Yugoslav Journal of Operations Research
(20##), Number #, #-#
DOI: https://doi.org/10.2298/YJOR240819019B

Research article

BARRIERS TO ADAPT QUANTUM CRYPTOGRAPHY TECHNOLOGY IN DIGITAL SUPPLY CHAINS: A Q RUNG ORTHOPAIR FUZZY MODEL

Sanjib BISWAS*
Amity Business School, Amity University Kolkata,
sanjibb@acm.org, ORCID: 0000-0002-9243-2403

Kaushik MITRA
Amity Business School, Amity University Kolkata,
mitras1983@gmail.com, ORCID: 0000-0002-3507-5999

Biplab BISWAS
Amity Business School, Amity University Kolkata,
biplabdimat@gmail.com, ORCID: 0000-0001-5869-4998

Received: August 2024 / Accepted: April 2025

Abstract: The massive digitalization of supply chains has made information security and privacy of the utmost importance. Quantum cryptography (QC) technology has gained notable importance for data encryption to ensure these. This paper aims to fulfill two objectives: a) to unveil the barriers to the adaptation of QC in digital supply chains, and b) to develop innovative Comparisons between Ranked Criteria (COBRAC) framework using q-rung Orthopair fuzzy Einstein weighted averaging (q-ROFEWA) for multi-criteria decision-making (MCDM). The present work designs a group decision-making study based on the opinions of 12 experts, expressed in linguistic terms. To derive the barriers, the current work uses the theoretical framework of Technology-Organization-Environment (TOE). From the analysis, it is revealed that lack of awareness and knowledge (w = 0.1733), trust and privacy issues (w = 0.1624), and scale-up and infrastructural capability (w = 0.1348) are the top three barriers. It is seen that the model provides a robust result, maintaining a statistically significant high correlation with other MCDM methods. The sensitivity analysis demonstrates no considerable variation in the final result, given the changes in parameter values. The findings provide significant impetus for the decision-makers to create a reliable and secure ecosystem for DSCM.

*Corresponding author

Keywords: Quantum cryptography, digital supply chain management, q rung orthopair fuzzy numbers, Einstein aggregation, COBRAC.

MSC: 81P94, 90B06, 90B50, 90C70

1. INTRODUCTION

The evolution of Quantum Cryptography (QC) dates back to the early 1970s, starting with the invention of quantum conjugate coding by Stephen Wiesner [1]. QC is a field utilizing quantum mechanics that ensures secure communication and information exchange. Quantum key distribution (QKD) is a key protocol that generates secure keys, even in the presence of potential eavesdroppers [2]. This method guarantees confidentiality and integrity of communication, ensuring the integrity of information exchange. Quantum secure direct communication (QSDC) also facilitates direct and secure transmission of messages without prior key encryption, further enhancing the security of information exchange [3]. Security in the realm of cryptographic systems has been increased thanks to QC, a safe technique based on the ideas of quantum physics. It protects secret key transfer, guards against unwanted access, and strengthens established encryption methods against quantum attacks. A vital component of contemporary cryptographic systems, QC makes use of quantum entanglement for applications such as secure direct communication and quantum key distribution [4, 5].

In time, QC has garnered interest from both academic and industrial sectors due to its potential to revolutionize everyday applications and enhance security in online infrastructures and applications, particularly in fields like blockchain technology [6, 7, 8]. Technologies related to quantum computing are revolutionizing the world of cryptography and guaranteeing strong security in networks such as the Internet of Things (IoT). The development of post-quantum cryptography aims to mitigate the threats that quantum computing poses to established cryptographic frameworks [6]. This change affects sectors such as machine learning, simulation, and optimization. The potential of QC to overcome encryption system obstacles and explore new cryptographic frontiers is highlighted by its versatility and applicability in cutting-edge technologies, such as quantum networks and communications [9].

QC has several potential applications in the industry. Quantum cryptography offers potential advantages in the financial sector, particularly in data security. It provides unbreakable encryption, bolstering digital security. The spectral properties of quantum entanglement can refine protocols in quantum communications and cryptography, leading to the development of a quantum Internet [10]. Quantum secret sharing (QSS) is a vital aspect of quantum cryptography, emphasizing secure information-sharing protocols in industrial applications. QC is a significant solution in healthcare, offering unparalleled encryption capabilities [6]. This technology is being implemented globally, enabling advancements in drug development, DNA sequencing, and processing large volumes of information [11]. QC holds significant potential for industrial applications, particularly in the service industry [12]. It provides secure communication channels, protects sensitive data and transactions, and integrates with practical applications like the BB84 algorithm, ensuring efficient and secure communication networks [6]. It addresses the complex dynamics of the market, including risk transmission mechanisms and environmental pollution. It aims to mitigate adverse effects, demonstrating the industry's potential to transform the real estate sector [13].

Over the last few decades, supply chain management (SCM) has evolved rapidly, leveraging massive technological developments. The conventional SCM has undergone a metamorphosis in the modus operandi. In the aftermath of Industry 4.0, a new era of DSCM has begun, driven by artificial intelligence and big data analytics, cloud computing, IoT, blockchain, automated vehicles, robots, drones, and smart devices [14] [15]. DSCM operates with a smart and cloud-based ecosystem, seamlessly integrating all stakeholders on a real-time basis through the exchange of information [16, 17, 18]. SCM in the era of Industry 4.0 is fast, agile, highly flexible, complex, real-time, and data-driven. As information is one of the strategic assets of any organization's supply chain for winning over the competition, security and privacy have emerged as critical issues. It is mentioned in [19] that "information flows affect a firm's ability to integrate value-adding operations and improve innovation, considering the new and changing role of information. Consequently, the virtual value chain is a key integration mechanism via dynamic information". Therefore, information plays a pivotal role in successfully operating with a smart and intelligent DSCM. The sharing of real-time information helps firms achieve transparency, visibility, accountability, traceability, and reliability in the SCM. However, researchers [20, 21] apprehended the security and trust issues as hindrances to effective DSCM. Information security is essential for firms to achieve a competitive advantage through DSCM [22]. Cyber-attacks are critical yet inevitable risks for smart supply chain management [23, 24]. Blockchain is a key technology DSCM uses to ensure secure data transfer, visibility, accessibility, and integration of the chain members [25, 26]. However, to combat the cyber threat and ensure security and privacy in a data-driven DSCM, it is essential to have a robust real-time cybersecurity and threat detection system [27]. QC, therefore, is relevant to next-generation smart DSCM.

1.1. Motivation for the study and research objectives

Having been motivated by the significance of QC for digital supply chains, we reviewed the extant literature. A review of the related literature reveals a scantiness of work studying the criticalities of implementing QC in DSCM.

Lately, some studies have been conducted to showcase the significance of the quantum concept in SCM. For example, Souza [28] advocates for using quantum computing to solve complex optimization and forecasting problems in the supply chain management of the retail sector. Maheshwari et al. [29] showcase the necessity of QC for secured data transmission in smart manufacturing. Whig et al. [30] stress utilizing the synergistic effect of AI-based predictive models with quantum computing for sustainable SCM. Cheung et al. [31] reviewed potential applications of quantum computing in logistics and supply chain management and have brought off the necessity to conduct quantitative research related to information security. However, to the researchers' best knowledge, no past study has discerned the critical issues for the implementation of QC in DSCM. We therefore undertake the present work with the research question: What are the critical issues to adapting QC in digital supply chains?

Since several factors influence the adaptation of advanced technology [32], the MCDM approach based on group decision-making is appropriate. Further, group decision-making involves experts' opinions associated with subjective bias. Hence, the present work fulfills two objectives such as:

a) To unearth the key challenges or barriers to adapting QC technology in DSCM.

b) To develop a robust group decision-making framework dealing with uncertainties for discerning critical issues to adapt an advanced technology like QC.

To this end, the ongoing study proposes a multi-criteria decision-making (MCDM) model based on experts' opinions. Considering the subjective nature of the information, the present work uses q Rung Orthopair fuzzy set (q ROFS) for analysis. The current work follows a group decision-making approach based on experts' opinions. To aggregate the experts' views, we use Einstein aggregation for a better approximation than simple algebraic products and unions [33,34]. The factors representing the barriers to adapting QC in SCM are compared based on calculated weights by a recently developed MCDM model, such as comparisons between ranked criteria (COBRAC) [35]. COBRAC offers several advantages: a more significant scale range through local pairwise comparisons, a lesser number of pairwise comparisons reducing the effect of subjectivity, and a reliable and stable solution with an inherent consistency checking mechanism. Table 1 provides a comparative analysis of some of the contemporary methods with COBRAC.

Table 1: Comparison of features of MCDM models

Method	No. of pairwise comparisons	Feature	No. of criteria handled	Consistency checking	Initial sorting	Complexity
AHP [36]	$n(n-1)/2$	Hierarchy-based intuitive approach. It requires expertise for pairwise comparison.	Less to moderate	Not available	Not required	Moderate to High
SWARA [37]	$n-1$	It is a simple algorithm but needs additional care to assign rating values (dependent on expert judgment)	Moderate to high	Not available	Required	Low
BWM [38]	$2n-3$	Defines the best and worst criteria at the beginning	Moderate	Not available	Required	Moderate to High
LBWA [39]	$n-1$	Works on level-based partitioning, which becomes difficult for the criteria having close score values	High	Not available	Required	Low
FUCOM [40]	$n-1$	Governed by mathematical transitivity. Pairwise comparison is simple and can be done objectively or subjectively using any scale (either decimal or integer).	High	Available	Required	Low
DIBR [41]	$n-1$	Maintains a recurrence dependency on the most crucial criterion. Works with distance-based calculations	Moderate to high	Not available	Required	Low to moderate
COBRAC [35]	$n-1$	It follows a similar mechanism to FUCOM, but it depends on local pairwise comparison, helping to carry out a granular analysis.	High	Available	Required	Low

1.2. Contributions

The contributions of the ongoing work are manifold.

i) <u>Practical contributions:</u>

a) It addresses a vital agenda critical in next-generation supply chain management. The supply chains become digitalized and are operated in Industry 4.0. A lot of data transactions are being made. This necessitates the need for secured transactions. This research fills the gap in the literature by examining the challenges of implementing an advanced albeit necessary technology like QC in supply chain management. To the best of the knowledge of the researchers, no prior study exists that introspected the barriers to implementation of QC in DSCM. The framework can be used to analyze the barriers to adapting advanced technologies of Industry 4.0, such as digital twin, blockchain, 3D printing, AR/VR, and metaverse, in the supply chains across industries.

b) The q-ROFEWA-based COBRAC model provides a structured decision-making framework for managers to assess and rank the challenges associated with QC implementation. This approach facilitates data-driven decisions while offsetting subjective bias to solve other complex business problems and helps formulate strategies.

ii) Theoretical contributions:

a) The present work expands the horizons of the application of the TOE framework in supply chain management and adds value to the literature by using the TOE framework in the context of QC adaptation in DSCM.

b) From the methodological perspective, the current study provides an innovative computational intelligence framework by applying a q-rung Orthopair fuzzy Einstein weighted averaging (q-ROFEWA)- based MCDM model such as COBRAC that offers robust and consistent results.

