Critical success factors for implementing blockchain-based circular supply chain

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Critical success factors for implementing blockchain-based circular supply chain

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Abstract

The growing importance of the circular economy has emphasised optimal utilisation of resources within the constraints of economic development and protection of the environment. Digital technologies associated with Industry 4.0, such as blockchain, facilitate the implementation of circular economy principles throughout the supply chain. However, because blockchain implementation in the supply chain is still in the early stages, real-world examples of the blockchain-based circular supply chains (CSCs) are limited. The principal purpose of the paper is to examine the critical success factors (CSFs) for implementing blockchain-based CSCs. Following that, 10 CSFs are identified through a short systematic literature review, and then, the integrated fuzzy cognitive mapping and fuzzy best-worst method (FCM-FBWM) is implemented to examine CSFs for the blockchain-based CSC. The study's main findings demonstrate that network collaboration is the best CSF, while the shared circular economy toolbox is counted worst of all. This research enriches the literature by identifying the CSFs for implementing blockchain-enabled CSCs to address the lack of a suitable decision-making framework that assists managers in comprehending how blockchain technology can be adopted in the circular economy context. Implications for theory and practice are also discussed, offering new insights into the measures necessary to ensure successful blockchain implementations in CSCs.

KEYWORDS

blockchain, circular economy, circular supply chain, critical success factors, FBWM, FCM

1 | INTRODUCTION

Circular Economy (CE) has gained traction among researchers and practitioners worldwide (Kristoffersen et al., 2020). This increasing importance of CE has defined efficient usage of resources within the limits of economic growth and protection of the environment (Morseletto, 2020). There is a high expanse of waste generated with the current linear ways of production (Patwa et al., 2021). The CE principles made aware by the Ellen MacArthur Foundation (2013) demonstrate the proven transition from a linear economy to the CE while creating value. Moving from a linear economy to a CE provides promising growth and aims to eliminate waste while moving towards

Abbreviations: CE, circular economy; CSC, circular supply chain; CSF, critical success factor; DM, decision maker; FBWM, fuzzy best-worst method; FCM, fuzzy cognitive mapping; MCDM, multi-criteria decision-making; P2P, peer-to-peer; PoW, proof-of-work.

the usage of resources in a better manner (Fehrer & Wieland, 2021). The CE was originally based on three principles, called "3Rs": Reduce, Reuse and Recycle (Kristoffersen et al., 2020). Therefore, the early frameworks of CE were designed to include only these 3Rs (Parida et al., 2019). However, over time they transformed into the 4Rs, then the 6Rs, and finally the 9Rs (Kayikci, Gozacan, Lafci, & Kazancoglu, 2021), which are Reuse, Recycle, Reduce, Remanufacture, Recover, Repair, Refurbish, Repurpose and Rethink (Kayikci, Kazancoglu, Lafci, & Gozacan, 2021). Although there has been an effort to apply a CE industrially, the concept is not fully understood. Conceptually, the CE represents "a change of paradigm in the way that human society is interrelated with nature and aims to prevent the depletion of resources, close energy and material flows, and facilitate sustainable development through its implementation at the micro (enterprises and consumers), meso (economic agents integrated in symbiosis), and macro (city, regions, and governments) levels" (Prieto-Sandoval et al., 2018, p. 610). The idea of the CE has been lauded as a substitute for the conventional linear economy and an essential agenda for the establishment of more ethical corporate practices (Snellinx et al., 2021). Geissdoerfer et al. (2017) point out that the CE constitutes an innovative approach that strives to build a closed-loop and reduce resource waste and emission levels, thereby fostering sustainability. Similarly, Aranda et al. (2019) argue that issues arising from global environmental degradation have prompted organisations to become proactive in adopting cleaner production techniques and implementing CE principles to maintain the value of materials and products for the longest time possible while reducing waste. Jensen (2021) also stated the necessity of CE as "Globally, the CE concept is increasingly seen as a way forward to achieve the necessary transformation into a resource-efficient economy, and the only way to achieve climate neutrality by 2050." Furthermore, achieving carbon neutrality by 2050, preserving our natural environment, and strengthening our economic competitiveness need a complete CE (Jensen, 2021). Implementing CE principles in the European Union (EU) economy can boost EU GDP by 0.5% by 2030, resulting in about 700,000 new employments (EC, 2020; Jensen, 2021).

The term Circular Supply Chain (CSC) has been increasingly discussed by practitioners and academicians worldwide (Ellen MacArthur Foundation, 2013). Hussain and Malik (2020) stated that CE practices need to be implemented to attain CSC. Moreover, Genovese et al. (2017) explained how CSC could be integrated with the CE principles to create a circular and sustainable supply chain. CSC has been expressed as:

> The coordinated forward and reverse supply chains via purposeful business ecosystem integration for value creation from products/services, by-products, and useful waste flows through prolonged life cycles that improve the economic, social and environmental sustainability of organisations. (Batista et al., 2019)

It has been observed from recent studies that digital technologies with the emerging Industry 4.0 (e.g., Internet of Things, artificial intelligence, and blockchain) play a major role in facilitating the adoption of CE principles in the supply chain (Kayikci, Kazancoglu, Lafci, Gozacan-Chase, & Mangla, 2021). Consistent digital foundations must be developed to enable appealing CE business models globally and to accelerate the CE transition in an effective, sustainable way (Kayikci, Kazancoglu, Lafci, & Gozacan, 2021) since digitalisation enables interoperability, neutrality, open software platform, data owner controls, and also reduced cost, time, and risk (Jensen, 2021). Blockchain is viewed as the next technological behemoth (Kayikci, Usar, & Aylak, 2021). Blockchain has a great potential to support business, strategy, environment, and sustainability (Bai et al., 2020). In a simple term, blockchain represents an open and distributed ledger that simplifies data sharing on a peer-to-peer network (Rejeb et al., 2021). The technology incorporates several parties, and the data sharing process is validated using cryptographic mechanisms (Crosby et al., 2016). Blockchain is an exceptionally secure approach to storing and keeping data. In a blockchain, once a blockchain has been initiated and verified by all participants, it becomes immutable and cannot be edited or resequenced (Upadhyay et al., 2021). Therefore, blockchain is anticipated to disrupt exiting transactional techniques, allowing a deluge of novel applications in many potential domains (Fosso Wamba et al., 2020). By providing a decentralised (Lahkani et al., 2020) and distributed (Chang & Chen, 2020) database, blockchain guarantees a high level of integrity for business transactions made in the blockchain ecosystem (Nakamoto, 2008). Blockchain acts as a digital database that maintains any sort of information, such as transactions, records, and events, with specified protocols for information updates (Niranjanamurthy et al., 2019).

The importance of blockchain in the supply chain industry emphasises its ability for digitisation, traceability, data security, immutability, and disintermediation across global supply chains (Tsolakis et al., 2021). Blockchain is a core technology with potential uses in data protection as well as business activities, particularly its application to cryptocurrencies (Kumar et al., 2021). Kayikci, Usar, and Aylak (2021) suggested developing blockchain-based CSC. However, blockchain deployment in the supply chain is still in its infancy; Therefore, the real practices of blockchain-based CSC are still scarce (Wang et al., 2020). Table 1 presents the past research studies examining the application of blockchain in the context of CE. We notice that most of these studies are reviews or conceptual studies, and quantitative approaches on the topic are quite limited. In Table 1, four studies employed Multi-Criteria Decision-Making (MCDM) techniques to examine the interplay between blockchain and the CE. For instance, Erol et al. (2022) developed an integrated decision framework including the MCDM-based Quality Function Deployment (QFD) method with Hesitant Fuzzy Linguistic Term Sets (HFLTS) to explore the possibilities of blockchain to overcome the CE adoption barriers. Yildizbasi (2021) applied a Pythagorean Fuzzy Analytical Hierarchy Process method to prioritise the challenges of blockchain encountered during the integration to a CE. Using Intuitionistic Fuzzy (IF)-Decision-Making Trial and Evaluation Laboratory (DEMATEL), Erol et al. (2021) examined the interrelationships between the CSFs for blockchain-based solar photovoltaic energy ecosystem (SPVEE) and validated the results by applying IF-DELPHI. Finally, Huang et al. (2022) applied an

