined with social and organizational considerations. Blockchain-enabled HSCs should provide strong opportunities for transparency among supply chain actors (Dubey et al., 2020; Ozdemir et al., 2020). HSC transparency supports compliance with relief activity standards and strengthens sustainability. Because a blockchain network can store sustainability- and safety-related data, safety issues and actions linked to supply chain actors and injured individuals can be traced quickly. It also helps identify the most critical destinations for aid, which can remove unnecessary activities and reduce human and financial losses for both stakeholders and those affected by the event. Blockchain-based smart contracts can reduce unnecessary human involvement and help prevent operational delays by automating service execution. Blockchain can also improve HSC data integrity and increase visibility across the supply chain (Ølnes et al., 2017). In addition, as a digital platform, blockchain can integrate and work with emerging technologies such as artificial intelligence, the Internet of Things, and 3D printing, which can further improve HSC performance over time.

The findings are largely consistent with previous studies emphasizing the importance of transparency, traceability, and trust-building mechanisms in blockchain-enabled humanitarian supply chains. For example, Dubey et al. (2020) argued that blockchain enhances collaboration and resilience by improving visibility and trust among humanitarian actors. Similarly, Sahebi et al. (2020) identified transparency and traceability as critical sources of operational improvement in supply chain contexts. Our results extend these findings by demonstrating that transparency not only represents a direct performance driver but also functions as a central causal hub that influences multiple blockchain facilitators simultaneously. Furthermore, unlike prior studies that mainly examined blockchain adoption factors independently, the proposed MOIFFCM approach reveals the dynamic interdependencies among facilitators and their collective influence on SCOR-based performance dimensions.

Managerial implications

Our research offers several substantive real-world implications. First, by drawing on a real-life case during the proof-of-technology phase, we demonstrate that blockchain can enhance accountability, visibility, traceability, and trust in humanitarian supply chains. Because the findings are grounded in empirical field data, they provide practice-oriented insights that extend beyond conceptual discussions, narrative reviews, blog posts, and studies relying primarily on high-level, publicly available use cases. Second, we contribute to the literature by identifying and examining blockchain adoption enablers through structured engagement with professionals who have an active interest in blockchain technologies. The following are the practical suggestions to enhance actors' awareness in HSC:

- The facilitators of BT direct the humanitarian organizations toward implementing this technology in the supply chains as fast as possible.
- The goal of humanitarian actors should be to establish strong-bounded technical collaborations with providers of leading blockchain services to realize the gradual implementation of this technology in the supply chains of their organizations.
- Currently, it is quite a difficult task to implement BT to support sustainable supply chains. The post-interview reports show that despite this technology's great potential, more than one-third of the supply chain experts were completely unfamiliar with this technology. There is not adequate knowledge and experience about blockchain. Therefore, it is extremely difficult to integrate this technology into current supply chains. Hence, it is necessary to hold training workshops with the presence of advisors and experts in blockchain-based solutions to familiarize the actors of HSCs with BT.

Beyond humanitarian settings, the findings provide valuable implications for industrial managers involved in complex supply chain networks. The identified facilitators can assist managers in prioritizing digital transformation initiatives, allocating technology investments more effectively, and improving information-sharing mechanisms among supply chain partners. The proposed MOIFFCM framework can also serve as a decision-support tool for evaluating alternative technology adoption strategies, identifying critical success factors, and anticipating the performance consequences of managerial decisions. Consequently, organizations operating in manufacturing, logistics, healthcare, and service industries may utilize the framework to improve supply chain resilience, transparency, and operational efficiency.

Theoretical contribution

Based on our findings, this study makes several theoretical contributions. First, although prior research generally agrees that adopting blockchain in HSCs can improve performance, the specific benefits and practical challenges of applying blockchain in HSC contexts are still not well understood. Because HSCs are highly uncertain and dynamic, achieving visibility and effective data tracing remains difficult (Sahebi et al., 2020). While some studies suggest that blockchain could strengthen supply chain visibility and tracing and therefore improve HSC transparency

(Dubey et al., 2020) emphasize the need for evidence-based, multi-method research to assess blockchain's real added value in HSCs. Our empirical results support the view that blockchain can enhance transparency and trust in HSCs. Second, this research contributes to contingent resource-based view theory by showing that the effectiveness of blockchain in HSCs is conditional on contextual factors, including resource availability, the quality of technological infrastructure, local knowledge and literacy levels, and regulatory constraints. Third, our study provides a more granular account of implementation considerations that can inform HSC scholarship. Specifically, our findings suggest that prior literature and theory often place greater emphasis on adoption drivers than on facilitators when discussing blockchain use in HSCs. In contrast, our case evidence, reflected in both the number and strength of causal influences, indicates that facilitators related to stakeholder engagement, skills development, resource provision, privacy safeguards, and governance mechanisms are particularly critical and can meaningfully improve HSC performance.

