

RESEARCH ARTICLE

Enabling organizations to strategically manage risks in circular supply chains

Mladen Krstić¹ | Leonardo Agnusdei²  | Pamela Palmi³ | Tomas Baležentis⁴ 

¹Logistics Department, Faculty of Transport and Traffic Engineering, University of Belgrade, Belgrade, Serbia

²Department of Innovation Engineering, University of Salento, Lecce, Italy

³Department of Economic Sciences, University of Salento, Lecce, Italy

⁴Faculty of Economics and Business Administration, Vilnius University, Vilnius, Lithuania

Correspondence

Leonardo Agnusdei, Department of Innovation Engineering, University of Salento, Via Monteroni Snc, 73100 Lecce, Italy.
Email: leonardo.agnusdei@unisalento.it

Abstract

Circular supply chains (CSCs) prioritize resource efficiency by reusing, remanufacturing, and recycling materials, offering environmental benefits and competitive advantages. However, they are facing various risks and organizational challenges that hinder their efficiency. To ensure long-term sustainability, this study identifies the key risks and introduces a prioritization model for risk management in CSC strategies proposing a framework for the risk evaluation based on the set of criteria and prioritization model using a combination of three multicriteria decision-making (MCDM) methods. The model applies fuzzy Delphi-based analytical hierarchy process (AHP) method to determine the criteria weights and fuzzy axial distance-based aggregated measurement (ADAM) method for ranking the alternatives. The findings of this study allow for the identification of the most important risks associated with CSC enabling stakeholders to allocate resources strategically and focus efforts on crucial areas. Results highlight that the most important risks are supply chain complexity, resource availability, and quality and technological challenges. The most important contributions are the identification of the most relevant risks that threaten the resilience and sustainability of CSCs, the establishment of the framework for their evaluation, and the development of a novel hybrid MCDM model for their ranking. These contributions are also the main theoretical implications of the study. On a practical level, it enables organizations to strategically manage risks, standardize risk assessment, and improve their competitive advantage by enhancing resilience, reducing disruptions, and lowering operational costs.

KEYWORDS

circular economy, multicriteria decision analysis, resilience, risk management, supply chain management

1 | INTRODUCTION

Circular supply chains (CSCs), also known as closed-loop supply chains, represent a revolutionary shift in the way goods and materials

flow through the economy. Unlike traditional linear supply chains, which follow a “take, make, dispose” model, CSCs are designed to minimize waste and maximize resource efficiency. In a CSC, products and materials are continually reused, remanufactured, and recycled,

Abbreviations: ADAM, axial distance-based aggregated measurement; AHP, analytic hierarchy process; ANP, analytical network process; CI, consistency index; CR, consistency ratio; CRITIC, criteria importance through intercriteria correlation; CSC, circular supply chain; DEMATEL, decision making trial and evaluation laboratory; EPR, extended producer responsibility; Gov, government; ITARA, indifference threshold-based attribute ratio analysis; LFPP, logarithmic fuzzy preference programming; LSP, logistics service providers; LSU, logistic service users; MACONT, mixed aggregation by comprehensive normalization technique; MCDM, multicriteria decision-making; MOORA, multi-objective optimization on the basis of ratio analysis; ROI, return on investment; TOPSIS, technique for order of preference by similarity to ideal solution; WENSLO, weights by envelope and slope; WISP, weighted sum-product; WPM, weighted product model.

creating a sustainable and regenerative system. CSCs are at the forefront of the transition toward a more sustainable and responsible global economy.

However, like linear supply chains, CSC can face various challenges and risks. Managing these risks and ensuring a smooth transition to CSCs is essential for companies and organizations looking to reap the long-term benefits of sustainability and resource efficiency. By prioritizing risks, companies can allocate resources and focus their attention on the most critical areas, ultimately enhancing the resilience and sustainability of their CSC processes. The main objectives of this study are to identify the key risks within the context of CSC and introduce a comprehensive model that takes into account various factors in an attempt to prioritize them. This prioritization approach will provide organizations with a structured, data-driven methodology to proactively manage and mitigate risks, ensuring the successful implementation of CSC strategies while promoting environmental and economic sustainability.

Adequate prioritization and ranking of risks in the supply chain requires a comprehensive analysis of a number of measures that can reduce the likelihood of risk occurrence, mitigate its severity, or enable rapid response and recovery, if it does occur. Accordingly, in this paper, the risks are evaluated in relation to a set of preventive, protective, and corrective measures. To solve this multicriteria decision-making (MCDM) problem, a new model is proposed in the study. The proposed hybrid model integrates the Delphi, analytic hierarchy process (AHP), and the axial distance-based aggregated measurement (ADAM) methods within a fuzzy environment. The Delphi method facilitates expert consensus on the initial identification and assessment of risk factors and allows for the unification of various evaluations. Subsequently, the AHP framework structures the hierarchical relationships among these factors and derives pairwise comparisons to determine their relative importance. The ADAM method ranks the risks according to the provided evaluations and obtained criteria weights. This hybrid MCDM model not only offers a structured and systematic approach for risk prioritization but also considers the uncertain aspects of CSCs, making it a robust and practical tool for organizations seeking to navigate the complexities of sustainability while managing associated risks. Through this methodological approach, this study aims to contribute to the burgeoning field of CSCs by providing a valuable tool for risk assessment and management, ultimately facilitating the transition toward a more sustainable and resilient circular economy.