TABLE 1 Main studies examining blockchain implementation in the CE

Author(s)	Study type	Objective(s)	Key finding(s)
(Kouhizadeh et al., 2020)	Multiple case study approach	To investigate how blockchain is likely to transform and facilitate CE realisation	Link blockchain application to CE dimensions of regenerate, share, optimise, loop, virtualise, and exchange (ReSOLVE model).
(Esmaeilian et al., 2020)	Literature review	To offer an overview of blockchain and industry 4.0 for developing sustainable supply chains.	Blockchain's capabilities for increasing sustainability fall under four key areas: (1) design of incentive mechanisms and tokenisation to encourage consumer green behaviour, (2) enhance visibility across the whole product life cycle, (3) increase systems efficiency while reducing development and operational costs, and (4) enhance sustainability monitoring and reporting performance across supply chain networks.
(Kouhizadeh et al., 2019)	Conceptual research	To envision the links between blockchain, product deletion, and the CE.	Propose a conceptual framework of product deletion, CE, and blockchain relationships.
(Upadhyay et al., 2021)	Literature review	To critically review blockchain's present and potential contribution to the CE through the lens of sustainability and social responsibility.	Blockchain can contribute to the blockchain by enabling to minimise transaction costs, improve performance and communication along the supply chain, protect human rights, improve healthcare patient confidentiality and welfare, and minimise carbon footprint.
(Khan, Razzaq, et al., 2021)	Survey	To study the role of blockchain in CE practice and its impact on eco-environmental performance	Blockchain remarkably enhances CE practices (circular procurement, circular design, recycling, and remanufacturing) CE practices can improve organisations' environmental performance and boost their financial performance. Higher eco-environmental performance considerably improves organisational performance.
(Rehman Khan et al., 2021)	Survey	To explore the role of blockchain for the CE to improve organisational performance in the context of China-Pakistan-Economic-Corridor.	With the support of its features like transparency, visibility, smart contracting, and relationship management, blockchain could positively impact the CE.
(Wang et al., 2020)	System design	To develop a system architecture of blockchain-enabled CSC management in the fast-fashion industry.	A blockchain-based system architecture for operationalising CSC management to achieve environmental sustainability in the fast-fashion sector
(Nandi, Sarkis, et al., 2021a)	Case study	To examine how firms develop localisation, agility, and digitalisation (LAD) capabilities by adopting CE and blockchain-related resources and capabilities already possessed or acquired from external agents.	There are significant patterns on adoption levels of the blockchain-enabled CE system and LAD capability development. The greater the BCES adoption capabilities, the greater the LAD capabilities. Organisational size and industry both affect the relationship between BCES and LAD.
(Narayan & Tidström, 2020)	Literature review	To determine how coopetition could be operationalised and optimised using tokens in a blockchain to advance circular models of value creation and appropriation.	Tokens could allow previously fragmented product ecosystems to converge and unlock innovation and creativity necessary for circular business models.
(Erol et al., 2022)	Multi-criteria decision-making	To examine the true potential of blockchain to overcome the CE adoption barriers	Enhanced supply chain traceability management improved collaboration, and coordination in supply chain ecosystems, building higher levels of trust in supply chain ecosystems, and enhanced business models are the most important functions of blockchain to help overcome the CE adoption barriers.

(Continues)

TABLE 1 (Continued)

Author(s)	Study type	Objective(s)	Key finding(s)
(Yildizbasi, 2021)	Multi-criteria decision-making	To develop a new integration process of blockchain with renewable energy systems under the CE perspective to ensure the sustainability of energy grid management systems.	Investment costs and technological infrastructure are the greatest obstacles to integrating blockchain into energy management.
(Erol et al., 2021)	Multi-criteria decision-making	To identify and investigate the critical success factors to enhance the performance of a blockchain-based solar photovoltaic energy ecosystem.	Effective government incentive programs and regulations are significant for blockchain-based SPVEE towards the CE in Turkey.
(Huang et al., 2022)	Multi-criteria decision-making	To develop a framework that depicts the main phases of blockchain-enabled CSC management and assesses the critical success factors of blockchain implementation for CSC management.	Technical capability, technological maturity, and technological feasibility play important roles in CSC management. Knowledge training and data security should be critical causal elements impacting other factors.

integrated analytical hierarchy process (AHP) and DEMATEL technique to analyse the priorities and relationships of success factors utilising assessments from academic and professional specialists. While these research works have extended the literature in the blockchain-CE field, we note the rising need to understand how blockchain enables the CSC and how these case studies provide a role in adopting CE. Furthermore, since blockchain is a relatively immature technology, particularly in the CSC context, there is a scarcity of a decision-making framework using an integrated Fuzzy Cognitive Mapping (FCM)-Fuzzy Best-Worst Method (FBWM) that can assist managers in comprehending the importance of Critical Success Factors (CSFs) for implementing a successful blockchain-based CSC. A CSF is defined as any element or condition that is considered essential in order for blockchain implementation to be successful (Finney & Corbett, 2007). Therefore, it is crucial for the practitioners in the CSC to appreciate blockchain's potential for the CSC. Additionally, this study partly addresses the call by Böhmecke-Schwafert et al. (2022) for future studies on the need for further empirical analysis of the enabling role of blockchain in the transition to a CE.

To fill the knowledge gap, the primary objective of this research is to analyse the CSFs for blockchain-based CSC. In this regard, this study explores the two following research questions:

1. What are the CSFs for the adoption of blockchain in CSC?
2. What is the importance of each CSF to implement a successful blockchain-based CSC?

To answer these research questions, a short systematic literature review was conducted to identify CSFs and an integrated FCM-FBWM method was applied to explore the importance of each CSF for implementing a successful blockchain-based CSC. FCM was chosen as the study approach because it identifies causal interrelationships by incorporating subjective aspects and is suitable for feedback phases (Irannezhad et al., 2021). Moreover, as Kayikci (2019) and Kayikci and Stix (2014) stated, FCM is straightforward and simple for experts/evaluators; it has a significant degree of integration across qualities on both a casual as well as a hierarchical basis; it may be completed in a reasonably short amount of time; it provides a detailed description of the system; and if there are any misunderstandings, it is beneficial for extension activities for training decision-makers. Besides the advantages of FCM, integrated FCM-FBWM also includes FBWM. Because FBWM contains minimal comparisons to other MCDM approaches if combined with FCM. The solution may be accomplished faster and substantially lower complexity (Sagnak et al., 2021). In addition, since the FBWM approach employs a mathematical model, it is more dependable than other methodologies (Sagnak et al., 2021).

As seen in Figure 1., the remainder of this paper is organised as follows. Section 2 presents review background by providing information about blockchain-based CSC. The research design, including a systematic literature review and integrated FCM-FBWM, is explained in Section 3, also the list of CSFs is provided. In Section 4, an empirical study to identify the importance of CSFs is presented and its results are given. Section 5 presents the discussion about the numerical results, meanwhile Section 6 gives the theoretical as well as practical implications. Finally, Section 7 concludes the paper by providing some recommendations for future research and limitations of the study.

2 | REVIEW BACKGROUND

Ajwani-Ramchandani, Figueira, de Oliveira, and Jha (2021) explained how to use the blockchain view in circular and modified linear economy contexts. Bekrar et al. (2021) reviewed the interaction of transportation, reverse logistics, and blockchain, specifically as an immutable and trustworthy ledger, a tracking service, a smart contract, tokenisation and incentivisation. Boeckel et al. (2021) conducted a systematic literature review about blockchain for the CE to analyse research-practice gaps. The study found three main conclusions: a distinct terminology of blockchain structures; trustworthiness and confirmation are essential advantages but challenging to implement; and a further evaluation of possible advantages and obstacles. Li et al. (2021) proposed a hybrid method by combining blockchain and case-based reasoning for remanufacturing process planning to ensure the safety and trustworthiness of information sharing meanwhile examining the

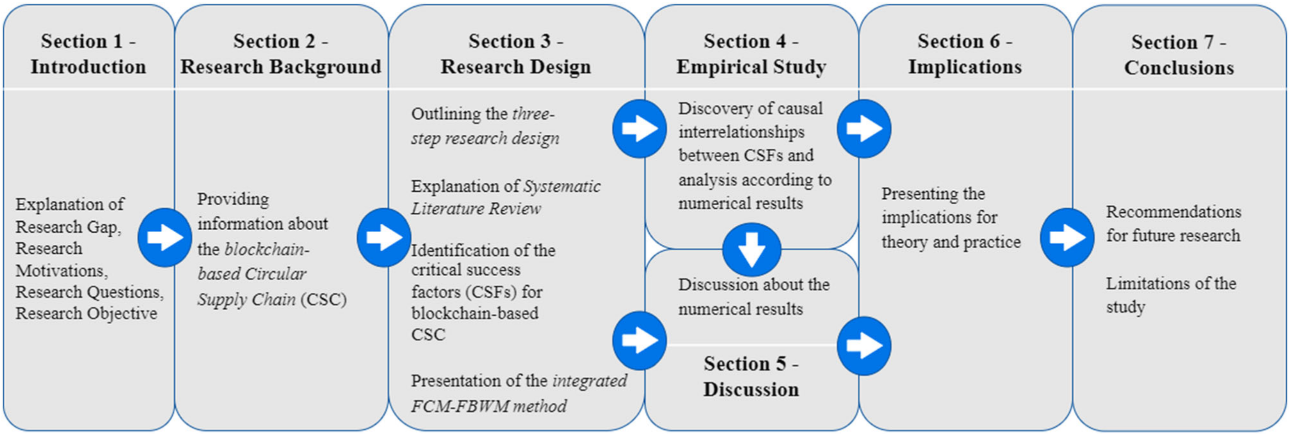

FIGURE 1 Flowchart of the study [Colour figure can be viewed at wileyonlinelibrary.com]

similarity between former remanufacturing cases and a new case with the nearest neighbour algorithm.

Several studies have been considered the impacts of the COVID-19 pandemic on different supply chains (Kayikci, Usar, & Aylak, 2021; Mosallanezhad et al., 2021; Zahedi et al., 2021). Nandi, Hervani, et al. (2021) used an abductive method to survey to investigate how businesses build Localisation, Agility, and Digitisation (L-A-D) skills by using essential CE and blockchain technology-related resources to improve post-COVID-19 supply chains. Upadhyay et al. (2021) conducted a literature review, emphasising blockchain's current and prospective convergence with the CE in sustainability. Yildizbasi (2021) formed a novel combination process of blockchain with the renewable energy systems following the CE perspective to defeat the difficulties endured in the energy grid management process, the blockchain concept, and its combination with renewable energy schemes. Kouhizadeh et al. (2020) investigated how blockchain technology is anticipated to transform and develop the CE dimension of regenerate, share, optimise, loop, virtualise, and exchange (ReSOLVE model) by utilising grounded theory building from various case studies. Kouhizadeh et al. (2019) conceptualised the relationships between blockchain technology, product deletion, and the CE, presenting prospective assessment and critical reflections. Finally, Sankaran (2019) focused on CE and energy transition by addressing two continuing projects: 1. converting industrial carbon emissions into green energy sources and 2. assisting in the effective and sustainable discrimination and recycling of plastic waste through the utilisation of multi-sensor-driven artificial intelligence and blockchain techniques. As the literature is evaluated, the originality of this paper can be explained as extending the literature by establishing CSFs for blockchain-enabled CSCs to consider the lack of an appropriate decision-making framework to help managers understand how blockchain technology may be used in the CE.