The remainder of this manuscript is built as follows. In the next section (section 2), a brief review of the theoretical framework (i.e., TOE) and related work (to figure out the barriers to adaptation of QC in SCM) are provided. In section 3, we describe the barriers. Section 4 briefly explains the preliminary concepts related to q ROFS. Section 5 lays out the methodological framework. In section 6, significant findings are exhibited. Section 7 is dedicated to discussions on the findings, including research implications. Finally, section 8 provides concluding remarks and possible further extensions.

2. LITERATURE REVIEW

2.1. Theoretical Underpinning

2.1.1. TOE framework

In this study, the researchers have consulted the TOE framework [42] to provide the theoretical background. The TOE framework is a widely used theoretical model for explaining various factors influencing the adaptation of new technologies. There are three aspects of the TOE framework such as *technology (T)* (considers the comparative advantage of the latest technology, its perceived cost, compatibility, and interoperability with the existing system, complexity, and security), *organization (O)* (deals with internal factors like readiness and capability of the organizations to embrace the new technology, availability of resources, organizational internal environment and culture, mobility of funds and top management support) and *environment (E)* (indicates the external issues like dynamics of business environment, stakeholder relation, resource mobilization, regulation and statutory issues) [43]. There are umpteen applications of the TOE framework found in the extant literature addressing the factors influencing the adaptation of new technologies [44, 45, 46, 47].

There have been several occasions where researchers have applied the TOE framework in supply chain-related decisions. Amini and Jahanbakhsh [48] worked on an adaptation of cloud computing technologies in the supply chain using a mixed theoretic lens, including TOE. Lin [49] utilized the TOE framework to investigate the underlying factors influencing electronic SCM. Tian et al. [50] examined the role of human-technology interaction in supply chain integration for carving out competitive advantages. Ganguly [51] used the TOE framework to determine the challenges for successfully adopting blockchain technology in logistics. Shahadat et al. [52] intended to discover the factors influencing the adoption of digital technologies by small and medium-scale industries. Various past studies have been found that applied the TOE framework to discern the factors driving the adaptation of advanced technologies in Industry 4.0 [53, 54, 55]. Therefore, it is evident that the TOE model has been widely applied to explain the role of various factors in adopting new technologies in different contexts, including SCM. However, the application of the TOE model related to the adaptation of a security framework like QC in SCM is not seen in the literature.

2.1.2. Development of q ROFS

Zadeh [56] introduced the concept of ordinary fuzzy sets that offer a variable degree of membership function (DMF) in uncertainty modeling with imprecise information. For a more realistic analysis, Atanassov [57] brought in the definition of the degree of non-membership function (DNF) and defined intuitionistic fuzzy sets (IFS) that follow the relationship as $DMF + DNF \leq 1$. However, in several real-life instances, the researchers are constrained by selecting DMF (μ) and DNF (ϑ) values. To remove this barrier, Yager [60] provided an innovative use of the natural integer $q \geq 1$for extending the family of IFS. The new concept, known as q ROFS, provides flexibility to the decision-makers in selecting the values of μ and ϑ by adjusting the values of q, with the condition $\mu^q + \vartheta^q \leq 1$. Since its introduction, q ROFS has been extensively used in several problems [59, 60, 61, 62, 63].

2.2. Related work

The extant literature reflects that QC can be a game changer for the supply chain industry, enabling secure communication and integrating quantum principles into classical processes. However, within the purview of the literature search, it is evident that no contribution has been made towards discerning the critical issues for implementing QC in SCM. However, we use some allied studies in the present work to relate the barriers to adapting QC in intelligent supply chains. Integrating advanced quantum-based technology like QC into the supply chain poses several challenges, such as interoperability, data privacy, and specialized expertise [64].

The skill gap in various industries is a significant issue, causing challenges like unemployment and business failures. Successful implementation requires specialized data science, machine learning, and supply chain management skills. Adaptation of QC, a key technology for DSCM, poses a challenge due to its specialized knowledge and potential security vulnerabilities. Addressing these skill gaps is crucial for effective supply chain functioning, especially in developing countries [65,66]. Cybersecurity concerns are significant in implementing QC in the supply chain industry, as it presents potential vulnerabilities. The advent of quantum computers threatens network infrastructures and services, prompting the exploration of post-quantum cryptographic solutions to address these concerns [67].

Another possible concern for implementing advanced technology like QC in smart supply chains is the lack of business case validation due to its complexity and the need for robust security measures. Quantum computing is crucial for real-time cryptography, communication security, and data integrity. As quantum computing advances, post-quantum blockchain cryptography is needed to withstand quantum attacks, ensuring the security and resilience of blockchain networks in the supply chain industry [68, 69]. Quantum technology presents significant costs and investment challenges for businesses. Research and development costs are high, requiring resources for algorithms, hardware, and software optimization. Infrastructure costs are high, including quantum processors, cryogenic systems, and control electronics. Operational costs include energy consumption and maintenance of hardware. Talent acquisition and training costs are high, requiring investment in skilled professionals. Risk management costs involve technical uncertainties and regulatory challenges. The long-term ROI of quantum computing applications is uncertain, necessitating careful evaluation. Partnership and collaboration costs involve licensing fees and joint development expenses [70].

International regulations, security regulations, and ethical considerations are crucial in developing QC applications. These regulations ensure global data protection, align with existing standards and standardize quantum key distribution protocols. Ethical considerations are essential for sensitive applications like secure communications and financial transactions. Public awareness campaigns, stakeholder consultations, and collaboration with legal experts are crucial to understanding and addressing regulatory concerns in the rapidly evolving regulatory landscape [70]. Organizations using QC must follow several rules and guidelines because it is a constantly developing technology. For QC solutions to be secure and interoperable, compliance with international and security legislation, like GDPR and HIPAA, is essential. Integration of QC into existing systems presents significant technical and logistical challenges. Key management strategies are crucial for secure key transfer, while AI technology integration with quantum cryptography presents unique challenges related to regulatory compliance and standards adherence [71]. Compatibility issues arise due to different principles of quantum cryptographic protocols, requiring significant modifications to existing infrastructure. Key management complexity and computational requirements can introduce performance overhead. Resource requirements for integrating quantum cryptographic systems may require additional resources, investments, and expertise. Security assurance is crucial, and regulatory compliance is a concern to ensure alignment with legal frameworks and industry guidelines [72].

3. BARRIERS TO ADAPTATION OF QC IN SCM

This section briefly discusses various barriers to adapting QC technology in digital supply chains. The barriers are primarily identified through a literature review of past allied contributions. It is worth mentioning that no specific contribution was found that outlined the challenges of adapting QC in digital supply chains. Hence. the experts' views during informal discussions are also considered when finalizing the list of barriers. The barriers are outlined and classified according to the TOE framework in Table 2. A brief description of the barriers is given below.

B1. ***Operational complexity***: Operational complexity includes the challenge of interoperability of the existing decision support and information systems maintained by various supply chain stakeholders. Another issue is quantum decoherence (QD), which occurs due to the loss of some quantum properties subject to the influence of surroundings [73]. A supply chain is a complex system with many heterogeneous parties involved. Due to the integration of several subsystems within the supply chain main system, QD may impose a notable complexity.

B2. ***Scale up and infrastructural capability***: Implementing QC requires establishing smart devices, high-speed internet connectivity across the supply chain, large-scale data handling, storage and sharing capability, and adequate R&D facilities [73]. In many cases, this may constrain the successful adaptation of QC.

B3. ***Lack of cooperation, coordination, and collaboration***: The supply chains are often fragmented. Many players are involved in the SCM, and they have different processes and objectives. Effective coordination, cooperation, and collaboration among the supply chain members result in a synergistic effect in sharing ownership and risk, and it provides structural flexibility in the system for successful adaptation of a new technology like QC and ensures malleable performance [74].

B4. ***Lack of awareness and knowledge***: It talks about a lack of tacit knowledge, familiarity and awareness about advanced technologies. It also entails a shortage of the requisite skill set to adapt QC in the supply chain. QC is an advanced concept to the supply chains. The immaturity of the industry poses challenges to adapting to new technology like QC [75].

B5. ***Trust and privacy issues***: In this digital age, information security and privacy are major concerns for firms. It posits a major challenge at the time of accepting a new technology. To embrace a new technology like QC, trust plays a vital role in internalizing the changes among different members of the supply chain [76].

B6. ***Statutory and regulatory issues*****:** QC is a new technology often criticized for fragility, qubit interconnection, decoherence, and external noise. Transitioning from a traditional security system to quantum-resistant cryptographic methods over the entire supply chain is a regulatory challenge. Moreover, the absence of statutory and regulatory norms and standards creates difficulty in governance and control. Often it leads to unethical practices [76].

B7. ***Commitment of management and stakeholder support****:* To embrace a new technology in a supply chain, it is required to have commitments from all firms associated with the value chain. Without top management commitment, a malleable adaptation of a new technology is not possible [77]. Moreover, transitioning to a new system like QC requires the mobilization of resources and capital investment with an acceptable time delay and initial technical issues. Hence, top management commitment and support from all stakeholders are necessary for the adaptation of QC.

B8. ***Adaptation cost***: It covers the following: a) initial investment required to set up the technology; b) maintenance cost; c) Training and development cost; d) Cost incurred by using energy; e) Hardware setup cost; f) Switchover cost. Therefore, implementation of QC in supply chains requires a substantial amount of cost which acts as a hindrance [77].

B9. ***Lack of fund support***: It is evident from previous discussions that implementation of QC in the supply chain requires a lot of capital expenditure at the initial phase and operational cost. To cover such costs fund support is critical for the successful implementation of QC [77].

Table 2: List of barriers to adapting QC in supply chains

SL	Barrier	Dimension	References
B1	Operational complexity	T	[75]
B2	Scale-up and infrastructural capability	O	[75]
B3	Lack of cooperation, coordination, and collaboration	E	[76]
B4	Lack of awareness and knowledge	O	[77]
B5	Trust and privacy issues	O	[78]
B6	Statutory and regulatory issues	E	[76]
B7	Commitment of management and stakeholder support	O	[79]
B8	Adaptation cost	T	[79]
B9	Lack of fund support	O	[79]

4. PRELIMINARY CONCEPTS

In this section, some preliminary concepts and operational rules related to q ROFS [58] are outlined.

