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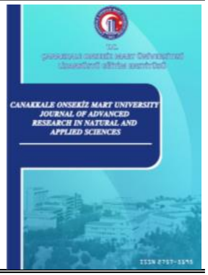

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Evaluation of Blockchain Technology for Supply Chains using an Integrated Fuzzy Cognitive Map-QFD Methodology

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Research Article

Abstract − The rapid advancement of technology has made it imperative for supply chains to adapt to the changing landscape. Blockchain technology holds immense potential to transform supply chain processes, but the challenge lies in identifying the most suitable blockchain characteristics to meet the various performance indicators of a supply chain. To overcome this challenge, this study aims to prioritize the most critical blockchain characteristics in a supply chain. The study adopts a two-stage Quality Function Deployment (QFD) methodology to rank blockchain characteristics based on supply chain and software requirements. The methodology evaluates the supply chain performance indicators using the Supply Chain Operations Reference (SCOR) model and software needs using the International Organization for Standardization (ISO) software quality characteristics. After determining the problematic SCOR and ISO software-related metrics, the study utilizes the QFD Stage 1 to obtain the weights of ISO software characteristics and employs the Fuzzy Cognitive Map (FCM) to determine the most crucial blockchain characteristics for QFD Stage 2. The results of this study show that the top priorities for blockchain characteristics in a supply chain are smart contract functionality, privacy, transaction per second, tokenization, security, permissioned network, scalability, cost, modularity, and licensing, in order of importance.

Keywords − *Blockchain, fuzzy cognitive map, fuzzy QFD, supply chain management*

1. Introduction

Supply chains must adapt their operations to fulfil the demands of their customers, which requires a harmonized approach that encompasses various processes, such as design, manufacturing, logistics, marketing, and more [1]. Technology serves as a crucial tool in advancing business processes [2]. As a novel technology, blockchain promises to disrupt the traditional methods of handling transactions and managing organizational processes [3]. By redesigning business processes to fully leverage the benefits of blockchain, organizations can attain greater efficiency [4]. To this end, it is important to thoroughly examine the blockchain characteristics relevant to supply chain processes. These characteristics encompass complex architectural, permission-related, and consensus-based elements that must be considered from multiple perspectives within the context of supply chains.

This study aims to prioritize the most significant blockchain technology characteristics for a supply chain. By utilizing a combination of supply chain and software-related metrics and problems, we employed an integrated FCM-QFD methodology in our examination. The integration of FCM into the QFD process reflects the complex relationships and trade-offs between blockchain characteristics. The processes within the supply chain are largely automated, thus requiring an increased focus on software to thoroughly address any supply

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chain-related problems. The current state of software characteristics and metrics within the supply chain is not well-defined, and utilizing organization-specific, non-standard quality frameworks, metrics, and models may pose difficulties in comparability [5]. Therefore, the problematic software quality characteristics were determined through the use of ISO/IEC 25010 [6] and ISO/IEC 25012 [7] standard quality characteristics in the supply chain.

Evaluating different dimensions of supply chain performance is crucial for the effective evaluation of blockchain technology. This is because supply chains are complex systems that encompass multiple processes, actors, and technologies. By using a range of performance metrics, supply chains can ensure that their technology evaluation is aligned with their specific goals and priorities. One of the key benefits of evaluating multiple performance dimensions is that it provides a more comprehensive view of the strengths and weaknesses of blockchain in the supply chain context. Studies on the application of blockchain technology in supply chain management have largely focused on a single dimension of performance, such as sustainability. For example, Bai and Sarkis [8] proposed a framework for sustainable supply chain transparency using hesitant fuzzy sets and regret theory. Yousefi and Tosarkani [9] evaluated the impact of blockchain technology on sustainable supply chain performance. Yadav et al. [10] evaluated the drivers of sustainable food security in India through blockchain technology, and Zkik et al. [11] evaluated the barriers and enablers of adopting blockchain for sustainable performance in e-enabled agriculture supply chains. Zhang and Song [12] evaluated the sustainability risks associated with blockchain adoption in sustainable supply chains. In the field of food supply chains, the impact of blockchain technology on performance has been explored, but with a limited focus on specific performance indicators [13]. Stranieri et al. [13] addressed this gap by evaluating the impact of blockchain technology on food supply chains in an exploratory manner. Kshetri [14] analyzed the mechanisms by which blockchain technology can support supply chain objectives, particularly regarding the roles of IoT in blockchain-based solutions and the degree of blockchain deployment for identity validation. The study also examined the potential impact of blockchain on primary supply chain management objectives such as cost, quality, speed, dependability, risk reduction, sustainability, and flexibility.

One of the key benefits of using standard characteristics and metrics is that they provide a common language and understanding for supply chain stakeholders. This promotes better communication and collaboration across the supply chain, leading to improved decision-making and increased operational efficiency. Furthermore, the use of standardized metrics facilitates benchmarking and enables organizations to identify best practices and opportunities for improvement. By providing a common language and consistent framework for performance evaluation, these standards support better communication, collaboration, and decision-making across the supply chain. Evaluating both supply chain metrics and software metrics is crucial in the assessment of blockchain technology in supply chains. Instead of evaluating them in isolation, it is important to take a holistic approach that considers both sets of metrics in a unified manner. This allows for a more comprehensive understanding of the interplay between the different metrics, leading to a more nuanced evaluation of the technology. The literature lacks studies that examine both supply chain and software performance indicators simultaneously through the application of standardized metrics and characteristics. In this study, the proposed methodology that integrates FCM and Fuzzy QFD evaluates a range of software issues and supply chain performance indicators. The indicators of the SCOR model and ISO quality models benefited.

The rest of the paper is organized as follows: Section 2 reviews the literature, and Section 3 outlines the methodology. Section 4 explains the application procedure, and Section 5 presents the conclusion.