2.1 | Blockchain-based CSC

The logic of blockchain was first defined by Haber and Stornetta (1991), who intended to timestamp digital documents to not be backdated or tampered with. Nevertheless, it remained mostly unutilised until it was modified by Nakamoto (2008) as the underlying infrastructure for the digital cryptocurrency Bitcoin. A blockchain is a distributed ledger that is completely open to every entity (Angelis & da Silva, 2019; Irannezhad et al., 2021) and can be operated by multiple nodes anywhere they are located (Wang et al., 2020). Blockchain is decentralised (Kayikci et al., 2022), meaning that each node can decide whether or not to generate a block that includes data, the *hash* of the block that is created once the block is generated (Irannezhad et al., 2021), and the hash of the previous block (Wang et al., 2020). The data included within a block is determined by the structure of blockchain, which can be public (non-permissioned), private (permissioned), or consortium (hybrid) (Dutta et al., 2020). The data can be protected securely (Bai et al., 2020; Kayikci et al., 2022) since a hash is unique so that it distinguishes a block and all of its inclusions (Dutta et al., 2020) similarly to a fingerprint. Hashes are highly effective in detecting block alterations as Dutta et al. (2020) stated that transaction histories are recorded in "chronological blocks," and blocks containing invalid transactions can be quickly detected and monitored. In addition, to secure blockchain, *Proof-of-Work (PoW)* is a mechanism of blockchains that is known as "blockchain mining" (Dutta et al., 2020). This mechanism entangles tampering with the blocks by decelerating the generation of new blocks. As depicted in Figure 2., there are three ways to secure blockchain. The third way to secure blockchain is the *Peer-to-Peer (P2P)* network, which decentralises blockchain (Irannezhad et al., 2021). All the nodes in this network create consensus (Kayikci et al., 2022). One of the more recent blockchain developments is smart contracts (Kayikci et al., 2022). To sum up, blockchain has four fundamental properties: decentralised consensus, information exchange, negotiating, and incentivising mechanisms (Saberi et al., 2019).

The previously mentioned blockchain transparency, traceability, security, reliability, real-time data, and smart contracts features greatly impact CSC activities, assets, raw materials, products, and processes (Khan, Razzaq, et al., 2021). The data are continuously open to CSC stakeholders by blockchain, and this enhances the collaboration skills of a firm internally and externally since a CE necessitates the

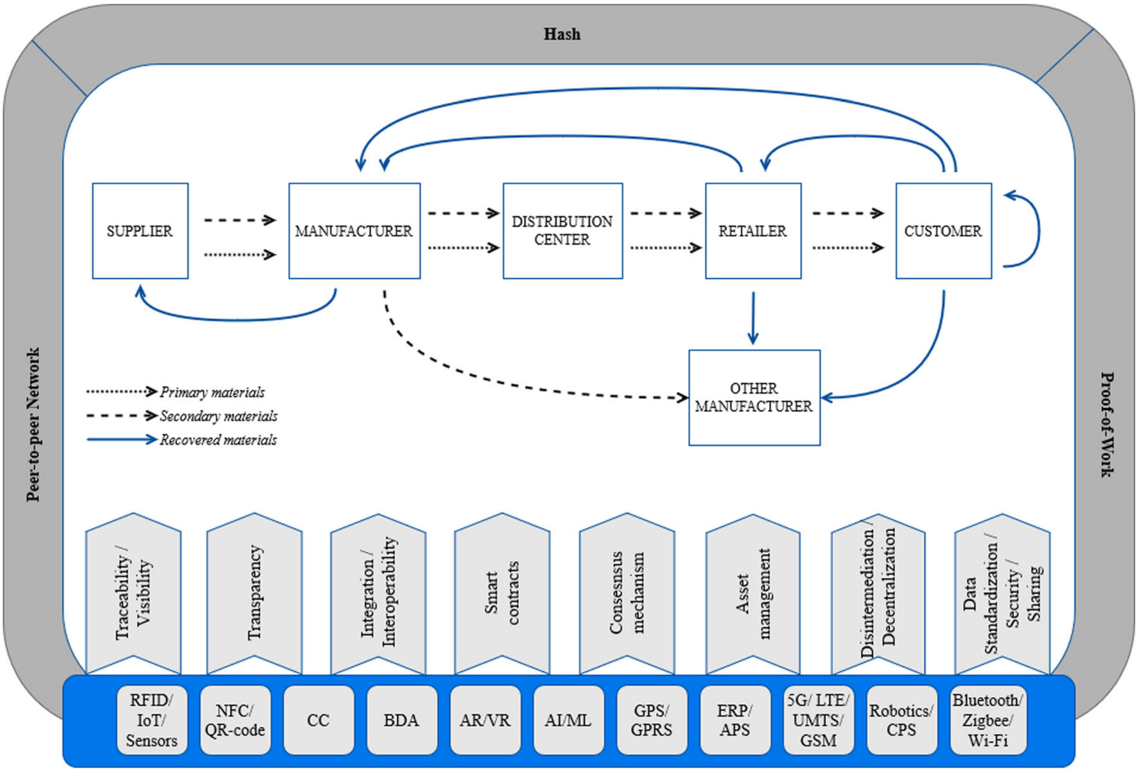

FIGURE 2 Blockchain-based CSC (source(s): Adapted from Batista et al., 2018, 2019, and Kayikci, Usar, & Aylak, 2021) [Colour figure can be viewed at wileyonlinelibrary.com]

development of viable loops at various supply chain suppositions (Nandi, Hervani, et al., 2021). Furthermore, blockchain provides extremely traceable products, decreasing the number of products and materials wasted in the CSC operations (Kayikci et al., 2022). In this context, through the traceability and transparency of transactions in the blockchain (Sislian & Jaegler, 2022), CSC stakeholders may have more authority over the efficiency of inventories, resource consumption, and operations (Tseng et al., 2018). Blockchain can monitor gas emissions and inform customers about products' green status (Wang et al., 2020). Blockchain can provide a platform to encourage the integration of the CE concept across different CSCs and all relevant stakeholders (Wang et al., 2020) by supporting product return management in reverse supply chains and waste minimisation, actively tracing materials, and encouraging cleaner production (Dutta et al., 2020). Blockchain characteristics can provide a solid platform for CSC in terms of reusing, repurposing, sharing economy, upcycling, and recycling-related information management (Kouhizadeh et al., 2020). Real-time data sharing in blockchain can promote consumer perception of the supply chain (Rusinek et al., 2018), supply chain collaboration (Saberi et al., 2019), and multi-tier supply chain insights originating at input suppliers to end-user consumers and likely CSC linkages (Kouhizadeh & Sarkis, 2018). Inventory information, digital content, machine operational status, transactions, logistics and shipping status, process management records, and any other sort of information are all examples of real-time shared data through blockchain (Nandi, Sarkis, et al., 2021b). In the logistics process, lead time can be reduced, and resource efficiency can be enhanced by blockchain implementation (Wang et al., 2020).

Additionally, blockchain allows consumers and suppliers to establish smart contracts that track and assess supplier performance (Kouhizadeh & Sarkis, 2018). Thus, proper suppliers can be quickly discovered for supplier selection (Saberi et al., 2019). When two firms from separate and independent CSCs require each other's discarded or used materials, they can use blockchain to conduct transactions and money transfers without the involvement of a third party (Wang et al., 2020). Thus, smart contracts facilitate quicker transactions with reduced cost alongside (Dutta et al., 2020).

3 | RESEARCH DESIGN

The objective of this paper is to analyse the CSFs for blockchain-based CSC. This study first aims to define the CSFs for implementing a successful blockchain-based CSC. A total of 10 CSFs has been identified by conducting a short systematic literature review as seen in Figure 3. State-of-the-art review is performed via search strings. As a result, 134 papers are found. The last number of the papers is 50 after the process of title/abstract monitoring, diagonal reading, and full paper reading. The list of CSFs is extracted from the papers. The final list of CSFs is agreed and endorsed by industry experts from blockchain-based CSC case companies. Moreover, the integrated FCM-FBWM method was selected as a research methodology to

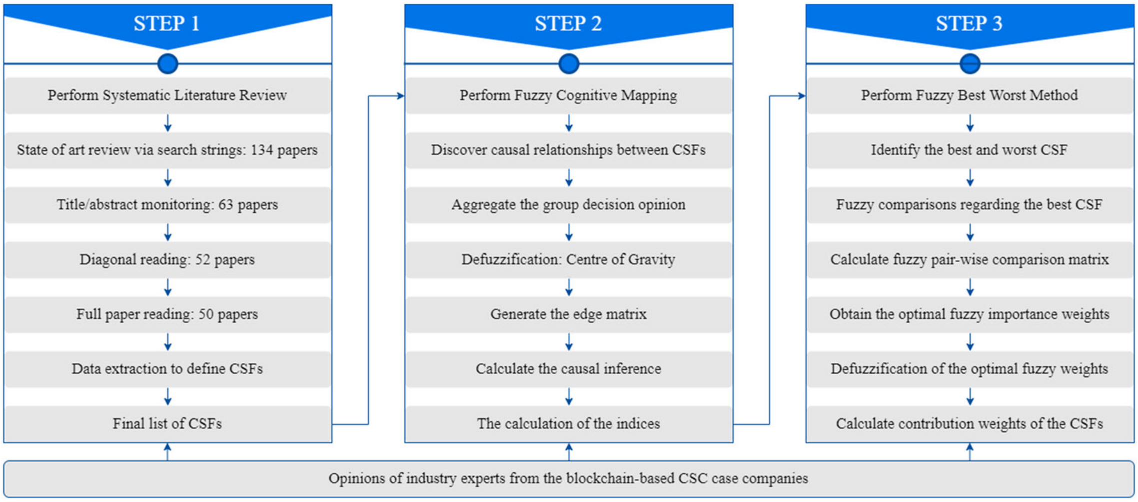

FIGURE 3 Research design [Colour figure can be viewed at wileyonlinelibrary.com]

investigate the importance of each CSF for implementing a successful blockchain-based CSC as explained in Section 3.2.