Notations:
$\widetilde{\mathbb{Q}}$: q ROFS
μ_Q: Degree of membership function (DMF)
ϑ_Q: Degree of non-membership function (DNF)
η_Q: Degree of indeterminacy (DI)
U: Universe of discourse
ζ: Scalar quantity >0
$\hbar$: Score function
λ: Accuracy function

Definition 1. *q rung Orthopair fuzzy sets (q ROFS) is defined as*

$$\widetilde{\mathbb{Q}} = \left\{\left\langle x, \mu_Q(x), \vartheta_Q(x)\right\rangle; x \in U; \mu_Q(x), \vartheta_Q(x): U \to [0,1]\right\} \tag{1}$$

Such that $0 \le (\mu_Q(x))^q + (\vartheta_Q(x))^q \le 1; \forall x \in U$.
The DI is found as

$$\eta_Q(x) = \sqrt[q]{1 - \mu_Q(x))^q - (\vartheta_Q(x))^q} \forall x \in U; \eta_Q(x): U \to [0,1] \tag{2}$$

It may be noted that by changing the values of qwe can convert q ROFS into other versions as follows:

$q = 1$ q ROFS→ Intuitionistic Fuzzy Sets (IFS)
$q = 2$ q ROFS→ Pythagorean Fuzzy Sets (PyFS)
$q = 3$ q ROFS→ Fermatean Fuzzy Sets (FFS)

Hereafter, for the sake of simple representation, we use q rung Orthopair fuzzy number (q ROFN) $\mathbb{Q} = (\mu, \vartheta)$without losing the terms and definition of q ROFS.

Definition 2. *Operations on q ROFNs*

Let, $\mathbb{Q} = (\mu, \vartheta), \mathbb{Q}_1 = (\mu_1, \vartheta_1)$and $\mathbb{Q}_2 = (\mu_2, \vartheta_2)$are three q ROFNs. In what follows are some fundamental operations:

i) Complement operation: $\mathbb{Q}^c = (\vartheta, \mu)$

ii) $\mathbb{Q}_1 \oplus \mathbb{Q}_2 = \left\{ \sqrt[q]{\mu_1^q + \mu_2^q - \mu_1^q \mu_2^q}, \vartheta_1 \vartheta_2 \right\}$

iii) $\mathbb{Q}_1 \otimes \mathbb{Q}_2 = \left\{ \mu_1 \mu_2, \sqrt[q]{\vartheta_1^q + \vartheta_2^q - \vartheta_1^q \vartheta_2^q} \right\}$

iv) $\zeta \mathbb{Q} = \left\{ \sqrt[q]{1 - (1 - \mu^q)^\zeta}, \vartheta^\zeta \right\}$

v) $\mathbb{Q}^\zeta = \left\{ \mu^\zeta, \sqrt[q]{1 - (1 - \vartheta^q)^\zeta} \right\}$

Definition 3. *Score and accuracy functions for q ROFNs*

The score function [78] is defined as follows

$$\hbar = \frac{(\mu^q - 2\vartheta^q - 1)}{3} + \frac{\lambda}{3}(\mu^q + \vartheta^q + 2); \lambda \in [0,1] \tag{3}$$

Here, λ is a constant scalar value.

The accuracy function is defined [79] as under

$$\lambda = \mu^q + \vartheta^q; \lambda \in [0,1] \tag{4}$$

The comparison of two q ROFNs is done as given below

i) If $\hbar_1 \succ \hbar_2 \Rightarrow \mathbb{Q}_1 \succ \mathbb{Q}_2$

ii) Else if $\hbar_1 \prec \hbar_2 \Rightarrow \mathbb{Q}_1 \prec \mathbb{Q}_2$

iii) Else if $\hbar_1 = \hbar_2$ then if $\lambda_1 \succ \lambda_2 \Rightarrow \mathbb{Q}_1 \succ \mathbb{Q}_2$; $\lambda_1 \prec \lambda_2 \Rightarrow \mathbb{Q}_1 \prec \mathbb{Q}_2$; $\lambda_1 = \lambda_2 \Rightarrow \mathbb{Q}_1 = \mathbb{Q}_2$

Definition 4. *q ROFN Weighted Averaging Operator (q ROFWA)*

For a series of q ROFNs $\mathbb{Q}_k (k = 1,2\ldots,n)$ with weights $\zeta_k > 0; \sum \zeta_k = 1$, q ROFWA operation is defined as [79]

$$\mathrm{q-ROFWA}(\mathbb{Q}_1, \mathbb{Q}_2, \ldots, \mathbb{Q}_n) = \left\langle (1 - \prod_{k=1}^n (1 - \mu_k^q)^{\zeta_k})^{\frac{1}{q}}, \prod_{k=1}^n \vartheta_k^{\zeta_k} \right\rangle \tag{5}$$

Definition 5. *Einstein sum and product*

Given $\alpha, \beta \in [0,1]$, the definitions of Einstein's sum and product are defined [80] below.

$$\alpha \oplus_\varepsilon \beta = \frac{\alpha + \beta}{1 + \alpha\beta} \tag{6}$$

$$\alpha \otimes_\varepsilon \beta = \frac{\alpha\beta}{1 + (1-\alpha)(1-\beta)} \tag{7}$$

Definition 6. *q ROF Einstein weighted aggregation*

For a series of q ROFNs $\mathbb{Q}_k (k = 1,2\ldots,n)$ with weights $\zeta_k > 0; \sum \zeta_k = 1$, q ROF Einstein weighted average (qROFEWA) and q ROF Einstein weighted geometric average (qROFEWGA) are defined as follows [34] [81]:

$$\mathrm{qROFEWA}\ (\mathbb{Q}_1, \mathbb{Q}_2, \ldots, \mathbb{Q}_n) = \left\langle \begin{array}{c} \left(\frac{\prod_{k=1}^n (1+\mu_k^q)^{\zeta_k} - \prod_{k=1}^n (1-\mu_k^q)^{\zeta_k}}{\prod_{k=1}^n (1+\mu_k^q)^{\zeta_k} + \prod_{k=1}^n (1-\mu_k^q)^{\zeta_k}} \right)^{\frac{1}{q}} \\ \left(\frac{2 \prod_{k=1}^n \vartheta_k^{\zeta_k q}}{\prod_{k=1}^n (2-\vartheta_k^q)^{\zeta_k} + \prod_{k=1}^n \vartheta_k^{\zeta_k q}} \right)^{\frac{1}{q}} \end{array} \right\rangle \tag{8}$$

$$qROFEWG\ (\mathbb{Q}_1, \mathbb{Q}_2, \ldots, \mathbb{Q}_n) = \left\langle \begin{array}{c} \left(\dfrac{2\prod_{k=1}^{n} \mu_k^{\zeta_k q}}{\prod_{k=1}^{n}(2-\mu_k^q)^{\zeta_k} + \prod_{k=1}^{n} \mu_k^{\zeta_k q}} \right)^{\frac{1}{q}} \\ \left(\dfrac{\prod_{k=1}^{n}(1+\vartheta_k^q)^{\zeta_k} - \prod_{k=1}^{n}(1-\vartheta_k^q)^{\zeta_k}}{\prod_{k=1}^{n}(1+\vartheta_k^q)^{\zeta_k} + \prod_{k=1}^{n}(1-\vartheta_k^q)^{\zeta_k}} \right)^{\frac{1}{q}} \end{array} \right\rangle \tag{9}$$

5. MATERIALS AND METHODS

This section describes the procedural steps followed in the research methodology.

Step 1. *Identification of the barriers to adapting QC in supply chains*

As discussed earlier, the present study uses the TOE framework to decide the barriers in line with the discussions made in related past studies (Table 2). Let, $B_j (j = 1,2 \ldots, n)$ denotes the j^{th}barrier or challenging factor. In this study, we have $n = 9$ the number of barriers.

Step 2. *Formation of the expert group*

In the current study, we form a focused group of 12 experts with substantial experience in cryptography, technology management, and supply chain management. The experts were selected conveniently and using snowball sampling. We approached the experts and had informal discussions with them before finalizing the questionnaire. Upon getting their views and consent, we prepared the online questionnaire link and circulated it to them to collect the responses. The sample size of the respondents conforms to the minimum requirement for group decision-making [82, 83]. The profile of the experts is exhibited in Table 3. Let, Let, $E_i (i = 1,2 \ldots, m)$ denotes the i^{th}expert. In this work, there are $m = 12$ experts who rated the barriers.

Table 3: Profile of the experts

Expert	Experience (years)	Area of expertise
E1	15 to 20	Information technology
E2	15 to 20	Information security
E3	10 to 15	Information security
E4	20 and above	Logistics & supply chain management
E5	20 and above	Technology management
E6	15 to 20	Information technology
E7	15 to 20	Logistics & supply chain management
E8	20 and above	Logistics & supply chain management
E9	15 to 20	Technology management
E10	10 to 15	Fund Management
E11	15 to 20	Logistics & supply chain management
E12	20 and above	Logistics & supply chain management

Step 3. *Collection of responses*

The responses (i.e., rating of each barrier based on their significance) were made in a five-point linguistic scale corresponding to q ROFNs as given in Table 4. The responses are given in Table A1 (Appendix A).

Step 4. *Aggregation of individual responses*

Suppose, $\mathbb{Q}_{ij} = (\mu_{ij}, \vartheta_{ij})$is the rating of the j^{th}barrier (B_j) by the i^{th}expert (E_i). Then by applying q ROFEWA (see expression (8)) we obtain the aggregated rating for $B_j$as

$$\mathbb{Q}_j = (\mu_j, \vartheta_j) = qROFEWA\ (\mathbb{Q}_{1j}, \mathbb{Q}_{2j}, \ldots, \mathbb{Q}_{mj}) = \left\langle \begin{array}{c} \left(\frac{\prod_{i=1}^{m}(1+\mu_{ij}^{q})^{\zeta_i}-\prod_{i=1}^{m}(1-\mu_{ij}^{q})^{\zeta_i}}{\prod_{i=1}^{m}(1+\mu_{ij}^{q})^{\zeta_i}+\prod_{i=1}^{m}(1-\mu_{ij}^{q})^{\zeta_i}}\right)^{\frac{1}{q}} \\ \left(\frac{2\prod_{i=1}^{m}\vartheta_{ij}^{\zeta_i q}}{\prod_{i=1}^{m}(2-\vartheta_{ij}^{q})^{\zeta_i}+\prod_{i=1}^{m}\vartheta_{ij}^{\zeta_i q}}\right)^{\frac{1}{q}} \end{array} \right\rangle \quad (10)$$

It may be noted that the aggregated response $\mathbb{Q}_j$is also a q ROFN. Here, $\zeta_i$indicates the relative importance (i.e., weight) of the i^{th}expert (E_i). If all experts are given equal priority, then $\zeta_i = \frac{1}{m}$.