2. Literature Review

2.1. Blockchain Technology and Supply Chain Management

Blockchain revolutionizes business models in many fields, particularly in logistics and supply chain management [8,14]. Blockchain applications improve the monitoring and screening performance of suppliers and provide verification claims about their products [15]. In supply chain activities, communication problem is generally intense [14]. This is precisely an issue satisfied thanks to blockchain technology in supply chains [14]. Numerous studies have been conducted on the topic of blockchain and supply chain management. Kamble et al. [16] identified key enablers of blockchain technology for supply chain applications using a combination of Interpretive Structural Modelling (ISM) and Decision-Making Trial and Evaluation Laboratory (DEMATEL) methods. The authors found that traceability was the most important reason for companies to adopt blockchain in agriculture supply chains. Korpela et al. [17] examined the disruptive potential of blockchain in digital supply chains, using QFD to translate integration requirements into system functionalities. Erol et al. [18] evaluated blockchain technology applicability in sustainable supply chains using an integrated method combining Fuzzy Stepwise Weight Assessment Ratio Analysis (SWARA), Complex Proportional Assessment (COPRAS), Evaluation based on Distance from Average Solution (EDAS) and COPELAND methods.

The utilization of standard software tools and performance metrics in evaluating blockchain technology for supply chains is important for its wider adoption. This is crucial because the use of standard metrics and tools will allow for comparison across different studies and applications of blockchain in supply chains, which will lead to a better understanding of its impact and how to optimize its implementation. The domain-independent software quality model ISO/IEC 25010 [6] helps ensure that the evaluation is based on widely accepted and recognized standards, which will increase the reliability and validity of the results. This will also encourage wider adoption of blockchain technology in supply chains as it demonstrates its potential benefits and helps address challenges. The choice of blockchain technology and its specific characteristics should align with the requirements and goals of the application in consideration of the trade-offs between performance, security, and scalability [19]. Trade-off analysis between blockchain characteristics is important for supply chains as it helps them make informed decisions about the implementation of blockchain technology. This analysis enables them to optimize their supply chain processes, improving efficiency, transparency, and security while also reducing costs. In a highly competitive business environment, the ability to effectively evaluate and manage the trade-offs between blockchain characteristics can give a supply chain a significant advantage, allowing it to remain competitive and respond effectively to changes in the market.

Evaluating the trade-offs between different blockchain characteristics is crucial for supply chain management. This is because blockchain is a complex technology that has a range of features, each of which may have different implications for the supply chain. For example, the transparency and security benefits of blockchain may come at the cost of scalability or data privacy. It is important to understand these trade-offs when evaluating the potential of blockchain for supply chain improvement. This helps organizations to identify the most appropriate use cases for blockchain, as well as the specific features and configurations that are best suited to their needs. For instance, a supply chain that prioritizes traceability and security may be better suited to a permissioned blockchain, which allows for the controlled sharing of data, while a supply chain that places greater emphasis on efficiency and scalability may be better suited to a more decentralized blockchain architecture. In literature, limited studies on the impact of blockchain on supply chain performance dimensions exist, with a narrow focus on specific supply chain performance indicators. Additionally, the current literature on the intersection of supply chain and blockchain often uses domain-specific software characteristics, hindering comparison between different software systems. Most of the studies on blockchain characteristics do not deal with trade-offs between blockchain characteristics. A literature review of blockchain technology and supply chains is shown in Table 1 (N/A is an abbreviation for Not Available, and A is an abbreviation for Available).

Table 1. A brief literature review of blockchain technology and supply chains

Study	Supply Chain Performance	Focus area on Blockchain	Methods and Tools	Area	Blockchain Trade-offs	Standard Metrics/Features
[14]	Cost, speed, dependability, risk reduction, sustainability, flexibility	Supply chain management objectives	Multiple-case studies	Logistics, insurance etc.	N/A	N/A
[20]	N/A	Challenges in blockchain adoption	Grey-DEMATEL, fuzzy Delphi, WASPAS	Manufacturing	N/A	N/A
[8]	Sustainable supply chain transparency	A supply chain transparency and sustainability	Integrated hesitant fuzzy set and regret theory	N/A	N/A	N/A
[21]	Circular economy	Circular economy adoption barriers	QFD, Hesitant Fuzzy Linguistic Term Sets (HFLTS)	N/A	N/A	N/A
[9]	Sustainability	Blockchain benefits	Analytical hierarchical process	N/A	N/A	N/A
[22]	Sustainable food security	Blockchain drivers	Total Interpretive Structural Modelling, Fuzzy MICMAC, Fuzzy DEMATEL	Agriculture	N/A	N/A
[23]	Overall Supply Chain Performance	Blockchain-enabled supply chain	Simulation	N/A	N/A	N/A
[11]	Sustainability	Blockchain barriers	(CoCoSo) and (CRITIC), Pythagorean fuzzy sets	Agriculture	N/A	N/A
[24]	Sustainability	Blockchain barriers and enablers	Pythagorean Fuzzy sets (PFS), Cumulative Prospect Theory (CPT), and VIKOR	N/A	N/A	N/A
[25]	Efficiency, flexibility, responsiveness, food quality, and transparency of supply chains	Blockchain impact on agri-food supply chain performance	Case Study	Manufacturing	N/A	N/A
[26]	N/A	Blockchain barriers	Best worst method (BWM)	N/A	N/A	N/A
[16]	Sustainability	Blockchain enablers	Interpretive Structural Modelling (ISM), DEMATEL	Agriculture	N/A	N/A
[13]	Supply chain risks	Blockchain-enabled supply chain	Fuzzy analytical hierarchical processing (F-AHP)	Agri-food	N/A	N/A
[27]	Effective digital supply chain	Blockchain barriers	House of Quality, Intuitionistic fuzzy sets, Incomplete preferences	Food supply chain	N/A	N/A
[18]	Sustainability	Blockchain benefits	Fuzzy SWARA-COPRAS-EDAS and COPELAND	Agriculture	N/A	N/A
[28]	Sustainability	Sustainability risk assessment of blockchain adoption	Best-Worst Method (BWM), CoCoSo	Pharmaceutical, Fast moving consumer goods, Precious metals and automotive	N/A	N/A
[29]	N/A	Blockchain readiness	FCM, Fuzzy best–worst method (FBWM)	N/A	A	N/A
[12]	Sustainable supply chain	Blockchain adoption enablers	Network theory, FCM, Fuzzy data envelopment analysis	N/A	A	N/A
[30]	Cost, customer demand etc.	Blockchain’s impact on the supply chain	Hesitant fuzzy cognitive map (HFCM), Probabilistic-linguistic fuzzy cognitive map (PL-FCM), Rough set cognitive map (RS-CM)	N/A	A	N/A