The three-step research design of CSFs for blockchain-based CSC assessment is demonstrated in Figure 3. The steps of the adopted methodology are conducted based on the opinions of industry experts from blockchain-based CSC case companies and the state-of-the-art review regarding blockchain-based CSC.

3.1 | Systematic literature review: Critical success factors for blockchain-based CSC

The CSFs for blockchain-based CSC are briefly explained in this section. Dinter (2013) defined CSF theory as "the areas in which the results if they are satisfactory, will ensure successful competitive performance for the firms." Since the main purpose of this paper is to present, identify, and analyse the CSFs for implementing a successful blockchain-based CSC, the clearly identified steps by conducting a systematic literature review outlined below were used to determine CSFs. The systematic literature review identifies, selects and critically appraises research in order to answer clearly formulated research questions (Thomé et al., 2016). First, a search string was established for the search of the state-of-the-art review. Search string is as follows:

> Search string. TITLE-ABS-KEY {"supply chain" AND "blockchain" AND "circular economy" OR "circularity" AND "success factor" OR "enabler" OR "driver" OR "motivator" OR "incentive" OR "facilitator"}.

Following a comprehensive review and analysis of the available literature, the top relevant articles for consideration in this research were identified. Second, relevant publications were identified by making a detailed search in Web of Science and Scopus databases. The initial goal was to use the search string in the titles, abstracts, and keywords fields. The initial search query returned 81 and 53 hits in Web of Science and Scopus. The returned documents were screened against the inclusion criteria, ensuring documents were English-language speaking and peer-reviewed to obtain high-quality and certified knowledge (Alnajem et al., 2021). Documents were also analysed to eliminate the duplicates, and we independently assessed the relevance of the remaining 75 publications. Next, we shortlisted all articles discussing blockchain applications for CE based on screening the titles and abstracts. A total of 63 publications passed the initial screening and were read entirely. Publications not aligning with our study's goal were filtered out, and 52 publications were selected after diagonal reading. In the end, 50 publications were qualified for the research and retained for the final analysis after full paper reading. These publications are 46 journal articles, one book chapter, and three conference papers. To mine the CSFs, two reviewers were involved in the detailed reading of articles and the coding process to minimise bias (Thomé et al., 2016) and ensure the reliability and validity of the findings. Based on the extensive systematic literature review, 10 CSFs were identified and gathered. Furthermore, these CSFs were finalised by group consensus through eight industry experts from different blockchain-based CSC case companies who possess both CE and blockchain knowledge. The meetings with experts were held asynchronously, as scheduling real-time meetings is difficult because industry experts are in different time zones. These asynchronous meetings also led to the addition of novel CSFs applicable to blockchain-based CSCs, the removal of duplicated CSFs (if applicable), as well as deciding on the final titles and contents of CSFs. As a result of this systematic literature review, the identified 10 CSFs to answer research question 1 can be seen in detail in Table 2.

3.2 | Methodology: Integrated FCM-FBWM

Utilising expert opinions is a beneficial strategy in the presence of uncertainty generated by technological innovations (Irannezhad

TABLE 2 List of critical success factors

CSF#		Explanation	References
CSF1	Network collaboration	Blockchain provides strong leadership as well as a horizontal and vertical collaboration by monitoring and auditing data utilising blockchain ledgers and adjusting inventories, optimising resource consumption, and modifying processes to create the least amount of waste. Blockchain provides direct interactions with increased engagement of producers and consumers to embrace CE initiatives. Furthermore, blockchain offers a more efficient method of analysing and selecting the best suppliers.	Ajwani-Ramchandani, Figueira, de Oliveira, and Jha (2021); Su et al. (2021); Esmaeilian et al. (2020); Hoosain et al. (2020); Kouhizadeh et al. (2020); Wang et al. (2020); Gopalakrishnan and Ramaguru (2019); Kouhizadeh et al. (2019)
CSF2	Many-to-many supply chain connectivity	Supply chain stakeholders can obtain better control of the efficiency of inventory, resource usage, and CE processes via the traceability and transparency of transactions in blockchain by enhancing the level of integration across supply chains and between various actors. Blockchain can enable interoperability, data immutability, new market development with fewer transaction fees, rapid execution and reduce frauds.	Bekrar et al. (2021); Boeckel et al. (2021); Jensen (2021); Rehman Khan et al. (2021); Salmon et al. (2021); Shojaei et al. (2021); Esmaeilian et al. (2020); Kouhizadeh et al. (2020); Liu et al. (2020); Paliwal et al. (2020); Wang et al. (2020); Gopalakrishnan and Ramaguru (2019); Guyot Phung (2019); Koscina et al. (2019); Kouhizadeh et al. (2019); Saberi et al. (2019); Vogel et al. (2019); Alexandris et al. (2018); Kouhizadeh and Sarkis (2018); Rusinek et al. (2018)
CSF3	Technology standardisation	Blockchain utilisation at the inter-firm level requires pre-defined standards, regulations and effective governance structures to clarify the actions provide data standardisation, prevent conflicts and the complexity of CE.	Bigerna et al. (2021); Nandi, Sarkis, et al. (2021b); Yildizbasi (2021); Kouhizadeh et al. (2020); Rosa et al. (2020); Sandhiya and Ramakrishna (2020); Taylor et al. (2020); Tozanlı et al. (2020a); Tozanlı et al. (2020b); Yadav and Singh (2020); Guyot Phung (2019); Xu et al. (2019)
CSF4	Regulations for incentives, recognition, and rewards	Blockchain increases the regulation of decentralised energy networks and microgrids, traceability and transparency of products with smart provision to enhance consumer awareness and incentivise product returns to the supply chain. Blockchain can incorporate rewards and encouragement programs by suggesting innovative regulatory ideas to the government and overcome management flaws.	Yildizbasi (2021); Kouhizadeh et al. (2020); Narayan and Tidström (2020); Paliwalet al. (2020); Kouhizadeh and Sarkis (2018)
CSF5	Sustainability and circularity behaviour	Blockchain facilitates the three pillars of sustainability, clean production and energy, the recycling and reusing of products, alternative green resources and behaviour by focusing on upstream business to mitigate the barriers of the “lack of collecting, sorting and recycling” and “problems of tracking and tracing” while reducing the costs of third-party supervision. Blockchain and smart contracts power by multi-sensor data fusion has the potential to ensure cleaner economic transactional processes; socially supportive activities of consumers and reward them though	Bressanelli et al. (2021); Li et al. (2021); Nandi, Sarkis, et al. (2021a); Salmon et al. (2021); Shojaei et al. (2021); Upadhyay et al. (2021); Yildizbasi (2021); Chidepatil et al. (2020); Esmaeilian et al. (2020); Gopalakrishnan et al. (2021); Hoosain et al. (2020); Kouhizadeh et al. (2020); Liu et al. (2020); Taylor et al. (2020); Wang et al. (2020); Kouhizadeh et al. (2019); Sankaran (2019); Rusinek et al. (2018); Wu et al. (2018)

TABLE 2 (Continued)

CSF#		Explanation	References
		cryptocurrencies token; fair labour practices; human rights protection.	
CSF6	Open innovation and co-creation platform	The blockchain-based application between the cooperating partners in four emerging product life cycle stages, including co-design and co-creation, quick and accurate information tracking and tracing, proactive maintenance, and regulated recycling. Also, blockchain can aid the collection of items through crowd shipping--a form of crowd sharing resources--capabilities of forwarding logistics providers who would like to return with cargo in a reverse logistics situation, especially for materials that can be remanufactured.	Bekrar et al. (2021); Dzhuguryan and Deja (2021); Liu et al. (2021); Shojaei et al. (2021); Demestichas and Daskalakis (2020); Kouhizadeh et al. (2019); Kouhizadeh and Sarkis (2018)
CSF7	Shared CE toolbox	Blockchain plays a role in monitoring the materials through the CE meanwhile reducing the time between processes especially for distributed systems, speeding up the ordering, transfer, payment, and ensuring the proper, timely movement of products.	Bekrar et al. (2021); Magrini et al. (2021); Demestichas and Daskalakis (2020); Esmaeilian et al. (2020); Kouhizadeh et al. (2020); Liu et al. (2020); Wang et al. (2020); Kouhizadeh et al. (2019); Wu et al. (2018)
CSF8	Product life cycle visibility and audit	Blockchain builds the visibility and feasibility of product life cycle and intelligence into assets. The use of the consortium blockchain allows for a fast, secure, and accessible information network by providing a decentralised ledger where the source of raw materials and produced products, the amount of energy used in their production, the source of the energy (renewable and non-renewable) used through their life cycle can be traced to their sources.	Bekrar et al. (2021); Shojaei et al. (2021); Demestichas and Daskalakis (2020); Esmaeilian et al. (2020); Liu et al. (2020); Wang et al. (2020); Kouhizadeh et al. (2019); Alexandris et al. (2018)
CSF9	Data ownership and control	Blockchain ensures trust, security, privacy, disintermediation solution, and decentralisation of data and elevates information verification, validity, and credibility flow within CE networks. Blockchain can address the social interactions critical to network creation and consensus-building that is required to promote CE business models by combining the secure recording of information for the coordination and transaction of such information.	Ajwani-Ramchandani, Figueira, de Oliveira, and Jha (2021); Ajwani-Ramchandani, Figueira, de Oliveira, Jha, Ramchandani, and Schuricht (2021); Narayan and Tidström (2020); Guyot Phung (2019); Morrow and Zarrebini (2019); Kouhizadeh and Sarkis (2018)
CSF10	Environmental performance and global resource deployment	Blockchain can help CSC management by speeding up resource deployment, reducing consumption and waste, and enhancing the resilience and flexibility of CSCs. Blockchain architecture needs to be extended to CE principles of stakeholders and post-consumer disposal to evaluate the efficiency of waste exchange programs.	Ajwani-Ramchandani, Figueira, de Oliveira, and Jha (2021); Chen and Ogunseitan (2021); França et al. (2020); Wang et al. (2020); Bai et al. (2020); Hagan et al. (2021); Kouhizadeh et al. (2019)