Table 4: Linguistic rating scale and corresponding q ROFNs

		q ROFN	
Linguistic Scale	Code	μ	ϑ
Very High	5	0.85	0.25
High	4	0.70	0.40
Medium	3	0.55	0.55
Low	2	0.40	0.70
Very Low	1	0.25	0.85

Step 5. *Obtain the score values for all q ROFNs (representing the aggregated responses)*

Using the expression (3), we find the score value for each barrier B_j as follows.

$$\hbar_j = \frac{(\mu_j{}^q - 2\vartheta_j{}^q - 1)}{3} + \frac{\lambda}{3}(\mu_j{}^q + \vartheta_j{}^q + 2); \lambda \in [0,1] \quad (11)$$

Now, we proceed to calculate the weights for all barriers using the steps of the COBRAC method [35], which are as follows.

Step 6. *Comparative ranking of the barriers based on score values*

Let us assume that $B_k(k \in [1, n])$ is the most critical barrier. Accordingly, as per relative importance, the order of priority is given as $B_{k(1)} > B_{k(2)} > \ldots\ldots > B_{k(t)}$where $t \in [1, n]$ is the rank of the factors.

Step 7. *Pairwise local comparison of the barriers*

After the local pairwise comparison of the barriers, each pair is assigned a preferred value ξ. For instance, $\xi_{1,2}$is the assigned value to the first and second-ranked barriers and$\xi_{n-1,n}$is the assigned value to the second-to-last and last-ranked barriers. Then the values $\xi_{1,2}, \xi_{2,3}, \ldots. \xi_{n-1,n}$meet the condition $\xi \in [0,1]$.

Step 8. *Derive the weights of the factors*

The COBRAC method performs $(n-1)$ number of pairwise comparisons for $n$barriers. Hence, there are $(n-1)$ number of relationships formulated as given below.

$$w_1 : w_2 = \xi_{1,2} : (1 - \xi_{1,2});$$

$$\ldots\ldots$$

$$w_{n-1} : w_n = \xi_{n-1,n} : (1 - \xi_{n-1,n}) \quad (12)$$

According to the condition of transitivity, we can write

$$\frac{w_{n-1}}{w_n} - \frac{\xi_{n-1,n}}{(1-\xi_{n-1,n})} = 0 \quad (13)$$

The objective is set to minimize the deviations from consistency, i.e.,

$$\left|\frac{w_{n-1}}{w_n} - \frac{\xi_{n-1,n}}{(1-\xi_{n-1,n})}\right| \leq 0; j = 1,2\ldots, n.$$

The final model for calculating the weights of the barriers is formulated as

$$\min \max_{j} \left\{ \left| \frac{w_{n-1}}{w_n} - \frac{\xi_{n-1,n}}{(1-\xi_{n-1,n})} \right| \right\}$$
$$s.t.$$
$$\sum_{j=1}^{m} w_j = 1; w_j \geq 0 \ \forall j \qquad (14)$$

The expression (14) can be then expressed as a MINLP model for calculating the weights as

$$Min\ \chi$$
$$s.t.$$
$$\left| \frac{w_{n-1}}{w_n} - \frac{\xi_{n-1,n}}{(1-\xi_{n-1,n})} \right| \leq \chi, \forall j$$
$$\sum_{j=1}^{n} w_j = 1; w_j \geq 0 \forall j \qquad (15)$$

The methodological steps are laid down in Figure 1.

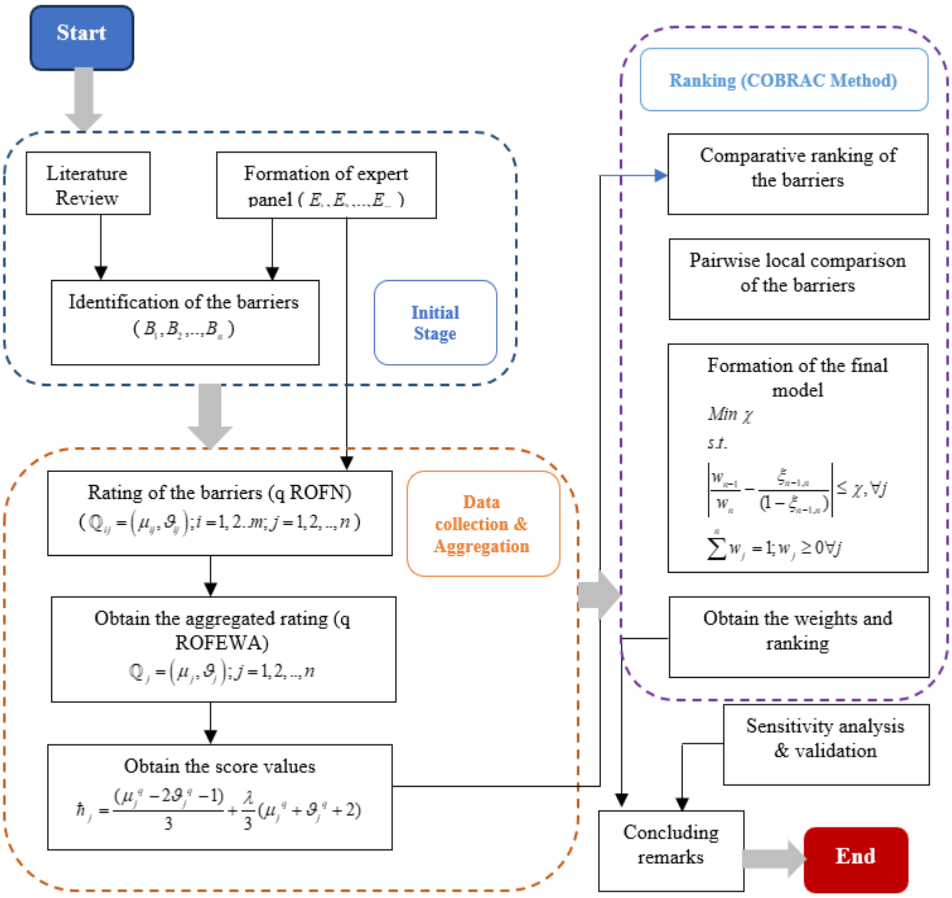

Figure 1: Steps of the research methodology

6. FINDINGS

This section summarizes the significant findings of the data analysis step by step. The experts' responses are recorded in Table A1 (Appendix A).

We formulate a q ROFN-based rating matrix (Table A2, Appendix A) using the q ROFNs corresponding to the linguistic rating.

Now, we aggregate individual ratings using q ROFEWA using the expression (10). Table 5 provides the aggregated rating (expressed in q ROFNs). For the initial case, we set $q = 3$ [84]. We assume that all experts are of equal priority. Hence, $\zeta_i = \frac{1}{m} = \frac{1}{12} = 0.08333$.

<u>Example of calculation</u>

Let us find out the aggregated response for the 5^{th}barrier (B_5). Applying the equation (10) we get the aggregated q ROFN value as follows.

$$\mathbb{Q}_5 = (\mu_5, \vartheta_5) = qROFEWA\ (\mathbb{Q}_{1(5)}, \mathbb{Q}_{2(5)}, \ldots, \mathbb{Q}_{12(5)})$$

$$= \left\langle \begin{array}{c} \left(\dfrac{\prod_{i=1}^{12}(1+\mu_{i5}^3)^{1/12} - \prod_{i=1}^{12}(1-\mu_{i5}^3)^{1/12}}{\prod_{i=1}^{12}(1+\mu_{i5}^3)^{1/12} + \prod_{i=1}^{12}(1-\mu_{i5}^3)^{1/12}}\right)^{\frac{1}{3}} \\ \left(\dfrac{2\prod_{i=1}^{12}\vartheta_{i5}^{3/12}}{\prod_{i=1}^{12}(2-\vartheta_{i5}^3)^{1/12} + \prod_{i=1}^{12}\vartheta_{i5}^{3/12}}\right)^{\frac{1}{3}} \end{array} \right\rangle$$

We get the q ROFN values of the individual responses from Table A2. For example, $(\mu_{1(5)}, \vartheta_{1(5)}) = (0.70, 0.40), (\mu_{2(5)}, \vartheta_{2(5)}) = (0.55, 0.55), \ldots\ldots, (\mu_{12(5)}, \vartheta_{12(5)}) = (0.70, 0.40)$.

Putting these values, we get the aggregated response for the 5^{th}barrier (B_5) as $\mathbb{Q}_5 = (\mu_5, \vartheta_5) = (0.78, 0.33)$

Similarly, the aggregated responses (expressed as q ROFNs) for all other barriers are calculated and recorded in Table 5.

Table 5: Aggregated rating of the barriers

Barrier	μ	ϑ	Barrier	μ	ϑ	Barrier	μ	ϑ
B1	0.62	0.48	B4	0.81	0.29	B7	0.48	0.63
B2	0.69	0.42	B5	0.78	0.33	B8	0.61	0.50
B3	0.51	0.61	B6	0.39	0.74	B9	0.59	0.52

Next, we use the expression (11) to find the score values of all barriers. In this case, we assume $\lambda = 0.8$ as used in [80]. Example of calculation:

$$\hbar_5 = \frac{({\mu_5}^3 - 2{\vartheta_5}^3 - 1)}{3} + \frac{\lambda}{3}({\mu_5}^3 + {\vartheta_5}^3 + 2)$$

$$= \frac{(0.78^3 - 2 \times 0.33^3 - 1)}{3} + \frac{0.8}{3}(0.78^3 + 0.33^3 + 2) = 0.5339$$

We now use the score values and apply the procedural steps of the COBRAC method [35] to obtain the barriers' weights. Table 6 shows how the weights of the barriers were calculated.