2.2. Blockchain Technology and Supply Chain Management

Blockchain technology is renowned for its complex characteristics, including its architectural design, permission types, and consensus mechanisms, making it challenging to comprehend and assess. Multiple studies have been conducted on evaluating blockchain characteristics through the application of Multi-Criteria Decision-Making (MCDM) methods. Maden and Alptekin [31] employed the use of Fuzzy DEMATEL to identify and evaluate the critical factors driving blockchain adoption in the logistics sector, based on the needs of the company. As per the experts' assessments, the most significant factors influencing the adoption of blockchain technology, in order of priority were: cryptocurrency, instant money transfer, privacy, real-time processing, smart contract, security, authentication, transparency, immutability, traceability, distributed ledger, reduced delays, and peer-to-peer networks. Orji et al. [32] proposed a technology-organization-environment (TOE) structure for the critical factors that impact the successful adoption of blockchain in the freight logistics industry and prioritized them using the Analytic Network Process (ANP). They concluded that the three most important factors affecting blockchain technology adoption in the freight logistics sector are: the availability of specific blockchain tools, infrastructural facilities, and government policy and support.

Zarour et al. [33] conducted a study to evaluate the impact of various blockchain frameworks in healthcare management by gathering expert evaluations. They used Fuzzy ANP to determine the weights of the blockchain criteria and applied the Fuzzy TOPSIS method to evaluate blockchain alternatives. Tang et al. [34] conducted an extensive evaluation of public blockchains using the TOPSIS method to rank alternative public blockchains and the entropy method to calculate the weight of indicators. Garriga et al. [35] presented a conceptual framework aimed at supporting software architects, developers, and decision-makers in selecting the appropriate blockchain technology. They validated the framework through architectural trade-off analysis to evaluate real-world blockchain case studies. Farshidi et al. [36] proposed a decision framework for blockchain platform selection, modelling it as an MCDM problem and using the ISO/IEC 25010 [6] as a standard set of quality attributes. This domain-independent software quality model provides reference points for software systems. Mingxiao et al. [37] reviewed the fundamental principles and characteristics of blockchain consensus algorithms.

Decentralization is a crucial aspect of blockchain technology [38]. However, the decentralized nature of blockchain can hinder its performance concerning throughput and latency [39]. Immutability refers to the inability to alter or modify a thing over time, or for it to remain unchanged for a specific period [16]. The chain of cryptographic hashes connecting blocks in the blockchain ensures immutability for historical transactions [40]. However, practical challenges may arise in real-world blockchain systems, such as disputed transactions, wrong addresses, private key loss or disclosure, data entry errors, and unexpected changes to assets tokenized on the blockchain [40]. Advances in cryptography and computer science enable secure, encrypted operation of data-based applications through techniques like zero-knowledge proofs, homomorphic encryption, secure multiparty computation, and trusted execution environments [41]. These technologies are often utilized in blockchain-based use cases to maintain an audit trail of transactions between users [41]. However, businesses may not want to share data on public ledgers, or certain data may not be made public due to GDPR (General Data Protection Regulation) protections [42].

Blockchain is a decentralized database that is highly tamper-resistant, designed to operate in extreme byzantine environments, and has a dominant design target of security [43,44]. It has scalability limits, such as the size of data, transaction processing rate, and latency of data transmission [19]. Smart contracts and cryptographic tokens are used to digitize assets and currencies in blockchain [16,45]. Deciding which data and computation to keep on-chain or off-chain can affect the blockchain's scalability and performance [46,47]. Off-chain data storage can provide more computation power, data storage, and lower costs [19,46]. Cryptographic tokens can only be accessed with a private key and can only be signed by that key [45].

In a permissioned blockchain, only authorized participants can take part in network operations with their revealed identity [48]. Permissionless blockchains have a large network size with low transaction capacity, while permissioned blockchains have a small network size with high transaction capacity [48]. The consensus algorithm is crucial in maintaining the security and efficiency of blockchains [37] as it is used to agree on the value of data among many nodes in a distributed framework [49]. TPS (Transactions Per Second) measures the speed of the platform or network in processing transactions, while block time or latency refers to the delay in approving transactions and adding them to a block [49]. The block is then joined to the blockchain [49]. A double-spending attack occurs when the same amount of money is attempted to be spent multiple times [49]. After inspecting the literature in detail, the architecture, permission type, consensus mechanism, and other characteristics of blockchain were summarized in Table 2.

Table 2. Blockchain characteristics

Architectural	Decentralization [35,38]
	Immutability [19]
	Privacy [35,41]
	Security [35,36,43,50,51]
	Performance & Scalability [19,35,51]
	Cost [35,51]
	Smart contract functionality [16,35,52]
	On-chain transactions [36,47]
	Off-chain transactions [36,47]
	Tokenization [36,45]
Permission Type	Permissioned blockchain [36,45,51]
	Permissionless blockchain [36,45,51]
	Governance [45]
	Participation [36,45]
	Transparency [45]
	Network size [45]
	Transaction capacity [19,45]
Consensus Mechanism	Transaction per second (TPS) [37,53,54]
	Verification speed/Block verification time [37,54]
	Double spending [54]
	Throughput [37,53,54]
	Adversary tolerance (Fault tolerance) [37,53,54]
Other Features	Blockchain data structure [19,39]
	Non-blockchain data structure [39]
	Enterprise system integration [36,55]
	API support [51,55]
	Popularity [36,51]
	Licensing [51,55]
	Community support [51,55]
	Modularity [55]
	Ease of use [51,55]

In the literature, studies related to blockchain have generally focused on the consensus mechanism or architectural characteristics of blockchain. However, with this study, we have summarized blockchain characteristics more comprehensively, as shown in Table 2. This is because the evaluation of blockchain technology in supply chains requires the assessment of other diverse characteristics such as enterprise system integration and ease of use.

The trade-off between performance and security can be managed by choosing the appropriate consensus mechanism, network architecture, and permission type [37]. Some consensus mechanisms, such as Proof of Work (PoW), require a lot of computational resources and can lead to high energy consumption, which can hinder performance [48]. It is also important to consider scalability in blockchain applications as more users and transactions can increase the latency and overhead of the system [42]. The scalability can be improved by implementing techniques such as sharding, where the network is divided into smaller components to handle transactions in parallel [35]. The choice of blockchain technology and its specific characteristics should align with the requirements and goals of the application in consideration of the trade-offs between performance, security, and scalability [19].