Conclusion

Humanitarian aid operations involve a diverse set of actors and organizations, each pursuing distinct objectives and relying on different systems, data standards, and operating procedures. When rapid response is required to support disaster-affected populations, humanitarian supply chains often lack end-to-end visibility and traceability, resulting in fragmented and poorly coordinated flows. This fragmentation can lead to delays, inefficient resource utilization, and heightened exposure to fraud and corruption. In many contexts, limited transparency and low interorganizational trust further constrain effective collaboration. Consequently, additional verification and control mechanisms are introduced, which increase administrative burden and transaction costs. Blockchain technology remains an evolving solution, and its deployment faces substantial barriers, including regulatory and legal constraints, technical challenges, and the need for reliable supporting infrastructure. Limited access to high-speed internet, as well as the computational requirements of blockchain applications, can also hinder adoption and impose significant setup time and cost (Aranda et al., 2019). Nevertheless, when supported by appropriate policies and implementation strategies, blockchain has the potential to improve the effectiveness and integrity of humanitarian supply chains. In this study, potential adoption enablers were initially identified through a review of the relevant literature, then validated by domain experts, and subsequently modeled using intuitionistic fuzzy cognitive mapping.

This study contributes to both theory and practice by integrating blockchain technology facilitators, SCOR-based humanitarian supply chain performance attributes, and multi-objective intuitionistic fuzzy cognitive mapping within a unified analytical framework. Unlike previous studies that primarily examined blockchain adoption factors in isolation, the proposed approach captures the complex interdependencies among facilitators and their collective influence on multiple performance dimensions. The results identify transparency, smart contracts, and secure decentralized information infrastructures as the most influential enablers of blockchain-enabled performance improvement. Future research may extend the proposed framework through longitudinal validation studies, comparative analyses across different industries and countries, and the integration of advanced technologies such as artificial intelligence, digital twins, and predictive analytics into blockchain-enabled supply chain ecosystems.

Future research directions

The present work extracted 13 blockchain facilitators from the literature. Iranian HSC and technology experts validated the facilitators. It is possible that the experts missed some facilitators. This could have a significant effect on the findings. Hence, in future studies, the following suggestions are recommended:

- When presenting the multi-objective cognitive mapping model, sensitivity analysis can be applied, and related scenarios can be developed to assess how the presence or absence of each BT facilitator, together with other facilitators, influences the supply chain performance characteristics.
- The proposed multi-objective intuitive fuzzy cognitive mapping model can be simulated using alternative learning algorithms, and the outcomes can be compared with the results of this study. Future research can also apply interval-valued intuitionistic fuzzy sets or hesitant fuzzy sets. In addition, system dynamics could be used as an appropriate modeling approach for extending this work.
- This study's main focus is on the first level of the supply chain operations reference model, which looks at the main processes. So, future research could take a closer look at the process classification or process element levels and see how BT facilitators affect these areas.

From a managerial perspective, the findings suggest that humanitarian organizations should prioritize investments in secure and shared digital infrastructures before pursuing large-scale blockchain deployment. Managers should focus on developing interoperable databases, strengthening cybersecurity capabilities, and establishing governance mechanisms that facilitate information sharing among relief actors. The results also indicate that smart contracts can significantly reduce administrative burden and accelerate procurement and financial settlement processes during emergencies. Therefore, policymakers, donors, and humanitarian agencies should collaborate to establish regulatory frameworks and technical standards that support blockchain adoption while ensuring data protection, accountability, and operational continuity.

Author Contributions

For research articles with several authors, a short paragraph specifying their individual contributions must be provided. The following statements should be used "Conceptualization, X.X. and Y.Y.; methodology, X.X.; software, X.X.; validation, X.X., Y.Y. and Z.Z.; formal analysis, X.X.; investigation, X.X.; resources, X.X.; data curation, X.X.; writing—original draft preparation, X.X.; writing—review and editing, X.X.; visualization, X.X.; supervision, X.X.; project administration, X.X.; funding acquisition, Y.Y. All authors have read and agreed to the published version of the manuscript." Please turn to the CRediT taxonomy for the term explanation. Authorship must be limited to those who have contributed substantially to the work reported.

Data Availability Statement

Data available on request from the authors.

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Ethical considerations

The authors avoided data fabrication, falsification, and plagiarism, and any form of misconduct.

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Conflict of interest

The authors declare no conflict of interest.

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