First, we order the barriers based on their score values. We obtain that $B_{4(1)} \succ B_{5(2)} \succ B_{2(3)} \succ B_{1(4)} \succ B_{8(5)} \succ B_{9(6)} \succ B_{3(7)} \succ B_{7(8)} \succ B_{6(9)}$. The values inside the bracket in the suffix indicate the corresponding ranks of the barriers. Next, we proceed to conduct pairwise local comparisons and determine the preferred value for each pair. For instance, while comparing B_4 (the most significant barrier) and B_5 (the second-most significant barrier), the preference value for $B_4$is calculated as

$$\xi_4 = \left(\frac{\hbar_4}{\hbar_4 + \hbar_5}\right) = \frac{0.5698}{0.5698 + 0.5339} = 0.5163$$

Similarly, the preference values for all other barriers are obtained through pairwise local comparisons. The advantage of the COBRAC method lies in fewer pairwise comparisons. For instance, in this case, there are nine barriers. But we require only $(9 - 1) = 8$pairwise comparisons. The counterparts of the COBRAC method, for example, BWM requires $(2 \times 9 - 3) = 24$and AHP needs $9(9 - 1)/2 = 36$ pairwise comparisons respectively. Clearly, COBRAC is less susceptible to subjective bias. Now, we move forward to formulate the MILP model to determine the weights and examine the consistency in the decision-making. Utilizing the equation (15), the final model is formulated as

$$\begin{aligned}
&Min\ \chi \\
&s.t \\
&\left|\frac{w_4}{w_5} - 1.0672\right| \le \chi, \left|\frac{w_5}{w_2} - 1.2045\right| \le \chi, \left|\frac{w_2}{w_1} - 1.1639\right| \le \chi, \\
&\left|\frac{w_1}{w_8} - 1.0354\right| \le \chi, \left|\frac{w_8}{w_9} - 1.0507\right| \le \chi, \left|\frac{w_9}{w_3} - 1.3366\right| \le \chi, \\
&\left|\frac{w_3}{w_7} - 1.1001\right| \le \chi, \left|\frac{w_7}{w_6} - 1.6726\right| \le \chi; \textstyle\sum_{j=1}^{9} w_j = 1; w_j > 0
\end{aligned} \tag{16}$$

The MINLP model is solved by using Lingo solver (version 20). The source code is given in the Appendix.

Table 6: Calculated weights of the barriers

Barriers	Score	ξ	1-ξ	ξ/(1-ξ)	w	Rank
B4	0.5698	0.5163	0.4837	1.0672	0.1733	1
B5	0.5339	0.5464	0.4536	1.2045	0.1624	2
B2	0.4433	0.5379	0.4621	1.1639	0.1348	3
B1	0.3808	0.5087	0.4913	1.0354	0.1158	4
B8	0.3678	0.5124	0.4876	1.0507	0.1119	5
B9	0.3501	0.5720	0.4280	1.3366	0.1065	6
B3	0.2619	0.5238	0.4762	1.1001	0.0797	7
B7	0.2381	0.6258	0.3742	1.6726	0.0724	8
B6	0.1423				0.0433	9
	χ	0.00000		Sum	1.0000	

It is seen that the deviation from consistency $\chi = 0.0000$. Therefore, the model (expression (16)) provides a robust result. To further ascertain its reliability, we compare the results with other MCDM models for criteria weight determination, as recommended in past studies.

6.1. Comparison with other MCDM models

The results of MCDM models are dependent on underlying assumptions. Hence, it is recommended in past studies [85,86] to compare the findings of several MCDM models to ascertain the reliability of the result. Accordingly, we use the obtained score values of the barriers to calculate their weights using several other models like FUCOM [40], BWM [38], SWARA [37], and LBWA [39]. We then rank the barriers based on their calculated weights for each method and carry out Spearman's rank correlation (SRC) test. The result of the SRC test (Table 7) shows that COBRAC maintains statistically significant and high correlation coefficient (ρ) values with other MCDM models. Hence, it confirms the reliability of the COBRAC model used in this paper.

Table 7. Spearman's rank correlation test among various MCDM models

Method	FUCOM	BWM	LBWA	SWARA
COBRAC	ρ = 0.98**	ρ = 0.91**	ρ = 0.98**	ρ = 0.95**

** significant at 0.01 level (two-tailed)

In addition to the above-mentioned comparisons, we also carried out an analysis with the DIBR [41] method to determine the barriers' weights. The DIBR method follows almost a similar principle of assigning significance value based on the proportional holding of the criteria while carrying out local pairwise comparisons. However, the COBRAC method provides an inherent consistency checking facility. We then calculate the mean absolute deviation (MAD) between the derived weights using COBRAC and DIBR. It is seen that the MAD value is very negligible (≈ 0) and Spearman's rank correlation coefficient = 1.000**. This finding strengthens the reliability of our approach.

6.2. Sensitivity Analysis

The MCDM models often suffer from abrupt variations in the ranking result because of changes in the underlying assumptions and external conditions affecting the model [87,88]. This results in a transient outcome. Sensitivity analysis is carried out to examine the extent of instability of the result obtained by a specific MCDM model [89,90]. In this work, we follow the prescribed approach of parameter variations [91,92] to examine the effect on the final ranking. We vary the values of $q$and λ. Table 8 shows the experimental cases. Figure 2 exhibits the variations in the ranking under several experimental cases. We do not observe any effect of parameter variations on the final ranking of the barriers. Hence, it indicates the stability of the model used in this paper.

Table 8: Experimental cases of sensitivity analysis

Cases	q	λ	Cases	q	λ	Cases	q	λ
Initial	3	0.8	Exp. 5	10	0.8	Exp. 10	3	0.4
Exp. 1	2	0.8	Exp. 6	20	0.8	Exp. 11	3	0.5
Exp. 2	1	0.8	Exp. 7	3	0.1	Exp. 12	3	0.6
Exp. 3	5	0.8	Exp. 8	3	0.2	Exp. 13	3	0.7
Exp. 4	7	0.8	Exp. 9	3	0.3	Exp. 14	3	0.9

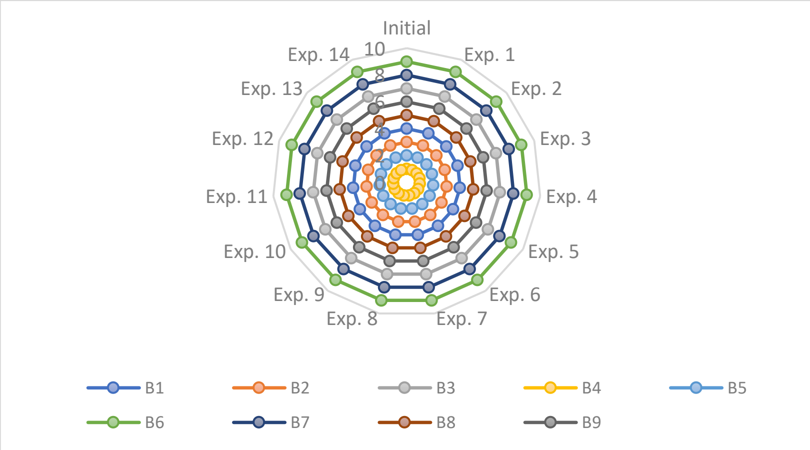

Figure 2: Results of sensitivity analysis

When other MCDM methods are compared, the barriers to QC adaptation are prioritized similarly. High correlation coefficient values reflect significant consistency among various methods. The objective function's calculated value is negligible, suggesting the model's high consistency and robustness while dealing with subjective opinions. Further, it is evident that COBRAC offers fewer pairwise comparisons than AHP or BWM and provides a granular analysis through local comparison. The outcome of sensitivity analysis showcases strong stability in the ranking despite variations in the parameter values. It indicates that the outcome is indifferent to the use of aggregation function and calculation of score values. In effect, these findings confirm the validity of our model.

7. DISCUSSION

Industry 4.0 has revolutionized supply chain management by offering new paradigms for efficiency and transparency. Transitioning from quantum to classical states in cryptographic systems is crucial for ensuring information exchange security. However, overcoming these challenges is essential for harnessing the full potential of digital transformation in supply chain management [93]. The findings of the present paper shed light on some significant implications for managerial decision-making, society, and scientific advancement.

From the findings, it is interesting to note that the top three barriers such as lack of awareness and knowledge (B4), trust and privacy issues (B5), and scale-up and infrastructural capability (B2) are from organizational dimension followed by two technology-related factors like operational complexity (B1) and adaptation cost (B8). This study shows that more than the complexity and uncertainty associated with new technology, it is vital to enhance awareness, imbibe new knowledge, and build a sustainable capability in an innovative and adaptive open culture [14,15]. The findings indicate the necessity of education and training initiatives [18]. The firms need to focus on building a skilled workforce capable of leveraging QC effectively. There is a requirement to create a knowledge-sharing and capability-building ecosystem through a collaborative effort of government, supply chain enterprises, higher educational institutions, chambers of commerce, and society. As awareness and knowledge levels increase, trust in new technology will improve increasingly [20, 21]. Organizations must support capability building by providing adequate digital infrastructure and R&D facilities and emphasizing resource mobilization and fund support [31]. There is a need to set comprehensive and robust norms, standards, and regulations.

The present work also provides valuable social implications. It is evident that there is a dearth of knowledge and awareness. This is a critical finding as it has a significant impact on employment. A series of advanced technologies feature the present age. One of the essential cornerstones of sustainable employability is the ability to adapt to new technologies. The current work advocates for skill development (re-skilling and up-skilling) and training programs to equip the workforce with the necessary expertise to bridge the gap between job descriptions and the availability of the right talents. It is also noted that there is a dying need for formulating policies to promote equitable access to technology and support for smaller businesses or developing regions in adopting quantum solutions. Public awareness campaigns and co-value creation through sharing knowledge, resources, and infrastructure help scale up the entire supply chain.

From the methodological point of view, the present study showcases an innovative and valuable application of the TOE framework. It highlights the need to instill a structured approach for replacing the old technology with a newer one while taking adequate care of interoperability, hardware and software support, operational complexity, and installation and maintenance costs. The current work demonstrates a novel extension of the COBRAC method with q ROFN that adds immense value to the extant literature on technology adaptation models and applications. The method used in this paper provides a robust outcome and showcases its ability to withstand variations in external conditions. The sensitivity analysis results show that the critical issues remain the same under several simulated practical situations.

From the perspective of computational complexity and handling pairwise comparisons, the model only requires $(n-1)$ number of local pairwise comparisons, unlike its counterparts like BWM $(2n-3)$, AHP $n(n-1)/2$and so on. For a problem involving a more significant number of criteria (like the present study), COBRAC demonstrates a clear difference in complexity. For example, if any problem deals with 15 variables, AHP posits difficulty in consistency checking. Also, for a case of 15 variables, the number of pairwise comparisons for BWM is 27, and that for AHP is 105, while COBRAC only requires 14 comparisons. Further, for a greater number of pairwise comparisons, in the case of AHP, it is difficult to handle the preference selection matrix. For a large set of criteria, some of them having similar importance, it is challenging to decide the best and worst criteria at the beginning for applying BWM. FUCOM works similarly to COBRAC. However, FUCOM needs additional steps to apply the mathematical transitivity property. FUCOM works with global comparisons. However, COBRAC deals with local pairwise comparisons and needs fewer steps. A method like DIBR decides the most preferential criterion and performs pairwise comparisons. However, there is no inherent consistency checking through a structured approach to solving for the objective function. Moreover, the success of decision-making applying DIBR lies in selecting the most preferential criterion and the separability of the preference values of the criteria. The same is the case for the LBWA method. Hence, COBRAC is superior to the contemporary methods.