3. Materials and Methods

In this study, we employed an integrated FCM-QFD methodology to evaluate supply chain-related and software-related problems. To accomplish this, we leveraged the SCOR) a modelling approach to address the vague and imprecise process and metric definitions commonly present in a typical supply chain scenario. The SCOR model enabled us to identify the problematic performance metrics for an engineer-to-order supply chain. For software-related problems, we relied on ISO standards to determine the problematic quality characteristics. After determining the problematic SCOR performance metrics and software characteristics, we utilized them in QFD Stage 1 to obtain the weights of technical characteristics.

The blockchain technology characteristics were gathered from the literature, specifically for use in the supply chain context (refer to Table 2). At this stage, we used FCM to determine the most critical blockchain characteristics, as it can showcase both positive and negative relationships between these characteristics. Subsequently, we calculated the QFD Stage 2 correlations and combined the results with those obtained from FCM to obtain the QFD Stage 2 technical characteristics' weights. The cross-functional and multi-staged structure of QFD allowed us to reflect both supply chain and software-related problems in the evaluation process of blockchain characteristics. The methodology we proposed is depicted in Figure 1.

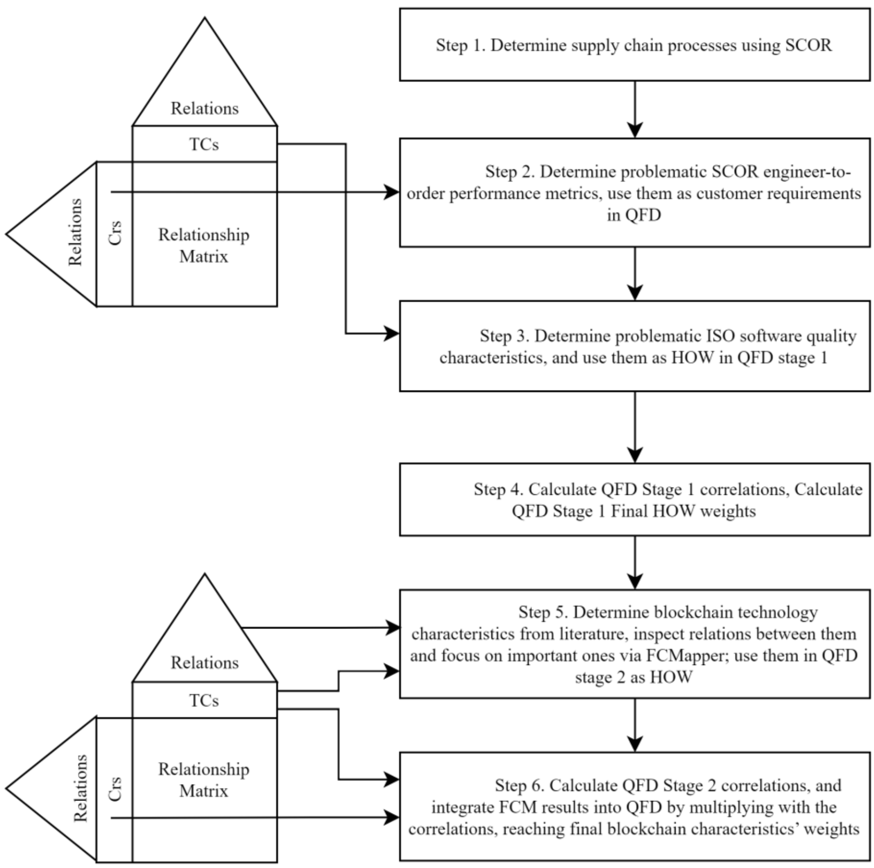

Figure 1. Methodology of the study

3.1. Models and Standards

3.1.1. SCOR Model and Performance Metrics

The Supply Chain Operations Reference (SCOR) is a widely recognized reference model that classifies business processes based on six fundamental management processes, including plan, source, make, deliver, return, and enable [56]. It consists of four levels, with the first level defining the scope and content, the second level dividing management processes into process alternatives (e.g., make-to-stock, make-to-order, engineer-to-order), and the third level serving as the basis for describing the supply chain performance metrics [57].

SCOR's performance component consists of two parts: performance attributes and metrics. A performance attribute is comprised of metrics used to describe a strategy [56], while typical SCOR metrics include reliability, responsiveness, agility, cost, and assets. The choice of supply chain performance metrics can be made using a process-based approach that takes into consideration the specific characteristics of a project and the requirements of stakeholders [57]. In this study, the SCOR 11.0 model [56] was utilized.

3.1.2. Software Quality Models

The software engineering domain contains a variety of quality models, including McCall's [58] (McCall et al., 1977), Boehm's [59], FURPS [60], Dromey's [61], and ISO 25010 [6]. Additionally, there exist several frameworks and procedures that enable the assessment of software architecture suited for specific purposes. In this study, we utilized ISO 25010 due to it being the most recent quality model constructed on an international agreement.

3.1.3. SQuaRE Standards Family

The Software Quality Requirements and Evaluation (SQuaRE) framework comprise three quality models that provide a comprehensive evaluation of software systems: quality in use, product quality, and data quality. The quality-in-use model, as described in ISO/IEC 25010 [6], evaluates both computer systems and software products in actual use. The product quality model, as described by Nakai et al. [5], assesses the extent to which critical software requirements such as performance, usability, and maintainability are met. The data quality model, as defined by ISO/IEC 25012 [7], evaluates how well the data meets the needs specified by the product owner. The data quality characteristics are divided into two categories: inherent data quality and system-dependent data quality.

In this study, we utilized all three SQuaRE quality models to conduct a broad evaluation of existing supply chain software systems. Our findings revealed that incorporating ISO data product quality characteristics into the evaluation proved beneficial when considering data-related concerns such as data cybersecurity and compliance with the General Data Protection Regulation (GDPR) data protection law.

3.2. Methods

3.2.1. Fuzzy Quality Function Deployment (QFD)

The objective of a House of Quality (HOQ) is to determine the relative importance of design requirements based on the perceived importance of customer needs and the correlation between customer requirements and design requirements [62]. QFD has been widely applied in various fields, including software systems, production, supply chain, service, and communication. QFD, a cross-disciplinary process involving teams from design engineering, manufacturing engineering, marketing, and others, has found widespread application in sectors such as software systems, production, supply chain, service, and communication [63,64]. It serves as a potent tool in development activities, particularly when addressing quality concerns [65]. As a quality management method, QFD undergoes continuous challenges, refinements, and developments, akin to other techniques within the quality management toolkit [66].