et al., 2021) since experts have a stronger comprehensive understanding of cause-effect relationships (Irannezhad et al., 2021). For this reason, opinions of the industry experts from blockchain-based CSC case companies are included into the steps of the integrated FCM-FBWM methodology as part of the three-step research design. Kosko initially developed FCM in 1986 as a mixture of neural networks and fuzzy logic that allows for the prediction of changes in the CSFs (concepts) expressed in causal maps (Kosko, 1986). FCM is utilised to discover causal relationships between the CSFs for blockchain-based CSC identified in Section 3. FCM was chosen as the research methodology because it allows for the discovery of causal interrelationships through including subjective factors and is well-suited for feedback cycles (Irannezhad et al., 2021). Furthermore, Kayikci and Stix (2014) stated that it is straightforward and easy, can be completed in a short amount of time, provides a robust system characterisation, and is beneficial for extension in case of misperceptions. FBWM is additionally integrated into FCM due to its beneficial impacts and suitability to the purpose of this research. This methodology was adopted since it has various advantages beyond other MCDM approaches, including assessing small group pair-wise comparisons instead of the complete pair-wise comparison matrix in those other MCDM methods (Agrawal & Vinodh, 2021). As supplementary comparisons are not required, FBWM is straightforward and precise (Rezaei, 2015).

3.2.1 | FCM

FCM is a flexible computing methodology for modelling and decision-making developed by combining fuzzy logic with neural networks (Kosko, 1986). It is composed of nodes defined as concepts (CSFs) and edges representing the causal links between them (Irannezhad et al., 2021). The development of the CSFs of the FCM model, and the causal relationships between CSFs, formed as arcs and expressed as *fuzzy if-then rules*, are built by industry and blockchain experts (Baykasoglu et al., 2011) with a fuzzy value ranging from $[-1,1]$ (Irannezhad et al., 2021). Each part of the fuzzy set embodies the specified triangular fuzzy membership (TFM) function $\mu_{\widetilde{w}}(x)$ by a triplet (l_{ij}, m_{ij}, u_{ij}) of two attributes (A_i, A_j) to integrate the multiple decision-maker (DM) opinions. l, m, u values represent the smallest possible, most promising, and largest possible value, respectively. Thus, TFM for kth DM can be described as $\widetilde{w}_{ij}^{k} = \widetilde{\mu}(x) = \{l_{ij}, m_{ij}, u_{ij}\}, i,j = 1,\ldots,n$. The weights of the CSFs are retrieved from the industry experts at the blockchain-based CSC case companies by providing the following aspects and applying *if-then rules* as below (Irannezhad et al., 2021):

1. The direction of the relationship: If CSF A_i affects A_j or the other way. This can be expressed as a question as:

"Do you think that the CSF A_i affects any other CSFs by any change or is affected by other CSF?" if yes, then

TABLE 3 Linguistic fuzzy terms utilised for causal relationships between CSFs (source: based on Irannezhad et al., 2021)

Linguistic terms		*l*	*m*	*u*
AP	Absolutely positive	0.90	1.00	1.00
EP	Extremely positive	0.70	0.90	1.00
STP	Strongly positive	0.50	0.70	0.90
MP	Moderately positive	0.30	0.50	0.70
SLP	Weakly positive	0.10	0.30	0.50
Z	Zero	0.00	0.10	0.30
SLN	Slightly negative	−0.10	0.00	0.10
WN	Weakly negative	−0.30	−0.10	0.00
MN	Moderately negative	−0.50	−0.30	−0.10
STN	Strongly negative	−0.90	−0.70	−0.50
EN	Extremely negative	−1.00	−0.90	−0.70
AN	Absolutely negative	−1.00	−1.00	−0.90

2. The sign of the relationship: A positive weight denotes a causal growth, while a negative weight reflects the reverse effect (Kayikci, 2019).
3. The strength of a relationship: The strength of the relationship is also identified as the weight of the relationship. The following if-then rule applied:

"If the value of activity A_i is changed, then this will cause activity A_j to change."

Step 1. *Aggregate the group decision opinion*: In this step, arithmetic mean is used to aggregate the group decision opinion as Ishikawa et al. (1993) recommended as in Equation 1.

$$l_{ij} = \frac{1}{k}\sum_{(i=1)}^{n} l_{ij}^{k};\ m_{ij} = \frac{1}{k}\sum_{(i=1)}^{n} m_{ij}^{k};\ u_{ij} = \frac{1}{k}\sum_{(i=1)}^{n} u_{ij}^{k}\,\forall k = 1,2,\ldots,K, \tag{1}$$

where k represents the number of DMs.

Step 2. *Defuzzification: Center of Gravity*: This step integrates the multiple DM opinions by aiming to defuzzify the fuzzy weight ($\widetilde{w}_{ij}$) of each relationship between A_i and A_j with the Equation 2 (Kayikci, 2019).

$$w_{ij} = CoG = \frac{\int_{min}^{max} \widetilde{\mu}(x).xdx}{\int_{min}^{max} \widetilde{\mu}(x)dx}, \tag{2}$$

where, w_{ij} represents the edge weight. x denotes the effect degree of a given linguistic term (see Table 3).

Step 3. *Generate the edge matrix*: The edge matrix ($E = (w_{ij})$, $w_{ij} \in E$, $i,j = 1, 2, ..., n$) includes the final (normalised) weights for the causal interference (Kayikci, 2019). It is a square $n \times n$ matrix as in Equation 3.

$$E = [w_{ij}] = \begin{matrix} & A_1 & A_2 & \dots & A_n \\ A_1 \\ A_2 \\ \vdots \\ A_n \end{matrix} \begin{bmatrix} 0 & w_{12} & \dots & w_{1n} \\ w_{21} & 0 & \dots & w_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ w_{n1} & w_{21} & \dots & 0 \end{bmatrix}_{nxn}, \forall w_{ij} \in [-1,1]. \tag{3}$$

Step 4. *Calculate the causal inference*: it is calculated as demonstrated in Equation 4.

$$A_i^{t+1} = f\left(A_i^t + \sum_{\substack{j=1 \\ j \neq i}}^{n} A_j^t . w_{ji} \right), \forall i,j \in \{1,...,n\}; t = 0,1,2,...,T, \tag{4}$$

where A_i^{t+1} is the value of ith CSF at the iteration time $t+1$, $f(x)$: threshold function is $f(x)$:$1/(1+e^{-\lambda x})$, $0 \leq \lambda \leq 1$. The values are normalised in Equation 5; so, the final weights of the CSFs are obtained:

$$w_i = A_i / \sum_{(i=1)}^{n} A_i. \tag{5}$$

The final crisp weights are demonstrated in matrix as in Equation 6 (Kayikci, 2019):

$$I = \begin{matrix} A_1 \\ A_1 \\ \vdots \\ A_n \end{matrix} \begin{bmatrix} w_1 \\ w_2 \\ \vdots \\ w_n \end{bmatrix}_{nx1}, \text{ where } \sum_{(i=1)}^{n} w_i = 1. \tag{6}$$

Step 5. *The calculation of the indices*: Every CSF is identified by its out-degree, in-degree, and centrality as formulated in Equations 7–9 (Kayikci, 2019). *Out-degree* (out-arrows) is the absolute row sum of edge weights (w_{ki}) in the edge matrix and denotes the number of CSFs. *In-degree* (in-arrows) is the absolute column sum of edge weights. w_{ik}, in the edge matrix, represents the number of CSFs causally interacting on CSF A_i. The immediate domain or total degree of a CSF is the sum of its in-degree and out-degree. It denotes the dominance of CSF A_i to the causal flow on the cognitive map. The more central the CSF, the more significant the CSF is in the DM's perception.