Nevertheless, the current work could have used rough sets or other generalizations of fuzzy sets like IVIFS. We have selected q-ROFS for reasons like: a) it employs q-rung powers to provide a flexible depiction of membership and non-membership, enhancing modeling depth. In the case of IVIFS, we work with intervals, allowing a spread to selecting the membership grades, but that is too limited by the inequality that $\mu + \vartheta \leq 1$. However, interval-valued q-ROFN could have been an interesting option, although that increases the computational complexity; b) rough sets depend on equivalence or indiscernibility relations established within a domain of discourse. It is efficient for categorization, pattern recognition, and data processing in contexts where discrete links are evident. Data mining, classification, knowledge discovery, and rule extraction from ambiguous datasets. Thus, we find that q-ROFN is more appropriate for our problem. Nevertheless, in future work, we may use rough sets to discover the pattern of challenges while adapting various technologies of Industry 4.0.

8. CONCLUSION

As supply chains increasingly embrace digital technologies and operate on a real-time basis, the emergent need is information security and privacy. QC technology has become an essential framework for DSCM. To this end, the present work has been undertaken to unearth the critical barriers to successfully adapting QC in supply chains. The present study has been designed to identify the barriers based on the TOE framework and then conduct an expert opinion-based group decision analysis to prioritize the obstacles. To avoid subjective bias, the current work has been carried out using q ROFN-based analysis. To this end, the present work has proposed a novel q ROFEWA-based COBRAC model. The findings reveal that operational complexity, infrastructural requirements, lack of awareness, trust and privacy issues, regulatory challenges, and cost implications are critical barriers that can hinder the successful implementation of QC. The model's strength lies in fewer local pairwise comparisons and robust and stable outcomes. Ultimately, by addressing these barriers and embracing the potential of quantum cryptography, supply chains can enhance their security, efficiency, and resilience in an increasingly digital landscape. The successful integration of QC represents a technological advancement and a strategic opportunity for organizations to gain a competitive edge in the evolving market. One possible limitation lies with the size of the expert group.

There are several further scopes for the extension of the current work.

(i) A future extension may try to comprehensively assess barriers to adapting many other technologies, such as blockchain, IoT, and digital twins vis-à-vis QC, and examine the commonalities of barriers and their interrelationships.

(ii) In the present work, we have only identified the priorities of several barriers. Future work may try to establish a causal relationship among the barriers. In this regard, the methodologies like interpretive structural modelling (ISM) and DEMATEL may be used in conjunction with COBRAC.

(iii) Further work may attempt to formulate universal standards for QC applications in SCM while ensuring interoperability and compatibility among existing systems across the supply chain. Given cyber-attacks, vulnerability analysis of supply chains may be conducted to examine the efficacy of QC.

(iv) A causal linkage between the barriers of QC adaptation and possible impact on ROI may also be investigated.

(v) An empirical study may be designed to explore users' awareness and knowledge level in several supply chains, especially for SMEs to conduct the need assessment for training and development programs.
(vi) The number of respondents limits the present work. Twelve experts took part in this work. Although the number satisfies the minimum requirement of the group decision-making framework, future work may seek the opinions of many practitioners to validate the findings through an empirical analysis.
(vii) The current model (q ROFN COBRAC) may be tested for its suitability for applications in many other complex problems. The COBRAC method may be extended by using rough numbers and other variants of fuzzy numbers and aggregation operators [94,95,96,97].
(viii) We have used the TOE model in this work. However, future work may try to incorporate a mixed-theoretic lens using TAM, UTAUT2, diffusion of innovation theory, and TOE to assess firms' readiness to adapt QC in the supply chain.

Nevertheless, the present work is an apparently rare contribution that has technical and practical usefulness.

Acknowledgements: The authors would like to express their gratitude to all anonymous reviewers whose valuable comments have improved the quality of the paper significantly.

Funding: The present paper has received no funding.

REFERENCES

[1] C. H. Bennett, F. Bessette, G. Brassard, L. Salvail, and J. Smolin, "Experimental quantum cryptography," *Journal of Cryptology*, vol. 5, pp. 3–28, 1992.
[2] X. J. Li, D. Pan, G. L. Long, and L. Hanzo, "Single-photon-memory measurement-device-independent quantum secure direct communication—Part II: A practical protocol and its secrecy capacity," *IEEE Communications Letters*, vol. 27, no. 4, pp. 1060–1064, 2023. [Online]. doi: 10.1109/lcomm.2023.3247176
[3] T. Li and G. L. Long, "Quantum secure direct communication based on single-photon Bell-state measurement," *New Journal of Physics*, vol. 22, no. 6, p. 063017, 2020. [Online]. doi: 10.1088/1367-2630/ab8ab5
[4] N. Das and G. Paul, "Measurement device–independent quantum secure direct communication with user authentication," *Quantum Information Processing*, vol. 21, no. 7, p. 260, 2022. [Online]. doi: 10.1007/s11128-022-03572-z
[5] S. Nagpal *et al*., "Quantum computing integrated patterns for real-time cryptography in assorted domains," *IEEE Access*, 2024. [Online]. doi: 10.1109/access.2024.3401162
[6] M. Mehic *et al*., "Quantum key distribution: a networking perspective," *ACM Computing Surveys (CSUR)*, vol. 53, no. 5, pp. 1–41, 2020. [Online]. doi: 10.1145/3402192
[7] M. Wazid, A. K. Das, and Y. Park, "Generic quantum blockchain-envisioned security framework for IoT environment: Architecture, security benefits and future research," *IEEE Open Journal of the Computer Society*, vol. 5, no. 01, pp. 248–267, 2024. [Online]. doi: 10.1109/ojcs.2024.3397307
[8] A. Kumar, C. Ottaviani, S. S. Gill, and R. Buyya, "Securing the future internet of things with post-quantum cryptography," *Security and Privacy*, vol. 5, no. 2, p. e200, 2022. [Online]. doi: 10.1002/spy2.200
[9] S. Pierini *et al*., "Hybrid devices for quantum nanophotonics," *Journal of Physics: Conference Series*, vol. 1537, no. 1, p. 012005, May 2020, IOP Publishing. [Online]. doi: 10.1088/1742-6596/1537/1/012005

[10] S. Sonko, K. I. Ibekwe, V. I. Ilojianya, E. A. Etukudoh, and A. Fabuyide, "Quantum cryptography and US digital security: a comprehensive review: investigating the potential of quantum technologies in creating unbreakable encryption and their future in national security," *Computer Science & IT Research Journal*, vol. 5, no. 2, pp. 390–414, 2024. [Online]. doi: https: 10.51594/csitrj.v5i2.790

[11] S. Pulipeti and A. Kumar, "Secure quantum computing for healthcare sector: a short analysis," *Security and Privacy*, vol. 6, no. 5, p. e293, 2023. [Online]. doi: 10.1002/spy2.293

[12] S. Prajapat *et al*., "Designing high-performance identity-based quantum signature protocol with strong security," *IEEE Access*, vol. 12, pp. 14647–14658, 2024. [Online]. doi: 10.1109/access.2024.3355196

[13] W. Gong and Y. Kong, "Nonlinear influence of Chinese real estate development on environmental pollution: new evidence from spatial econometric model," *International Journal of Environmental Research and Public Health*, vol. 19, no. 1, p. 588, 2022. [Online]. doi: 10.3390/ijerph19010588

[14] P. Agrawal and R. Narain, "Digital supply chain management: An overview," *IOP Conference Series: Materials Science and Engineering*, vol. 455, no. 1, p. 012074, Dec. 2018, IOP Publishing.

[15] G. Büyüközkan and F. Göçer, "Digital supply chain: Literature review and a proposed framework for future research," *Computers in Industry*, vol. 97, pp. 157–177, 2018.

[16] S. Biswas and J. Sen, "A proposed architecture for big data driven supply chain analytics," *arXiv preprint*, arXiv:1705.04958, 2017.

[17] S. Biswas and J. Sen, "A proposed framework of next generation supply chain management using big data analytics," Proceedings of National Conference on Emerging Trends in Business and Management: Issues and Challenges, Mar. 2016.

[18] B. Ageron, O. Bentahar, and A. Gunasekaran, "Digital supply chain: challenges and future directions," *Supply Chain Forum: An International Journal*, vol. 21, no. 3, pp. 133–138, July 2020. [Online]. doi: 10.1080/16258312.2020.1786210

[19] C. L. Garay-Rondero *et al*., "Digital supply chain model in Industry 4.0," *Journal of Manufacturing Technology Management*, vol. 31, no. 5, pp. 887–933, 2020.

[20] H. Zhang, T. Nakamura, and K. Sakurai, "Security and trust issues on digital supply chain," 2019 IEEE Intl Conf on Dependable, Autonomic and Secure Computing, Intl Conf on Pervasive Intelligence and Computing, Intl Conf on Cloud and Big Data Computing, Intl Conf on Cyber Science and Technology Congress (DASC/PiCom/CBDCom/CyberSciTech), pp. 338–343, 2019.

[21] F. Kache and S. Seuring, "Challenges and opportunities of digital information at the intersection of Big Data Analytics and supply chain management," *International Journal of Operations & Production Management*, vol. 37, no. 1, pp. 10–36, 2017.

[22] Z. Li, X. Kong, and X. Jiang, "The relationship between digital information security of the supply chain and enterprise development," *International Journal of Information and Computer Security*, vol. 24, no. 1–2, pp. 60–79, 2024.

[23] Y. Fernando *et al*., "Cyber supply chain risk management and performance in industry 4.0 era: information system security practices in Malaysia," *Journal of Industrial and Production Engineering*, vol. 40, no. 2, pp. 102–116, 2023.

[24] B. Hammi, S. Zeadally, and J. Nebhen, "Security threats, countermeasures, and challenges of digital supply chains," *ACM Computing Surveys*, vol. 55, no. 14s, pp. 1–40, 2023.

[25] K. Korpela, J. Hallikas, and T. Dahlberg, "Digital supply chain transformation toward blockchain integration," 2017. [Online]. Available: http://hdl.handle.net/10125/41666. [Accessed: July 6, 2024].

[26] G. Büyüközkan, G. Tüfekçi, and D. Uztürk, "Evaluating Blockchain requirements for effective digital supply chain management," *International Journal of Production Economics*, vol. 242, p. 108309, 2021.