Unlike conventional quality frameworks that aim to minimize negative quality in the product, QFD centers on maximizing positive quality by incorporating customer requirements into product design from the conceptual phase [65]. The competitive advantage of QFD lies in its structured implementation of strategic concepts [67]. The protection of customers' voices ensures that customer requirements remain unaltered during the development phase, thereby safeguarding the voice of the customer in the design features [67]. In this study, QFD has been employed in conjunction with fuzzy expressions at various QFD stages.

3.2.2. Fuzzy Cognitive Map (FCM)

The FCMs (Fuzzy Cognitive Maps) are robust but simple tools that utilize fuzzy logic to model dynamic networks [68]. The original cognitive maps considered the values of concepts and connection matrices to be negative, positive, or neutral. Kosko [69] built upon this study by incorporating fuzzy causality into the directed edges and concepts. Various MCDM methods such as ANP, DEMATEL, and FCM can demonstrate relationships between concepts [70]. However, FCM has the advantage of being able to display both positive and negative relationships between criteria. The steps of the technique are as follows [71]:

Step 1: Aggregation of fuzzy weights of the attributes. The arithmetic mean of the fuzzy weights taken from decision-makers is computed as:

$$\widetilde{w}_p = \frac{\sum_i^s \widetilde{w}_{pi}}{s}, p \in \{1,2,3,\cdots,n\} \tag{3.1}$$

The $\widetilde{w}_{pi}$ values represent the aggregated fuzzy weights.

Step 2: Normalization of the crisp weight vector. The centroid method is usually preferred because of its simplicity. This method is applied using the following formula,

$$\text{Centroid}(\tilde{A}) = \frac{l+m+u}{3} \tag{3.2}$$

The normalized crisp weight vector (nw_p), is computed using (3.3),

$$nw_p = \frac{w_p}{\sum_{i=1}^n w_i} \tag{3.3}$$

The FCMs are versatile tools that can be easily adapted by adding new concepts and relationships or by altering the weight of causal linkages [72]. Furthermore, FCM models can be made more manageable by simplifying them. Homenda et al. [73] analyzed the effects of removing weak relationships or concepts a posteriori. As a result, the map can be pruned iteratively by eliminating weights weaker than thresholds of 0.2, 0.4, and 0.6. Weights that fall below these threshold values can be considered insignificant and set to zero, indicating the absence of relationships. In our study, we pruned the map by removing weights weaker than a threshold of 0.5. This helped simplify the FCM model, as larger maps are challenging to interpret and apply.

3.2.2.1. Establishing FCM Structure

As the first step, initial concept values are determined using the normalized weight vector as in (3.4) [71]:

$$\left(C_{MA_1}^{t=0} \quad ..C_{MA_p}^{t=0}.. \quad C_{MA_n}^{t=0}\right) = \left(nw_1..nw_p..nw_n\right) \tag{3.4}$$

where $C_{MA_i}^{t=0}$ is the concept value of the *i*th main attribute when t = 0.

Then, fuzzy influence matrices, which are taken from a group of decision-makers are aggregated,

$$\tilde{e}_{ji}^{MA} = \frac{\sum_{u=1}^{S} \tilde{e}_{jiu}^{MA}}{S} \tag{3.5}$$

where $\tilde{e}_{ji}^{MA}$ shows the aggregated fuzzy influence matrix of the main attributes. Finally, aggregated fuzzy weights are defuzzified, and the aggregated crisp influence matrix e_{ji}^{MA} is calculated.

3.2.2.2. Simulating FCMs and Obtaining the Final Weights

After establishing the FCM structure, first, the parameters of the activation function are specified. Different activation (threshold) functions can be utilized for this purpose. In this study, the sigmoidal function was chosen for its ability to produce outcome values ranging from 0 to 1, which can be used as criteria weights without any additional transformation. During the FCM simulation process, the dynamic behavior of the relationships is determined using (3.6).

$$C_{MA_i}^{t+1} = f\left(C_{MA_i}^{t} + \sum_{\substack{j=1 \\ j=1}}^{n} e_{ji}^{MA} \times C_{MA_j}^{t}\right) \tag{3.6}$$

where $\mathrm{C}_{\mathrm{MA_i}}^{\mathrm{t}}$ is the concept value of the *i*th main attribute at time *t*.

Next, the steady-state concept values are normalized, and the final steady-state weights of the primary attributes are determined:

$$w_i = \frac{C_{MA_i}}{\sum_{i=1}^{n} C_{MA_i}} \tag{3.7}$$

The final step of the process is to calculate the crisp weights. It is an open-licensed Excel macro developed by Michael Bachhofer and Martin Wildenberg [74]. In this study, the FCM method provided a means to prioritize the most important characteristics of blockchain technology, and also evaluate the trade-offs between different characteristics through the use of FCM analysis.

3.3. Application

The purpose of this study is to prioritize the most important blockchain characteristics to be implemented in the supply chain of a case company. The case company utilizes state-of-the-art technology and industry expertise to support global mechanical and plant engineering projects. Through cutting-edge technology, it provides customer-specific integrated automation solutions, offering a comprehensive range of products and services required by the industry. Moreover, the company's experts offer unique services and resources throughout the project lifecycle, from design to project realization. The company is committed to delivering customer-specific products with precise timing, quality, and quantity while emphasizing cost efficiency. Given the diverse nature of customer demands, the company strives to ensure diversity in all aspects. Unfortunately, the company fell short of its performance targets in the procurement processes, where challenges were particularly pronounced. To address the issues the company faces, we propose using blockchain technology as a solution. The prioritization of blockchain characteristics will be based on the company's strategy, which is centered around reliability, responsiveness, cost, and agility. The study's results will help the company make informed decisions about which blockchain characteristics to implement in its supply chain to achieve its performance targets.

To prioritize the blockchain characteristics for the company's supply chain, it would be helpful to first assess the current challenges and pain points in the procurement process. This could include issues with transparency, traceability, and collaboration between different supply chain partners. Once these issues have been identified, the most relevant blockchain characteristics can be prioritized based on their ability to address the specific problems at hand. For example, if the issue is a lack of trust between supply chain partners, then a blockchain with strong security and privacy features would be more important. If the issue is a lack of transparency and traceability, then a blockchain with robust data sharing and tracking capability would be more critical. In addition, factors such as scalability, cost-effectiveness, and ease of integration with existing systems should also be considered.