TABLE 4 Linguistic terms for triangular fuzzy numbers

Linguistic terms	Triangular fuzzy numbers
Equally important (EI)	(1,1,1)
Weakly important (WI)	(2/3,1,3/2)
Fairly important (FI)	(3/2,2,5/2)
Very important (VI)	(5/2,3,7/2)
Absolutely important (AI)	(7/2,4,9/2)

$$out-degree = od(A_i) = \sum_{k=1}^{n} |w_{ki}|, \tag{7}$$

$$in-degree = id(A_i) = \sum_{k=1}^{n} |w_{ik}|, \tag{8}$$

$$centrality = cen(A_i) = od(A_i) + id(A_i). \tag{9}$$

3.2.2 | FBWM

In MCDM methods, the calculation begins with n criteria and it aims to obtain a pair-wise comparison on a scale shown in Table 4 as demonstrated in Equation 10:

$$A = \begin{bmatrix} a_{11} & a_{12} & \dots & a_{1n} \\ a_{21} & a_{22} & \dots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{bmatrix}, \tag{10}$$

where a_{ij} represents the relative preference of criterion i to criterion j. Here, the significance of j to i is shown by a_{ji}. a_{ji} is needs to be equivalent to $1/a_{ij}$ as a result, it can be reciprocal (Rezaei, 2015). BWM is divided into reference pair-wise comparisons and secondary pair-wise comparisons (Rezaei, 2015). In this way, an advantage of BWM can be expressed as the required number of pair-wise comparisons can be reduced to $2n-3$ which involves pair-wise comparisons of best criteria to other criteria ($n-2$), pair-wise comparisons of other criteria to the worst criterion ($n-2$) and pair-wise comparisons of the best criterion to the worst criterion (+1). FBWM method is explained as follows (Irannezhad et al., 2021):

Step 1. Discover the DMs and criteria:{C_1, C_2, ..., C_m} is taken into consideration as a set of criteria and {DM_1, DM_2, ..., DM_n} is taken into consideration as a set of DMs.

Step 2. Determine which criteria are the most important (best) and which are the least significant (worst).

Step 3. Apply the scale (see Table 4) to conduct pair-wise comparisons of the best criterion with other criteria seen in Equation 11:

$$A_{Bj} = (a_{B1}, a_{B2}, ..., a_{Bm})(j = 1,2,3,...,m), \quad (11)$$

where a_{Bj} indicates the relative importance value of the best criterion over criterion j.

Step 4. Apply the scale to conduct pair-wise comparisons of the worst criterion with other criteria seen in Equation 12:

$$A_{jW} = (a_{1W}, a_{2W}, ..., a_{mW})(j = 1,2,3,...,m), \quad (12)$$

where a_{jW} represents the relative importance value of criterion j over the worst criterion.

Step 5. Calculate the optimum criterion weights (w_1, w_2, ..., w_n) for each group: $a_{Bj} = w_B/w_j$ and $a_{jW} = w_j/w_W$. The calculated weights are non-negative seen in Equation 13.

$$\begin{aligned} & minimize max_j \left| \frac{w_B}{w_j} - a_{Bj} \right|, \left| \frac{w_j}{w_W} - a_{jW} \right| \\ & subject\ to \begin{cases} \sum_{j=1}^{n} (w_j) = 1 \\ w_j \geq 0\ for all j \end{cases} \end{aligned} \quad (13)$$

Now, the equation can be expressed as in Equation 14 and optimal criteria weights for each group and the value of ξ can be obtained (Sagnak et al., 2021).

$$\begin{aligned} & minimize \xi \\ & subject\ to \begin{cases} \left| \frac{w_B}{w_j} - a_{Bj} \right| \leq \xi, \\ \left| \frac{w_j}{w_W} - a_{jW} \right| \leq \xi, \\ \sum_{j=1}^{n} (w_j) = 1 \\ w_j \geq 0\ for all j. \end{cases} \end{aligned} \quad (14)$$

Step 6. Calculate defuzzified weights (Irannezhad et al., 2021) seen in Equation 15:

$$W_j = \frac{l_j + 4m_j + u_j}{6}. \quad (15)$$

4 | EMPIRICAL STUDY

The evaluation of the study was performed by the five experts working in companies that actively perform CE practices and implement blockchain technology solutions in their supply chains. A survey was prepared to send them. For this purpose, a group decision-making environment was established in which a total of five experts/evaluators, one from each of these five companies, are involved as Irannezhad et al. (2021) suggested. As DMs for this study, experts were selected according to their qualifications, including professional experience, activities, and in-depth knowledge related to blockchain-based CSC. They have an average 13 years of work experience and all obtained master's degrees. The profile of the five experts and their blockchain-based CSC case companies are seen in Appendix A.

First, the FCM method was applied. The FCM determines the initial best and worst criteria for FBWM as the second method. The surveys were conducted using fuzzy linguistic terms with a value ranging from [−1, 1] in Table 3 for causal relationships between CSFs. Next, all received surveys' mean is calculated using arithmetic mean to aggregate the group decision opinion as recommended by Ishikawa et al. (1993) (see Table 5). For this step, Equation 1 is employed. Moreover, the edge matrix seen in Table 6, is calculated by applying the centre of gravity to defuzzify the values. Thus, Equation 2 is used to defuzzify the values. Normalised weights, which can also be considered initial values ($t = 0$), are calculated using the values given in Table 6 and are presented in Table 7. The main final attribute weights in accordance with Equation 4 and Equation 5 are depicted in Equation 16 after obtaining 15 times iterations ($t = 15$) to converge the results. Finally, the indices of each CSF are calculated as in step 5 according to the Equation 7, Equation 8, and Equation 9 as the results are seen in Table 8.

$$I_{CSF} = \begin{matrix} CSF_1 \\ CSF_2 \\ CSF_3 \\ CSF_4 \\ CSF_5 \\ CSF_6 \\ CSF_7 \\ CSF_8 \\ CSF_9 \\ CSF_{10} \end{matrix} \begin{bmatrix} 0.10133 \\ 0.10129 \\ 0.10098 \\ 0.10029 \\ 0.10058 \\ 0.10005 \\ 0.09726 \\ 0.10011 \\ 0.09873 \\ 0.09937 \end{bmatrix}. \quad (16)$$

Looking at the results of the FCM method, the best and worst methods determined to start the FBWM method were determined as CSF1 and CSF7, respectively. In other words, Network Collaboration was chosen as the best criterion, while the Shared CE Toolbox was chosen as the worst criterion. With these values, the survey required to start the FBWM method was filled by the same companies in line with these results by utilising linguistic terms, as seen in Table 4. At this stage, the FBWM application was implemented over IBM ILOG CPLEX Optimisation Studio 12 Software. First, the geometric mean of the surveys was taken to apply the formulation.

The data file for FBWM is illustrated in Table 9. Afterwards, the model file edited according to Section 3.2 is presented in Appendix B. FBWM result is shown in Table 10. For this step, Equation 15 is

TABLE 5 Aggregated dependency degrees among main attributes

	CSF1			CSF2			CSF3			CSF4			CSF5		
CSF#	*l*	*m*	*u*	*L*	*m*	*u*	*l*	*m*	*u*	*l*	*m*	*u*	*l*	*m*	*u*
CSF1	0.90	1.00	1.00	0.46	0.66	0.86	0.54	0.74	0.90	0.48	0.66	0.80	0.54	0.74	0.90
CSF2	0.66	0.86	0.98	0.90	1.00	1.00	0.46	0.66	0.86	−0.16	0.02	0.18	0.14	0.30	0.46
CSF3	0.50	0.70	0.88	0.70	0.86	0.96	0.90	1.00	1.00	0.08	0.22	0.42	0.04	0.20	0.38
CSF4	0.26	0.46	0.66	0.20	0.38	0.58	0.00	0.18	0.36	0.90	1.00	1.00	0.58	0.74	0.84
CSF5	0.66	0.84	0.96	0.38	0.58	0.76	0.10	0.30	0.46	0.44	0.58	0.70	0.90	1.00	1.00
CSF6	0.46	0.66	0.82	0.70	0.86	0.94	0.56	0.70	0.82	0.30	0.46	0.66	0.26	0.46	0.66
CSF7	0.32	0.50	0.70	0.42	0.62	0.78	0.32	0.50	0.70	0.08	0.26	0.42	0.06	0.22	0.42
CSF8	0.12	0.30	0.50	0.16	0.34	0.54	0.22	0.42	0.62	0.06	0.18	0.38	0.00	0.18	0.34
CSF9	0.50	0.70	0.86	0.40	0.58	0.74	0.48	0.62	0.74	0.26	0.46	0.66	0.34	0.50	0.66
CSF10	0.14	0.30	0.50	0.10	0.26	0.46	0.04	0.18	0.38	0.42	0.62	0.80	0.22	0.42	0.62

	CSF6			CSF7			CSF8			CSF9			CSF10		
CSF#	*l*	*m*	*u*	*L*	*m*	*u*	*l*	*m*	*u*	*l*	*m*	*u*	*l*	*m*	*u*
CSF1	0.26	0.46	0.66	−0.04	0.14	0.32	0.24	0.40	0.54	0.16	0.34	0.54	0.34	0.48	0.64
CSF2	0.24	0.42	0.62	0.04	0.20	0.36	0.32	0.50	0.68	0.22	0.38	0.58	0.08	0.22	0.42
CSF3	0.12	0.26	0.46	0.42	0.62	0.82	0.50	0.70	0.88	0.68	0.80	0.86	0.08	0.26	0.46
CSF4	0.12	0.30	0.50	−0.02	0.10	0.22	0.32	0.50	0.70	0.00	0.14	0.30	0.30	0.50	0.70
CSF5	0.06	0.22	0.42	0.04	0.22	0.38	0.06	0.18	0.38	0.10	0.26	0.46	0.40	0.58	0.74
CSF6	0.90	1.00	1.00	−0.02	0.14	0.32	0.12	0.26	0.46	−0.06	0.14	0.32	0.34	0.54	0.70
CSF7	0.06	0.22	0.42	0.90	1.00	1.00	0.02	0.14	0.34	−0.08	0.10	0.26	0.02	0.16	0.34
CSF8	0.10	0.30	0.48	−0.14	0.06	0.20	0.90	1.00	1.00	0.10	0.26	0.46	−0.20	−0.06	0.14
CSF9	0.38	0.58	0.76	0.38	0.54	0.70	0.18	0.38	0.58	0.90	1.00	1.00	0.02	0.18	0.34
CSF10	0.30	0.50	0.68	0.08	0.22	0.38	0.06	0.18	0.38	0.04	0.18	0.38	0.90	1.00	1.00