[27] M. O. Ibiyemi and D. O. Olutimehin, "Cybersecurity in supply chains: Addressing emerging threats with strategic measures," *International Journal of Management & Entrepreneurship Research*, vol. 6, no. 6, pp. 2015–2023, 2024.
[28] S. d'Souza, "Intelligent supply chain management using Quantum," Doctoral dissertation, TCS, 2022. [Online]. Available: https://hal.science/hal-03740772/
[29] D. Maheshwari, P. V. Florin, L. L. Dhirani, A. Waqas, B. S. Chowdhry, M. M. Ali, and G. Albeanu, "Role of Quantum Security in the Future of Smart Manufacturing," in *Integration of Heterogeneous Manufacturing Machinery in Cells and Systems*, pp. 216–236, CRC Press, 2024.
[30] P. Whig, R. Remala, K. R. Mudunuru, and S. J. Quraishi, "Integrating AI and Quantum Technologies for Sustainable Supply Chain Management," *Quantum Computing and Supply Chain Management: A New Era of Optimization*, pp. 267–283, IGI Global, 2024.
[31] K. F. Cheung, M. G. Bell, and J. Bhattacharjya, "Cybersecurity in logistics and supply chain management: An overview and future research directions," *Transportation Research Part E: Logistics and Transportation Review*, vol. 146, p. 102217, 2021.
[32] S. Biswas, D. Pamucar, and V. Simic, "Technology adaptation in sugarcane supply chain based on a novel p, q Quasirung Orthopair Fuzzy decision making framework," *Scientific Reports*, vol. 14, no. 1, p. 12345, Nov. 2024.
[33] S. Biswas, A. Sanyal, D. Božanić, S. Kar, A. Milić, and A. Puška, "A multicriteria-based comparison of electric vehicles using q-rung orthopair fuzzy numbers," *Entropy*, vol. 25, no. 6, p. 905, 2023.
[34] W. S. Du, "A further investigation on q-rung orthopair fuzzy Einstein aggregation operators," *Journal of Intelligent & Fuzzy Systems*, vol. 41, no. 6, pp. 6655–6673, 2021. doi: doi.org/10.3233/jifs-210548
[35] D. Pamucar, V. Simic, Ö. F. Görçün, and H. Küçükönder, "Selection of the best Big Data platform using COBRAC-ARTASI methodology with adaptive standardized intervals," *Expert Systems with Applications*, vol. 239, p. 122312, 2024.
[36] T. L. Saaty, "The analytic hierarchy process (AHP)," *The Journal of the Operational Research Society*, vol. 41, no. 11, pp. 1073–1076, 1980.
[37] D. Stanujkic, D. Karabasevic, and E. K. Zavadskas, "A framework for the selection of a packaging design based on the SWARA method," *Engineering Economics*, vol. 26, no. 2, pp. 181–187, 2015.
[38] J. Rezaei, "Best-worst multi-criteria decision-making method," *Omega*, vol. 53, pp. 49–57, 2015.
[39] M. Zizovic and D. Pamucar, "New model for determining criteria weights: Level Based Weight Assessment (LBWA) model," *Decision Making: Applications in Management and Engineering*, vol. 2, no. 2, pp. 126–137, 2019.
[40] D. Pamucar, Z. Stevic, and S. Sremac, "A new model for determining weight coefficients of criteria in MCDM models: Full consistency method (FUCOM)," *Symmetry*, vol. 10, no. 9, p. 393, 2018.
[41] D. Pamucar, M. Deveci, I. Gokasar, M. Işık, and M. Zizovic, "Circular economy concepts in urban mobility alternatives using integrated DIBR method and fuzzy Dombi CoCoSo model," *Journal of Cleaner Production*, vol. 323, p. 129096, 2021. [Online]. doi: 10.1016/j.jclepro.2021.129096
[42] L. Tornatzky and M. Fleischer, *The Process of Technology Innovation*, Lexington, MA: Lexington Books, 1990.
[43] J. Baker, "The technology–organization–environment framework," *Information Systems Theory: Explaining and Predicting Our Digital Society*, vol. 1, pp. 231–245, 2012.
[44] S. Chatterjee, N. P. Rana, Y. K. Dwivedi, and A. M. Baabdullah, "Understanding AI adoption in manufacturing and production firms using an integrated TAM-TOE model," *Technological Forecasting and Social Change*, vol. 170, p. 120880, 2021.

[45] S. D. Das and P. K. Bala, "What drives MLOps adoption? An analysis using the TOE framework," *Journal of Decision Systems*, pp. 1–37, 2023. doi: 10.1080/12460125.2023.2214306

[46] V. Chittipaka, S. Kumar, U. Sivarajah, J. L. H. Bowden, and M. M. Baral, "Blockchain Technology for Supply Chains operating in emerging markets: an empirical examination of technology-organization-environment (TOE) framework," *Annals of Operations Research*, vol. 327, no. 1, pp. 465–492, 2023.

[47] S. Hamadneh, M. Alshurideh, I. Akour, B. Kurdi, and S. Joghe, "Factors affecting e-supply chain management systems adoption in Jordan: An empirical study," *Uncertain Supply Chain Management*, vol. 11, no. 2, pp. 411–422, 2023.

[48] M. Amini and N. J. Jahanbakhsh, "A multi-perspective framework established on diffusion of innovation (DOI) theory and technology, organization and environment (TOE) framework toward supply chain management system based on cloud computing technology for small and medium enterprises," *International Journal of Information Technology and Innovation Adoption*, vol. 11, pp. 1217–1234, 2023.

[49] H. F. Lin, "Understanding the determinants of electronic supply chain management system adoption: Using the technology–organization–environment framework," *Technological Forecasting and Social Change*, vol. 86, pp. 80–92, 2014.

[50] M. Tian, B. Huo, Y. Park, and M. Kang, "Enablers of supply chain integration: a technology-organization-environment view," *Industrial Management & Data Systems*, vol. 121, no. 8, pp. 1871–1895, 2021.

[51] K. K. Ganguly, "Understanding the challenges of the adoption of blockchain technology in the logistics sector: the TOE framework," *Technology Analysis & Strategic Management*, vol. 36, no. 3, pp. 457–471, 2024.

[52] M. H. Shahadat, M. Nekmahmud, P. Ebrahimi, and M. Fekete-Farkas, "Digital technology adoption in SMEs: what technological, environmental and organizational factors influence in emerging countries?" *Global Business Review*, p. 09721509221137199, 2023.

[53] A. Raj and A. Jeyaraj, "Antecedents and consequents of industry 4.0 adoption using technology, organization and environment (TOE) framework: A meta-analysis," *Annals of Operations Research*, vol. 322, no. 1, pp. 101–124, 2023.

[54] Y. Zhong and H. C. Moon, "Investigating the impact of Industry 4.0 technology through a TOE-based innovation model," *Systems*, vol. 11, no. 6, p. 277, 2023.

[55] B. Santos, M. Dieste, G. Orzes, and F. Charrua-Santos, "Resources and capabilities for Industry 4.0 implementation: evidence from proactive Portuguese SMEs," *Journal of Manufacturing Technology Management*, vol. 34, no. 1, pp. 25–43, 2023.

[56] L. A. Zadeh, "Fuzzy sets," *Information and Control*, vol. 8, no. 3, pp. 338–353, 1965.

[57] K. T. Atanassov, "Intuitionistic fuzzy sets," *Fuzzy Sets and Systems*, vol. 20, pp. 87–96, 1986.

[58] R. R. Yager, "Generalized orthopair fuzzy sets," *IEEE Transactions on Fuzzy Systems*, vol. 25, no. 5, pp. 1222–1230, 2016.

[59] S. Cheng, J. Jianfu, M. Alrasheedi, P. Saeidi, A. R. Mishra, and P. Rani, "A new extended VIKOR approach using q-rung orthopair fuzzy sets for sustainable enterprise risk management assessment in manufacturing small and medium-sized enterprises," *International Journal of Fuzzy Systems*, vol. 23, pp. 1347–1369, 2021. doi: 10.1007/s40815-020-01024-3

[60] M. Deveci, I. Gokasar, D. Pamucar, S. Biswas, and V. Simic, "An integrated proximity indexed value and q-rung orthopair fuzzy decision-making model for prioritization of green campus transportation," *q-Rung Orthopair Fuzzy Sets: Theory and Applications*, Singapore: Springer Nature Singapore, pp. 303–332, 2022. doi:10.1007/978-981-19-1449-2_12

[61] S. Biswas, A. Sanyal, D. Božanić, A. Puška, and D. Marinković, "Critical success factors for 5G technology adaptation in supply chains," *Sustainability*, vol. 15, no. 6, p. 5539, 2023.

[62] B. Güneri and M. Deveci, "Evaluation of supplier selection in the defense industry using q-rung orthopair fuzzy set based EDAS approach," *Expert Systems with Applications*, vol. 222, p. 119846, 2023.