To prioritize blockchain characteristics for the supply chain, this study analyzed software-related issues by conducting an application study in the company. The company experienced issues such as security breaches, responsiveness problems, and compliance issues. The study conducted an interview-based discovery with stakeholders such as the company, customers, procurement personnel, and software developers to gather information. Each time, an assessment was carried out by a committee comprising three experts who have significant experience within the supply chain, each with more than five years of expertise. For the QFD Stage 1, the evaluation committee consists of a customer representative, a procurement personnel, and a software developer. For QFD Stage 2, the committee comprises three software stakeholders from the supply chain. These distinct committees have been formed due to the requirement for different expertise for each QFD stage. The methodology followed the steps outlined in Figure 1. In Step 1, we determined the supply chain processes using SCOR. For the case supply chain, the engineer-to-order approach is chosen. In Step 2, we determined the problematic engineer-to-order performance metrics. The metrics' representation values include RS (Responsiveness), CO (Cost), AG (Agility), and RL (Reliability). Among these metrics, the problematic six metrics are identified as Select Supplier and Negotiate Cycle Time (RS.3.125), Percent of the Orders/Lines Received Defect Free (RL.3.19), Sourcing Automation Cost (CO.3.006), Identify Sources of Supply Cycle Time (RS.3.35), Material Risk, and Compliance Cost (CO.3.012), and Demand sourcing-supplier constraints (AG.3.46). These metrics were used in QFD Stage 1 as customer requirements.

In Step 3, considering the supply chain's software problems, we evaluated the supply chain's existing software systems using all three quality models of the SQuaRE. We used ISO/IEC 25022 (Measurement of quality in use), ISO/IEC 25023 (Measurement of system and software product quality), and ISO/IEC 25024 (Measurement of data quality) to define and quantitatively evaluate the quality measures. Considering the measures and related performance gaps from their targets, the identified problematic software product quality, quality in use, and data quality sub-characteristics are summarized in Table 3.

Table 3. Problematic product quality, quality in use and data quality sub-characteristics

Sub-characteristics	Measures
Time behaviour	*Mean response time, Response time adequacy, Mean turnaround time, Turn-around time adequacy, Mean throughput
Resource Utilization	*Mean processor utilization, Mean memory utilization, Mean I/O devices utilization, Bandwidth utilization
Fault tolerance	*Failure avoidance, Redundancy of components, Mean fault notification time
Confidentiality	*Access controllability, Data encryption correctness, Strength of cryptographic algorithms
Compliance	*Regulatory compliance due to technology
Modularity	*Coupling components
Modifiability	*Modification correctness
Functional Completeness	*Functional correctness

The determined problematic 8 software characteristics were: resource utilization, time behavior, fault tolerance, confidentiality, compliance, modularity, modifiability, and functional completeness, respectively. These characteristics were used in QFD Stage 1 as technical characteristics. In Step 4, we calculated QFD Stage 1 correlations.

The determined SCOR Level 3 metrics of AG.3.46, CO.3.006, CO.3.012, RS.3.35, RS.3.125, and RL.3.19 were used, respectively, in the customer requirements part of QFD Stage 1. Aggregated evaluations of decision-makers using the 6 SCOR metrics and 8 ISO characteristics can be seen in Table 4. After the aggregation, we multiplied the SCOR metrics' weights with the aggregated correlation values. The normalized QFD Stage 1 final HOW weights of ISO characteristics can be seen in Table 5.

Table 4. Aggregated evaluations of decision-makers

	1	2	3	4	5	6	7	8
1	0.600	0.600	0.300	0.900	0.300	0.300	0.300	0.900
2	0.800	0.500	0.400	0.500	0.600	0.600	0.500	0.800
3	0.400	0.400	0.300	0.900	0.400	0.300	0.300	0.900
4	0.600	0600	0.500	0.500	0.600	0.600	0.500	0.600
5	0.800	0.800	0.500	0.500	0.500	0.600	0.600	0.600
6	0.500	0.500	0.400	0.600	0.500	0.500	0.500	0.500

Table 5. Normalized QFD Stage 1 final HOW weights of ISO characteristics

1	2	3	4	5	6	7	8
0.146	0.130	0.096	0.116	0.087	0.137	0.128	0.159

In Step 5, we determined blockchain characteristics and found the most significant ones using FCM. After inspecting the literature, we summarized 31 blockchain characteristics, including blockchain data structure, non-blockchain data, permissioned network, permissionless network, smart contract functionality, privacy, off-chain transactions, on-chain transactions, security, TPS, cost, community support, scripting language, governance, scalability, cryptocurrency support, tokenization, licensing, popularity, enterprise system integration, ease of use, modularity, API support, adversary fault tolerance, verification speed, block time, double spending, transparency, network size, transaction capacity, and participation, respectively. We inspected positive and negative relationships between these 31 blockchain characteristics.

In evaluating the positive and negative relationships between blockchain design requirements, we considered both the legal and architectural characteristics of blockchain technology. For example, the inability to delete data under GDPR laws was seen as a major barrier to the adoption of blockchain technology in the supply chain. Hence, on-chain transactions may limit privacy in the supply chain, especially when legal issues are significant. Permissioned blockchains, with their identity-shown characteristics and efficient network management, were seen as a more suitable solution compared to permissionless blockchains.

After determining the relations between blockchain characteristics as shown in Table 6, we aggregated and defuzzified the fuzzy influence matrix. Steady-state concept values were reached in 9 iterations using the FCMapper, as presented in Table 7. In Table 7, columns indicate blockchain characteristics, while rows indicate iterations. The final normalized weights of the blockchain characteristics can be seen in Table 8.