TABLE 6 The edge matrix: defuzzified values

	CSF1	CSF2	CSF3	CSF4	CSF5	CSF6	CSF7	CSF8	CSF9	CSF10
CSF1	0.97	0.66	0.73	0.65	0.73	0.46	0.14	0.39	0.35	0.49
CSF2	0.83	0.97	0.66	0.01	0.30	0.43	0.20	0.50	0.39	0.24
CSF3	0.69	0.84	0.97	0.24	0.21	0.28	0.62	0.69	0.78	0.27
CSF4	0.46	0.39	0.18	0.97	0.72	0.31	0.10	0.51	0.15	0.50
CSF5	0.82	0.57	0.29	0.57	0.97	0.23	0.21	0.21	0.27	0.57
CSF6	0.65	0.83	0.69	0.47	0.46	0.97	0.15	0.28	0.13	0.53
CSF7	0.51	0.61	0.51	0.25	0.23	0.23	0.97	0.17	0.09	0.17
CSF8	0.31	0.35	0.42	0.21	0.17	0.29	0.04	0.97	0.27	−0.04
CSF9	0.69	0.57	0.61	0.46	0.50	0.57	0.54	0.38	0.97	0.18
CSF10	0.31	0.27	0.20	0.61	0.42	0.49	0.23	0.21	0.20	0.97

TABLE 7 Normalised values for each CSF

	CSF1	CSF2	CSF3	CSF4	CSF5	CSF6	CSF7	CSF8	CSF9	CSF10
Normalised	0.12	0.10	0.12	0.09	0.10	0.11	0.08	0.07	0.12	0.09

TABLE 8 Dominance of CSFs

	CSF1	CSF2	CSF3	CSF4	CSF5	CSF6	CSF7	CSF8	CSF9	CSF10
$od(A_i)$	6.23	6.06	5.25	4.45	4.71	4.27	3.19	4.30	3.61	3.87
$id(A_i)$	5.55	4.53	5.59	4.27	4.72	5.16	3.74	2.99	5.47	3.91
$cen(A_i)$	11.79	10.59	10.84	8.72	9.43	9.43	6.93	7.29	9.08	7.79

TABLE 9 Data file for IBM ILOG CPLEX optimisation studio

	Best			Worst		
CSF#	*l*	*m*	*u*	*l*	*m*	*u*
CSF1	1.0	1.0	1.0	2.0	2.5	3.0
CSF2	2.3	2.8	3.3	1.9	2.2	2.5
CSF3	2.6	3.1	3.6	3.3	3.8	4.3
CSF4	1.9	2.4	2.9	2.0	2.6	3.1
CSF5	1.3	1.6	2.0	1.4	1.7	2.1
CSF6	0.9	1.1	1.4	0.9	1.3	1.8
CSF7	2.0	2.5	3.0	1.0	1.0	1.0
CSF8	1.3	1.4	1.5	1.0	1.3	1.7
CSF9	2.4	2.9	3.4	2.9	3.4	3.9
CSF10	1.4	1.6	1.9	1.4	1.9	2.4

TABLE 10 The final weights

CSF#	*l*	*m*	*u*	Defuzzification
CSF1	0.14	0.15	0.17	0.15
CSF2	0.07	0.08	0.09	0.08
CSF3	0.06	0.07	0.08	0.07
CSF4	0.08	0.09	0.11	0.09
CSF5	0.12	0.13	0.14	0.13
CSF6	0.10	0.11	0.13	0.11
CSF7	0.03	0.04	0.04	0.04
CSF8	0.10	0.11	0.12	0.11
CSF9	0.07	0.08	0.09	0.08
CSF10	0.12	0.13	0.15	0.13

applied for defuzzification. The defuzzified values are also demonstrated in Table 10.

As the final step of FBWM, the prioritisation result of CSFs for implementing a successful blockchain-based CSC is demonstrated as follows. This also answers the research question 2:

CSF1 > CSF10 > CSF5 > CSF6 > CSF8 > CSF4 > CSF2 > CSF9 > CSF3 > CSF7.

5 | DISCUSSION

This study considers the CSFs for blockchain-based CSC. Based on the findings, CSF1, network collaboration, is the first. Ajwani-Ramchandani, Figueira, de Oliveira, and Jha (2021) highlighted that the consumption of resources, including adapting operations to generate the minimum waste, could be improved by tracking and analysing data using blockchain ledgers and changing inventory. Moreover, as Yadav and Singh (2020) stated, blockchain offers excellent management and horizontal and vertical collaboration. CSF10, Environmental Performance and Global Resource Deployment, comes as the second. As it was also stated by Wang et al. (2020), blockchain can greatly help CSC management by accelerating resource deployment, lowering usage and wastage, and improving CSC resiliency, including adaptability. CSF5, which is Sustainability and Circularity Behaviour, is the third. Blockchain enhances the three pillars of sustainability, clean manufacturing, energy management, reusing and recycling, environmentally acceptable resources, or rather behaviour (Bressanelli et al., 2021). It concentrates on upstream to help offset barriers such as the absence of capturing, categorising, and recycling, real-time monitoring (Yildizbasi, 2021) and tracing challenges (Ajwani-Ramchandani, Figueira, de Oliveira, & Jha, 2021), whilst also lowering the expense of third-party guidance. CSF6, which is Open Innovation and Co-Creation Platform, comes next. The blockchain-based strategy allows cooperative stakeholders to collaborate in developing product life cycle stages, such as co-design and co-creation, fast and precise data monitoring and traceability (Bekrar et al., 2021), proactively upkeep and controlled recycling (Dzhuguryan & Deja, 2021). CSF8, Product Life Cycle Visibility and Audit, is obtained as the fifth. The cooperation with the support of blockchain enables a rapid, safe, as well as easily available communications system (Shojaei et al., 2021) by offering a distributed ledger (Demestichas & Daskalakis, 2020) in which the origin of materials as well as products, the energy used during the production, and also the source of energy utilised throughout the life cycle can be linked back to the sources (Esmaeilian et al., 2020). CSF4, which is Regulations for Incentives, Recognition, and Rewards, is the sixth CSF. By proposing creative regulation proposals to the government, blockchain may include incentives and support campaigns and solve administrative problems as Yildizbasi (2021) stated. CSF2, which is Many-to-Many Supply Chain Connectivity, comes as the seventh CSF. By increasing the degree of integration throughout supply chains, including diverse teammates, Rehman Khan et al. (2021) stated that supply chain stakeholders might have greater governance of the performance of inventory, resource utilisation, and CE operations through the visibility and accessibility of interactions in blockchain. CSF9, which is Data Ownership and Control, is obtained as the eighth CSF. By integrating the safe data gathering to coordinate and transfer this kind of information, blockchain can manage the interpersonal relationships necessary to network construction and general agreement necessary to support CE business strategies (Narayan & Tidström, 2020). CSF3, which is Technology Standardisation, is the ninth. As Nandi, Sarkis, et al. (2021b) expressed, inter-firm blockchain adoption necessitates pre-defined guidelines, regulations, including strong governance mechanisms to explain activities, offer data uniformity, minimise disputes, and lessen CE complications. CSF7, the Shared CE Toolbox, comes as the last CSF. The fact that this CSF is the last can be interpreted as follows: CE activities are successfully implemented due to the success factors in a blockchain-enabled CSC. Furthermore, as Magrini et al. (2021) highlighted that blockchain hubs have the prospects to be implemented at every essential extent in the supply chain, offering the structure of a decentralised and therefore shared database in which all stakeholders can trustfully hold as well as start securely sharing information.

6 | IMPLICATIONS

6.1 | Implications for theory

Because of the embryonic nature of blockchain (Esmaeilian et al., 2020) and the dearth of use cases in the CE realm (Andersen & Jæger, 2021), this paper attempts to contribute to theory by identifying the CSF for blockchain-enabled CSCs and their relative importance. This study provides three important contributions. First, the investigation revealed the potential CSF for adopting blockchain to promote circularity. Considering the tremendous human and environmental implications related to managing supply chain waste, a linear strategy is not desired; nevertheless, the integration of blockchain can make a circular approach more feasible. Although the extant literature (Ajwani-Ramchandani, Figueira, de Oliveira, & Jha, 2021; Magrini et al., 2021) has emphasised why a CE will not be achieved, it stays mute on the factors necessary to develop blockchain-enabled CSCs. This research demonstrated that a greater degree of collaboration among supply chain partners is required to attain circularity in the blockchain ecosystem. So far, supply chains are recognised for their extremely fragmented, complex, and inefficient nature (Zhang, 2021), which is viewed as one of the primary impediments in CE realisation (Leising et al., 2018). Consequently, we argue that network collaboration is vital to integrate blockchain and thus to narrow and close the loops of resource flows in the supply chain. Blockchain brings CSC partners efficient information exchange and transparent process coordination (Kouhizadeh et al., 2019). In contrast to conventional supply chains, CSCs necessitate novel collaboration and cooperation approaches throughout the supply chain. As a result, firms should innovate and invest in blockchain to develop long-lived and environmentally friendly products, thereby facilitating the implementation of the 9Rs.