[63] S. Biswas, D. Pamucar, P. Dey, S. Chatterjee, and S. Majumder, “A q-ROF Based Intelligent Framework for Exploring the Interface Among the Variables of Culture Shock and Adoption Toward Organizational Effectiveness,” *Computational Intelligence for Modern Business Systems: Emerging Applications and Strategies*, Singapore: Springer Nature Singapore, pp. 255–293, 2023.
[64] N. Makki, N. Lang, and H. P. Büchler, “Absorbing state phase transition with Clifford circuits,” *Physical Review Research*, vol. 6, no. 1, p. 013278, 2024.
[65] W. Chao, Z. Qiu, L. Wu, Z. Guo, Z. Zheng, H. Zhu, and H. Liu, “A Cross-View Hierarchical Graph Learning Hypernetwork for Skill Demand-Supply Joint Prediction,” Proceedings of the AAAI Conference on Artificial Intelligence, vol. 38, no. 18, pp. 19813–19822, Mar. 2024. doi: 10.1609/aaai.v38i18.29956
[66] N. C. Yiu, “An Empirical Analysis of Implementing Enterprise Blockchain Protocols in Supply Chain Anti-Counterfeiting and Traceability,” *arXiv preprint* arXiv:2102.02601, 2021.
[67] E. Zeydan, Y. Turk, B. Aksoy, and S. B. Ozturk, “Recent advances in post-quantum cryptography for networks: A survey,” 2022 Seventh International Conference On Mobile And Secure Services (MobiSecServ), 2022, pp. 1–8.
[68] C. Chareton, S. Bardin, D. Lee, B. Valiron, R. Vilmart, and Z. Xu, “Formal methods for quantum programs: A survey,” *arXiv preprint* arXiv:2109.06493, 2021.
[69] T. M. Fernandez-Carames and P. Fraga-Lamas, “Towards post-quantum blockchain: A review on blockchain cryptography resistant to quantum computing attacks,” *IEEE Access*, vol. 8, pp. 21091–21116, 2020.
[70] F. Bova, A. Goldfarb, and R. G. Melko, “Commercial applications of quantum computing,” *EPJ Quantum Technology*, vol. 8, no. 1, p. 2, 2021.
[71] P. Radanliev, “Artificial intelligence and quantum cryptography,” *Journal of Analytical Science and Technology*, vol. 15, no. 1, p. 4, 2024.
[72] V. K. Ralegankar et al., “Quantum cryptography-as-a-service for secure UAV communication: applications, challenges, and case study,” *IEEE Access*, vol. 10, pp. 1475–1492, 2021.
[73] V. Sharma, U. Shrikant, R. Srikanth, and S. Banerjee, “Decoherence can help quantum cryptographic security,” *Quantum Information Processing*, vol. 17, pp. 1–16, 2018.
[74] J. Feizabadi and S. Alibakhshi, “Synergistic effect of cooperation and coordination to enhance the firm's supply chain adaptability and performance,” *Benchmarking: An International Journal*, vol. 29, no. 1, pp. 136–171, 2022.
[75] V. Alcácer, C. Rodrigues, H. Carvalho, and V. Cruz-Machado, “Tracking the maturity of industry 4.0: the perspective of a real scenario,” *The International Journal of Advanced Manufacturing Technology*, vol. 116, pp. 2161–2181, 2021.
[76] K. Francisco and D. Swanson, “The supply chain has no clothes: Technology adoption of blockchain for supply chain transparency,” *Logistics*, vol. 2, no. 1, p. 2, 2018.
[77] S. Chatterjee, M. Mariani, and A. Ferraris, “Digitalization of supply chain and its impact on cost, firm performance, and resilience: technology turbulence and top management commitment as moderator,” *IEEE Transactions on Engineering Management*, vol. 71, pp. 10469–10484, 2023. doi: 10.1109/TEM.2023.3297251
[78] X. Peng and J. Dai, “Research on the assessment of classroom teaching quality with q-rung orthopair fuzzy information based on multiparametric similarity measure and combinative distance-based assessment,” *International Journal of Intelligent Systems*, vol. 34, no. 7, pp. 1588–1630, 2019.
[79] P. Liu and P. Wang, “Some q-rung orthopair fuzzy aggregation operators and their applications to multiple-attribute decision making,” *International Journal of Intelligent Systems*, vol. 33, no. 2, pp. 259–280, 2018.
[80] S. Weber, “A general concept of fuzzy connectives, negations and implications based on t-norms and t-conorms,” *Fuzzy Sets and Systems*, vol. 11, no. 1–3, pp. 115–134, 1983.
[81] M. Riaz, W. Sałabun, H. M. Athar Farid, N. Ali, and J. Wątróbski, “A robust q-rung orthopair fuzzy information aggregation using Einstein operations with application to sustainable energy planning decision management,” *Energies*, vol. 13, no. 9, p. 2155, 2020.

[82] S. Biswas, D. Pamucar, D. Bozanic, and B. Halder, "A New Spherical Fuzzy LBWA-MULTIMOOSRAL Framework: Application in Evaluation of Leanness of MSMEs in India," *Mathematical Problems in Engineering*, vol. 2022, no. 1, p. 5480848, 2022.
[83] S. Biswas, "Exploring the implications of digital marketing for higher education using intuitionistic fuzzy group decision making approach," *BIMTECH Business Perspective*, vol. 2, no. 1, pp. 33–51, 2020.
[84] S. Biswas, D. Pamucar, A. Raj, and S. Kar, "A Proposed q-Rung Orthopair Fuzzy-Based Decision Support System for Comparing Marketing Automation Modules for Higher Education Admission," *Computational Intelligence for Engineering and Management Applications: Select Proceedings of CIEMA 2022*, Singapore: Springer Nature Singapore, 2023, pp. 885–912.
[85] Ö. F. Görçün, P. Chatterjee, Ž. Stević, and H. Küçükönder, "An integrated model for road freight transport firm selection in third-party logistics using T-spherical Fuzzy sets," *Transportation Research Part E: Logistics and Transportation Review*, vol. 186, p. 103542, 2024.
[86] S. Zakeri, D. Konstantas, R. B. Bratvold, and P. Chatterjee, "A cleaner supplier selection model using rate-weight connected vectors processor (RWCVP): Type I," *Journal of Cleaner Production*, vol. 441, p. 140913, 2024.
[87] S. Biswas and D. Pamucar, "A modified EDAS model for comparison of mobile wallet service providers in India," *Financial Innovation*, vol. 9, no. 1, p. 41, 2023.
[88] B. Kizielewicz and W. Sałabun, "SITW Method: A New Approach to Re-identifying Multi-criteria Weights in Complex Decision Analysis," *Spectrum of Mechanical Engineering and Operational Research*, vol. 1, no. 1, pp. 215–226, 2024. doi: 10.31181/smeor11202419
[89] S. Biswas, D. Pamucar, and S. Kar, "A preference-based comparison of select over-the-top video streaming platforms with picture fuzzy information," *International Journal of Communication Networks and Distributed Systems*, vol. 28, no. 4, pp. 414–458, 2022.
[90] S. Kousar, A. Ansar, N. Kausar, and G. Freen, "Multi-Criteria Decision-Making for Smog Mitigation: A Comprehensive Analysis of Health, Economic, and Ecological Impacts," *Spectrum of Decision Making and Applications*, vol. 2, no. 1, pp. 53–67, 2024. doi: 10.31181/sdmap2120258
[91] Ö. F. Görçün, D. Pamucar, and S. Biswas, "The blockchain technology selection in the logistics industry using a novel MCDM framework based on Fermatean fuzzy sets and Dombi aggregation," *Information Sciences*, vol. 635, pp. 345–374, 2023.
[92] D. Pamucar, A. E. Torkayesh, and S. Biswas, "Supplier selection in healthcare supply chain management during the COVID-19 pandemic: a novel fuzzy rough decision-making approach," *Annals of Operations Research*, vol. 328, no. 1, pp. 977–1019, 2023.
[93] M. Javaid, A. Haleem, and R. P. Singh, "A study on ChatGPT for Industry 4.0: Background, potentials, challenges, and eventualities," *Journal of Economy and Technology*, vol. 1, pp. 127–143, 2023.
[94] A. Hussain and K. Ullah, "An Intelligent Decision Support System for Spherical Fuzzy Sugeno-Weber Aggregation Operators and Real-Life Applications," *Spectrum of Mechanical Engineering and Operational Research*, vol. 1, no. 1, pp. 177–188, 2024. doi: 10.31181/smeor11202415
[95] M. Asif, U. Ishtiaq, and I. K. Argyros, "Hamacher Aggregation Operators for Pythagorean Fuzzy Set and its Application in Multi-Attribute Decision-Making Problem," *Spectrum of Operational Research*, vol. 2, no. 1, pp. 27–40, 2024. doi: 10.31181/sor2120258
[96] J. Kannan, V. Jayakumar, and M. Pethaperumal, "Advanced Fuzzy-Based Decision-Making: The Linear Diophantine Fuzzy CODAS Method for Logistic Specialist Selection," *Spectrum of Operational Research*, vol. 2, no. 1, pp. 41–60, 2024. doi: 10.31181/sor2120259
[97] S. Eti, H. Dinçer, S. Yüksel, and Y. Gökalp, "A New Fuzzy Decision-Making Model for Enhancing Electric Vehicle Charging Infrastructure," *Spectrum of Decision Making and Applications*, vol. 2, no. 1, pp. 94–99, 2024. doi: 10.31181/sdmap21202513

APPENDIX A

Table A1: Responses (in linguistic scale) of the experts

	Rating of significance of the barriers								
Expert	B1	B2	B3	B4	B5	B6	B7	B8	B9
E1	3	5	3	5	4	2	3	3	3
E2	3	4	3	5	5	3	2	3	2
E3	4	3	4	4	4	3	2	4	4
E4	3	4	2	5	5	1	4	3	3
E5	3	3	2	5	4	2	3	3	3
E6	4	4	3	4	4	1	2	3	2
E7	4	4	2	4	4	2	2	3	3
E8	3	4	2	5	5	2	2	4	4
E9	4	3	3	5	4	1	2	3	3
E10	3	3	2	4	5	1	2	4	4
E11	3	5	2	5	5	2	3	4	4
E12	4	3	3	5	4	1	2	3	3

Table A2. Responses (in q ROFNs) of the experts

	Rating of barriers in q ROFNs									
Expert	B1		B2		B3		B4		B5	
E1	0.55	0.55	0.85	0.25	0.55	0.55	0.85	0.25	0.70	0.40
E2	0.55	0.55	0.70	0.40	0.55	0.55	0.85	0.25	0.85	0.25
E3	0.70	0.40	0.55	0.55	0.70	0.40	0.70	0.40	0.70	0.40
E4	0.55	0.55	0.70	0.40	0.40	0.70	0.85	0.25	0.85	0.25
E5	0.55	0.55	0.55	0.55	0.40	0.70	0.85	0.25	0.70	0.40
E6	0.70	0.40	0.70	0.40	0.55	0.55	0.70	0.40	0.70	0.40
E7	0.70	0.40	0.70	0.40	0.40	0.70	0.70	0.40	0.70	0.40
E8	0.55	0.55	0.70	0.40	0.40	0.70	0.85	0.25	0.85	0.25
E9	0.70	0.40	0.55	0.55	0.55	0.55	0.85	0.25	0.70	0.40
E10	0.55	0.55	0.55	0.55	0.40	0.70	0.70	0.40	0.85	0.25
E11	0.55	0.55	0.85	0.25	0.40	0.70	0.85	0.25	0.85	0.25
E12	0.70	0.40	0.55	0.55	0.55	0.55	0.85	0.25	0.70	0.40
Expert	B6		B7		B8		B9			
E1	0.40	0.70	0.55	0.55	0.55	0.55	0.55	0.55		
E2	0.55	0.55	0.40	0.70	0.55	0.55	0.40	0.70		
E3	0.55	0.55	0.40	0.70	0.70	0.40	0.70	0.40		
E4	0.25	0.85	0.70	0.40	0.55	0.55	0.55	0.55		
E5	0.40	0.70	0.55	0.55	0.55	0.55	0.55	0.55		
E6	0.25	0.85	0.40	0.70	0.55	0.55	0.40	0.70		
E7	0.40	0.70	0.40	0.70	0.55	0.55	0.55	0.55		
E8	0.40	0.70	0.40	0.70	0.70	0.40	0.70	0.40		
E9	0.25	0.85	0.40	0.70	0.55	0.55	0.55	0.55		
E10	0.25	0.85	0.40	0.70	0.70	0.40	0.70	0.40		
E11	0.40	0.70	0.55	0.55	0.70	0.40	0.70	0.40		
E12	0.25	0.85	0.40	0.70	0.55	0.55	0.55	0.55		

Source files