Table 6. Positive and negative relations between blockchain characteristics

Relation Type	Relation Pair
Positive relations	1-8;1-16;1-24;1-26;3-6;3-9;3-14;4-28;4-29;4-31;5-11;5-13;5-17;7-2;7-6;7-15;8-1;8-9;9-14;9-18;10-25;10-26;13-5;14-3;14-4;14-6;14-7;14-9;14-12;15-10;15-30;16-11;16-17;16-19;18-21;20-22;20-23;22-6;22-21;23-20;24-9;25-10;25-26;29-31
Negative relations	1-15;3-28;3-29;3-30;3-31;4-6;4-9;4-14;4-30;6-28;7-9;8-6;8-15;9-27;9-28;14-28;18-11;24-27;28-6

Table 7. Steady-state concept values

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	0.750	0.750	0.832	0.750	0.846	0.858	0.750	0.750	0.968	0.917	0.900	0.750	0.750	0.711	0.832	0.750
2	0.695	0.695	0.779	0.695	0.797	0.840	0.695	0.695	0.943	0.882	0.863	0.695	0.697	0.666	0.783	0.695
3	0.682	0.682	0.765	0.682	0.783	0.836	0.682	0.682	0.935	0.870	0.850	0.682	0.685	0.658	0.768	0.682
4	0.679	0.679	0.761	0.679	0.780	0.835	0.679	0.679	0.932	0.867	0.846	0.679	0.682	0.657	0.764	0.679
5	0.679	0.679	0.760	0.678	0.779	0.835	0.678	0.679	0.932	0.866	0.845	0.678	0.681	0.656	0.763	0.679
6	0.678	0.678	0.760	0.678	0.778	0.834	0.678	0.678	0.932	0.866	0.845	0.678	0.681	0.656	0.763	0.678
7	0.678	0.678	0.760	0.678	0.778	0.834	0.678	0.678	0.932	0.866	0.845	0.678	0.681	0.656	0.763	0.678
8	0.678	0.678	0.760	0.678	0.778	0.834	0.678	0.678	0.932	0.866	0.845	0.678	0.681	0.656	0.763	0.678
9	0.678	0.678	0.760	0.678	0.778	0.834	0.678	0.678	0.932	0.866	0.845	0.678	0.681	0.656	0.763	0.678

	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
1	0.917	0.832	0.750	0.731	0.750	0.769	0.750	0.750	0.750	0.750	0.450	0.500	0.769	0.550	0.622
2	0.882	0.804	0.695	0.675	0.696	0.714	0.695	0.695	0.699	0.695	0.359	0.400	0.703	0.481	0.548
3	0.871	0.797	0.682	0.663	0.683	0.700	0.682	0.682	0.687	0.682	0.349	0.383	0.686	0.473	0.536
4	0.867	0.795	0.679	0.660	0.680	0.697	0.679	0.679	0.684	0.679	0.349	0.381	0.682	0.473	0.534
5	0.866	0.795	0.679	0.659	0.679	0.696	0.678	0.679	0.684	0.679	0.350	0.381	0.681	0.473	0.534
6	0.866	0.795	0.678	0.659	0.679	0.696	0.678	0.678	0.684	0.679	0.351	0.381	0.681	0.474	0.534
7	0.866	0.795	0.678	0.659	0.679	0.696	0.678	0.678	0.684	0.679	0.351	0.381	0.681	0.474	0.534
8	0.866	0.795	0.678	0.659	0.679	0.696	0.678	0.678	0.684	0.678	0.351	0.381	0.681	0.474	0.534
9	0.866	0.795	0.678	0.659	0.679	0.696	0.678	0.678	0.684	0.678	0.351	0.381	0.681	0.474	0.534

Table 8. Normalized weights of the blockchain characteristics

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
0.0317	0.0317	0.0356	0.0317	0.0364	0.0390	0.0317	0.0317	0.0436	0.0405	0.0395	0.0317	0.0319	0.0307	0.0357	0.0317

17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
0.0405	0.0372	0.0317	0.0308	0.0318	0.0326	0.0317	0.0317	0.0320	0.0317	0.0164	0.0178	0.0319	0.0222	0.0250

Table 9. Steady-state concept values

	1	2	3	4	5	6	7	8	9	10
1	0.731	0.731	0.917	0.858	0.818	0.668	0.731	0.870	0.832	0.731
2	0.675	0.675	0.874	0.809	0.766	0.603	0.675	0.822	0.794	0.675
3	0.663	0.663	0.860	0.794	0.751	0.590	0.663	0.807	0.782	0.663
4	0.660	0.660	0.857	0.790	0.747	0.588	0.660	0.803	0.779	0.660
5	0.659	0.659	0.856	0.789	0.746	0.588	0.659	0.802	0.778	0.659
6	0.659	0.659	0.856	0.789	0.746	0.588	0.659	0.801	0.777	0.659
7	0.659	0.659	0.855	0.788	0.746	0.588	0.659	0.801	0.777	0.659
8	0.659	0.659	0.855	0.788	0.746	0.588	0.659	0.801	0.777	0.659

Table 10. Normalized weights of the blockchain characteristics

1	2	3	4	5	6	7	8	9	10
0.092	0.092	0.119	0.110	0.104	0.082	0.092	0.111	0.108	0.092

Table 11. QFD Stage 2 defuzzified correlation values

	1	2	3	4	5	6	7	8	9	10
1	0.400	0.600	0.400	0.400	0.700	0.900	0.600	0.400	0.600	0.200
2	0.800	0.700	0.200	0.200	0.900	0.600	0.700	0.400	0.200	0.200
3	0.300	0.900	0.800	0.800	0.500	0.500	0.500	0.600	0.100	0.100
4	0.500	0.800	0.900	0.900	0.500	0.500	0.500	0.800	0.100	0.100
5	0.600	0.800	0.800	0.800	0.500	0.500	0.500	0.400	0.200	0.200
6	0.600	0.600	0.500	0.500	0.600	0.600	0.600	0.400	0.200	0.900
7	0.900	0.700	0.400	0.300	0.700	0.700	0.900	0.400	0.200	0.600
8	0.500	0.900	0.400	0.400	0.200	0.200	0.300	0.800	0.100	0.300

Table 12. Normalized QFD Stage 2 HOW weights without cognitive map effect

1	2	3	4	5	6	7	8	9	10
0.112	0.144	0.101	0.098	0.111	0.109	0.111	0.103	0.043	0.066

Table 13. Final QFD Stage 2 HOW weights with cognitive map effect

1	2	3	4	5	6	7	8	9	10
0.104	0.133	0.121	0.109	0.116	0.090	0.103	0.115	0.047	0.061

4. Results and Discussion

After obtaining the steady-state concept values for the 31 blockchain characteristics, we calculated their normalized weights by dividing each characteristic value by the total of the steady-state values. These weights were used to prioritize the 10 blockchain characteristics. The characteristics with a normalized weight equal to or greater than the average value (0.0322) were considered for further analysis. The 10 prioritized characteristics were: permissioned network, smart contract functionality, privacy, security, TPS, cost, scalability, tokenization, licensing, and modularity, respectively.