Second, in this study, we clarify how blockchain technology can optimise environmental performance, increase sustainability, and support circular behaviour. Consistent with Khan, Razzaq, et al. (2021), we found that blockchain enhances CE practices, stimulating organisations' financial and environmental performance and ultimately translating into better firm performance. Data associated with production, consumption, and output emissions can be simply exchanged and integrated to assess the environmental performance of circular products. Based on blockchain, trustworthy data sources enable people to assess the environmental implications of waste emissions from the product life cycle perspective. These data are insightful and useful in decision-making and strategic policies for controlling waste. The evidence in this study corroborates Gassmann et al. (2014), who argued that the essential innovation potential rests not in products or processes alone but innovative business models. Technological innovations and solutions like blockchain can further boost CE, sustainability, and overall supply chain resilience (Nandi, Sarkis, et al., 2021a). Integrating blockchain in CSCs can successfully create shared value, promote innovation, and generate novel ideas. The technology can also incentivise collaborative efforts within the CSC. Similarly, blockchain offers the necessary data integration for circular product design and innovation by enabling transparent, secure, and streamlined information flows.

Third, our study stressed the importance of regulations and government incentive programs to facilitate the integration of blockchain in the CSC. This finding is echoed in the empirical study by Erol et al. (2021), where the authors argued that blockchain implementation for CE requires the government to enact new regulations and offer educational and financial support to firms in the energy sector. In turn, blockchain can provide the required assistance to develop legal systems and strengthen environmental legislation as transparency constitutes a major problem for incentive systems and taxation. Consequently, CSC can be successfully established via suitable laws, regulations, and policies. For example, in the energy sector, Zhu et al. (2020) posited that blockchain could be utilised to better regulate energy transactions; however, without an adequate regulation policy environment, the technology cannot achieve substantial development. In the CSC, interconnectivity is critical in fostering economic performance and sustainable development goals (Hoosain et al., 2020). Thus, it is essential to develop information models for integrated CSC management for CE to ensure interoperability and interconnectivity between supply chain systems and stakeholders in the entire product life cycle (Liu et al., 2020). Unless the blockchain discourse indicates its connection to concerns such as technological security and interoperability (Khan, Zia-ul-haq, et al., 2021), there is a likelihood that the technology will not find the necessary support to succeed in the CE.

6.2 | Implications for practice

The importance of cooperative networks is also underlined, because circularity is difficult to attain without collaboration (Alexandris et al., 2018). Thus, managers should focus on collaboration to address the challenge of supply chain transparency, which necessitates stakeholder collaboration and the deployment of technology solutions to facilitate the transition so, in this context, blockchain is a relatively new idea that has generated much excitement and offers to alter status quo processes in a variety of sectors and supply chains (Rusinek et al., 2018). Collaboration and coordination are pivotal to realising the system-wide objectives of blockchain in CSC. Involvement and collaboration are recommended at all stages and levels of the blockchain-enabled CSC as this allows organisations to offer an extended value proposition to their customers. Implementing blockchain may become a cost-effective effort marked with diminished performance when one partner fails to collaborate with other CSC members. As a result, organisations should take the initiative to cooperate with their stakeholders to make the greatest use of blockchain and to create a win-win situation for all members. Managers should also be aware that conventional firms are incorporating resource recovery requirements in collaboration as they are also transitioning to digital platforms (Guyot Phung, 2019). Waste exchange systems are crucial features of industrial symbiosis because they need collaboration to solve environmental performance and enhance global resource deployment (CSF10) (Kouhizadeh et al., 2019).

Moreover, lack of collaboration and efficient communication between supply chain networks, sometimes opposing business aims and values hamper the sustainability of supply chain operations (CSF5), as well as blockchain deployment to build sustainability benefits (Saberi et al., 2019). In addition, collaboration impacts product lifetime and is closely related to the ownership notion (CSF9) (Vogel et al., 2019). How blockchain technology may be used to suit specific industry demands and how possible obstacles and problems can be recognised and handled via significant concentrations of inter-organisational collaboration (Kouhizadeh et al., 2020). As open and accessible data are the basis for creating diverse resource and material flows, blockchain may provide data share as well as collaboration platforms that are fundamental to a Shared CE Toolbox (CSF7) (Boeckel et al., 2021). As can be seen from here, network collaboration has an enabler effect on most CSFs. For this reason, its importance as CSF is very evident.

Finally, our study would urge managers to reconsider the antecedents of successful blockchain implementation in their CSCs to face the increasing competition and persist in this highly turbulent business world. DMs should also be cautious when embracing this novel technology and leveraging its capabilities to motivate their members to engage in digital CE activities.

7 | CONCLUSIONS

The main objective of this research study is to investigate the CSFs for blockchain-based CSC. Even though previous research gives a full overview of blockchain-related potential and challenges in the CE, few studies concentrate on adopting the technology in CSCs, and no study has yet examined the CSF and their relative importance for blockchain-enabled CSCs. First of all, a literature study was conducted, and the 10 most emphasised CSFs were determined. Then, a survey was prepared to examine these found CSFs following the FCM method, and a second survey was prepared following the FBWM method following the result of the FCM method. The novelty of this study can be specified as the integrated FCM-FBWM approach. Five companies actively implementing blockchain were included in this survey assessment. Afterward, an integrated FCM-FBWM study was carried out and the best-worst criteria necessary to start FBWM study were determined with FCM, then FBWM method was applied using IBM ILOG CPLEX Optimisation Studio 12 Software by using FCM results. Unlike other pair-wise comparison methods, this approach allows fewer comparisons and more reliable and consistent findings.

Moreover, FBWM can manage the ambiguity and imprecision in judgments of experts. Through FCM, we were able to include feedback loops among the tasks. In line with the results, CSF1, that is, network collaboration was the best criterion, while the Shared CE Toolbox, which was CSF7, was the worst criterion. Thus, considering them one by one is vital to successfully implementing blockchain technology into the CSC. The evaluation of this CSF for blockchain-enabled CSC represents a decision-making procedure. The suggested model can distinguish more important CSFs among the many CSFs, thereby helping us to understand how the adoption of blockchain in CSC is an arduous decision that often entails significant changes to network collaboration, control and coordination mechanisms, organisational structure, regulations, and reward systems. In addition, we demonstrate how obtained findings can support managers in identifying the CSFs that demand special attention during their engagement in CSCs. Identifying the actual CSF will assist managers in better comprehending the best practices that can be pertinent in their context as they intend to develop CSCs.

The above CSFs are just a few examples of the elements playing a vital role in the successful implementation of blockchain in the CSC. The CSC needs further research to examine the barriers hampering the integration of blockchain in CE activities and how these barriers can be overcome one by one to ensure successful technology adoption. Moreover, additional studies and evidence are required to ascertain the extent to which CSFs impact the overall performance of firms adopting blockchain in their CE initiatives and convert potential technology challenges into opportunities. Once concrete use cases are developed in CSCs, organisations should incorporate the best lessons and practices learned from blockchain implementations to leverage the transition toward CE.

The limitation of this study can be stated as not examining the interaction between CSFs. We admit that the paucity of peer-reviewed publications and the number of data sources covered could be an issue in this paper. Furthermore, the theoretical aspect of research could also be another shortcoming. However, we believe that the field's immaturity, limited data sources, and the low number of theoretical studies on blockchain adoption in CSCs make our study a valuable contribution to this rapidly growing literature. In this respect, the relationship between CSFs in future research can be handled by applying the Total Interpretative Structural Modelling (TISM) method.

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CONFLICT OF INTEREST

There is no conflict of interest to be declared.

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APPENDIX A: PROFILE OF THE INDUSTRY EXPERTS AND BLOCKCHAIN-BASED CSC CASE COMPANIES

#	Profile of expert	Experience	Case-company	Sector	CE practices
1	Purchasing manager	14 years	Chemical producer	Chemical	Recycle
2	Operations director	10 years	Plastic producer	Plastic	Recycle
3	Quality manager	14 years	Multinational clothing company	Textile	Recycle, reuse
4	Production manager	9 years	Electric-vehicle-battery manufacturer	Battery	Recycle, repurpose
5	Supply director	16 years	Furniture manufacturer	Retail	Reuse, repurpose

APPENDIX B: THE MODEL FILE

```
/*********************************************
 * OPL 12.10.0.0 Model
 * Author:
 * Creation Date: 9 Ara 2021 at 10:48:56
 *********************************************/
int n = ...;
range j = 1..n;

float BL[j]= ...;
float BM[j]= ...;
float BU[j]= ...;
float WL[j]= ...;
float WM[j]= ...;
float WU[j]= ...;

dvar float+ L[j];
dvar float+ M[j];
dvar float+ U[j];
dvar float+ k;

minimize k;

subject to{

  forall (b in j)
    abs (L[1] - BL[b] * U[b]) <= k;

  forall (b in j)
    abs (M[1] - BM[b] * M[b]) <= k;

  forall (b in j)
    abs (U[1] - BU[b] * L[b]) <= k;

  forall (b in j)
    abs (L[b] - WL[b] * U[7]) <= k;

  forall (b in j)
    abs (M[b] - WM[b] * M[7]) <= k;

  forall (b in j)
    abs (U[b] - WU[b] * L[7]) <= k;

   (sum(b in j) L[b]/6) + (sum(b in j) (M[b]*4)/6) + (sum(b in j) U[b]/6) == 1;

   forall (b in j)
     L[b] >= 0;
   forall (b in j)
     L[b] <= M[b];
   forall (b in j)
     M[b] <= U[b];
     k >= 0;
     }
```