To further understand the inter-relationships between these characteristics, we used FCMapper with the previously determined aggregated relationships. Using the same aggregated relationships of blockchain characteristics, we activated the 10 characteristics by setting the other characteristics' values to 0 in FCMapper. The steady-state concept values for these characteristics can be seen in Table 9, and their normalized weights are listed in Table 10.

In Step 6, we calculated QFD Stage 2 correlations and integrated the FCM results into QFD by multiplying them with the correlations. After taking the fuzzy correlation values of three decision-makers in QFD Stage 2, we defuzzified them. QFD Stage 2 defuzzified correlation values can be seen in Table 11. After calculating the final QFD Stage 1 HOWs' weights, we used them in QFD Stage 2 as new customer requirements. After finding the QFD Stage 2 defuzzified correlation values, we multiplied them using the values obtained through QFD Stage 1 final weight. Here, the result of this multiplication does not include relationships between blockchain characteristics. Normalized QFD Stage 2 HOW weights without and with FCM effect can be seen in Tables 12 and 13, respectively.

In summary, we used a combination of QFD and FCM to prioritize and rank the most important blockchain characteristics for supply chain use. Considering the values in Table 13, this multiplication increased the QFD Stage 2 weights of privacy, security, TPS, tokenization, and licensing. However, the multiplication decreased the weights of permissioned network, smart contract functionality, cost, scalability, and modularity. Seeing

Table 13, the most important blockchain characteristics are, in the order of priority: smart contract functionality, privacy, TPS, tokenization, security, permissioned network, scalability, cost, modularity, and licensing. The current and alternative technologies can be compared against these characteristics to determine their suitability for supply chain use.

5. Conclusion

Evaluating both supply chain and software metrics in a unified approach is crucial for assessing blockchain technology in supply chains. In the existing literature, there are few comprehensive investigations into the influence of blockchain on various dimensions of supply chain performance, primarily concentrating on specific performance indicators. In this study, an attempt is made to explore the diverse impact of blockchain technology on various supply chain performances, aiming to address the existing gap in the literature. Moreover, the present body of literature examining the convergence of supply chain and blockchain frequently relies on software characteristics specific to certain domains, making it challenging to compare different software systems. In this study, an effort has been made to fill the relevant gap in the literature by utilizing standardized performance metrics. Thanks to the use of these standardized metrics, blockchain technology will become more comprehensible and comparable with different technologies. Many studies on blockchain characteristics also neglect to address the trade-offs that may exist between these characteristics. The objective of this research is to determine the key characteristics of blockchain technology that hold the utmost importance for a supply chain. Our approach involves the integration of supply chain and software-related metrics and issues, employing a unified FCM-QFD methodology for analysis. The incorporation of FCM into the QFD process is indicative of the intricate relationships and trade-offs inherent in blockchain characteristics. Examining the trade-offs among the characteristics of blockchain technology could contribute to a better understanding of this technology by supply chains. In this study, the integration of FCM and QFD provided a comprehensive evaluation of the performance metrics, resulting in a prioritized list of blockchain characteristics. The use of FCM allowed for a thorough evaluation of the complex relationships and trade-offs between blockchain characteristics, considering stakeholders’ differing opinions. With the advancement of blockchain technology, the characteristics may become outdated, and future studies may need to consider new trade-offs arising from changes in blockchain structure or regulations like GDP.

The evaluation of multiple performance dimensions in supply chains is of paramount importance when assessing blockchain technology. It is crucial to employ a diverse set of performance metrics that align with the specific goals and objectives of the supply chain. Standardized characteristics and metrics offer several benefits for supply chain stakeholders. Firstly, they provide a shared language and understanding, promoting better communication and collaboration. Secondly, standardized metrics allow for benchmarking and identifying best practices and areas for improvement, leading to better decision-making and operational efficiency. In this study, the SCOR modelling approach was used to address ambiguous and indistinct process and metric definitions in supply chain scenarios. To evaluate software-related issues, ISO standards were used to determine essential quality characteristics.

While this study assessed KPIs in the context of the overall projects of the case company, it is advisable to update and modify KPIs dynamically in response to changes in the business environment. Our evaluation of performance metrics primarily considered their understandability, measurability, and unambiguity. However, a more comprehensive evaluation can be achieved by examining criteria such as specificity, relevancy, verifiability, and comparability. Utilizing a Multi-Criteria Decision Making (MCDM) method can help weigh these criteria for the selection of appropriate performance metrics.

Although the linguistic evaluations in the created committees were conducted by three stakeholders each, the competence of the stakeholders in their respective fields deemed this number sufficient. However, increasing the number of stakeholders could lead to more reliable results. In addition to this, quality models enable the consideration of characteristics that hold significance for various stakeholders, including system integrators, acquirers, software developers, users, and more. In our case study, the software stakeholders were primarily software developers, who possessed expertise in software product quality, data product quality, and quality in use. However, it is crucial to involve all types of stakeholders, ranging from software developers to end-users, in the process of determining the quality characteristics that should be incorporated into a system.

Our study acknowledges the presence of uncertainty due to subjectivity in human judgments. The determination of the increase or decrease in SCOR performance metrics relied on subjective judgments, introducing uncertainty. Our future research will delve into a more detailed examination of the extent to which metrics deviate from their target values, employing data-driven modelling for a more accurate analysis.

Various blockchain characteristics were summarized to demonstrate the wide range of specific use cases in a supply chain context. The use of a threshold value for prioritizing characteristics in the FCM may not be necessary if fewer characteristics are considered, and different threshold values can be used for comparison purposes. This research primarily concentrated on assessing the procurement process. In future studies, we intend to expand our evaluations to encompass various processes beyond procurement. Additionally, our assessments will incorporate supply chain metrics from different companies within the case supply chain. Because the performance assessment of a supply chain necessitates the joint evaluation of performance metrics coming from various functions of multiple companies.

Author Contributions

The second author conceived and designed the analysis. The first author collected data and performed the analysis. This paper is derived from the first author's doctoral dissertation supervised by the second author. They all read and approved the final version of the paper.

Conflicts of Interest

All the authors declare no conflict of interest.

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