The applicability and effectiveness of the model was demonstrated by solving a case study that involved the evaluation and ranking of seven risks in relation to nine criteria. Results indicated that the most important risks are supply chain complexity, resource availability and quality, and technological challenges. The most important contributions of the study lie in identifying the most critical risks, which allows stakeholders to strategically allocate resources and focus efforts on the most vital ones, ultimately strengthening the resilience and sustainability of CSC operations. This study also makes a significant contribution by establishing a framework for risk evaluation and ranking. This not only allows for the identification of the key risks within a supply chain but

also provides criteria for prioritizing them based on their potential impact. Finally, another important contribution is the development of a novel hybrid MCDM model, which combines Delphi, AHP, and ADAM methods in a fuzzy environment. The remainder of the study is organized as follows. The next section provides background of the study corroborated with the appropriate literature. Afterwards, the main elements of the problem are explained: CSC risks as the alternatives, criteria for their evaluation and ranking, and stakeholders interested in finding a solution. The fourth section provides the detailed description of the newly developed MCDM model, while the fifth provides the results obtained from its application. The sixth section provides a discussion of the obtained results through the contributions, limitations and implications of the study. The final section provides concluding remarks and future research directions.

2 | THEORETICAL BACKGROUND

CSCs have garnered significant attention in recent years as a response to the growing global concern over resource scarcity, environmental degradation, and the need for sustainable economic development (Amir et al., 2023). A wealth of literature has emerged, exploring various aspects of CSCs, from design and management (e.g., de Lima et al., 2022) to their impact on sustainability metrics (e.g., Calzolari et al., 2022), from new business models (e.g., Geissdoerfer et al., 2020) to overall business performance (e.g., Farooque et al., 2022). This body of research underscores the importance of understanding the complexities and nuances associated with CSCs in today's global economy, shedding light on their potential to drive not only environmental benefits but also economic gains (Kiss et al., 2019).

This study contributes to this growing body of knowledge in this field by examining the integration of circular principles in a specific industry context, aiming to offer insights and practical implications for companies embarking on the circular journey. While the shift toward CSCs holds immense promise, it is essential to recognize that they are not without their share of risks and challenges. Commonly investigated risks encompass product quality and safety concerns in recycling and remanufacturing processes (Fofou et al., 2021), the uncertainty surrounding the availability and quality of recycled materials (Marcos et al., 2021), fluctuations in commodity prices, regulatory and policy changes (Mancheri et al., 2019), and the need for substantial investments in new technologies and infrastructure (Ada et al., 2021). Additionally, CSCs often entail more complex and interconnected networks, raising the risk of disruptions due to transportation issues, supplier reliability, and logistical bottlenecks (Rezaei et al., 2021). Understanding these risks and their potential impact is crucial for organizations seeking to embrace circularity while simultaneously protecting their bottom line and reputation. This study aims to contribute to the existing knowledge by analyzing and providing insights into specific risks within the context of CSCs, helping organizations navigate these challenges effectively and enhance their sustainability initiatives.

While existing research has provided valuable insights into the identification of these risks, there is a growing need for a systematic framework to evaluate and prioritize them based on their potential impact and likelihood. Efficient supply chain management requires identifying and prioritizing risks quickly and effectively (Abdel-Basset et al., 2019). Not all risks can be addressed simultaneously due to limited resources. Prioritizing risks involves selecting the most significant ones, that is, those with the greatest impact on the supply chain's success or those that can be resolved most efficiently. This approach helps supply chain participants make informed decisions about allocating their resources for risk management. Prior research has employed a variety of tools and techniques to prioritize risk in supply chains, including risk matrices or heat maps (Amalia et al., 2021), risk scoring (Handfield et al., 2020), criticality analysis (Colon et al., 2021), and failure mode and effect analysis (Zhu et al., 2021). Nonetheless, most studies have applied diverse MCDM methods to prioritize risks in supply chain management, such as AHP (Khan, Alam, et al., 2022), TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution) (Chatterjee & Kar, 2013), or combination of methods such as AHP and DEMATEL (Decision-Making Trial and Evaluation Laboratory) (Mzougui et al., 2020), ANP and DEMATEL (Thakkar & Thakkar, 2021), ANP and MOORA (Multi-Objective Optimization method on the basis of Ratio Analysis) (Chand et al., 2015), and TOPSIS and CRITIC (CRiteria Importance Through Intercriteria Correlation) (Rostamzadeh et al., 2018). To achieve the objective of prioritizing and ranking risks within CSCs, this study employs a novel and comprehensive methodology. Recognizing the complex and multifaceted nature of these risks, this study proposes a novel hybrid MCDM model that integrates the Delphi, AHP, and ADAM methods within a fuzzy environment.

3 | CSC RISK PRIORITIZATION

CSC risk prioritization requires the careful identification of risks, the selection of the appropriate criteria for their evaluation, and the involvement of the stakeholders interested in problem solving process.

3.1 | CSC risks

Global supply chains are becoming increasingly complex and thus more exposed to various risks. CSCs are particularly sensitive to these risks due to the specificity of the goods and materials flows within them, complex operations uncommon for linear supply chains, the number and structure of participants, and the relationships between said participants. Accordingly, the management of CSCs is a demanding undertaking that requires a proactive approach in order to identify these risks and assess their impact. The identified risks are described below. These are comprehensive risks that are normally present in supply chains, but in this study, they are viewed from the aspect of circularity, that is, the degree of negative impact on the establishment, functioning, management, and control of CSCs.

3.1.1 | Resource availability and quality (R_1)

Circular economy practices rely on the recycling and reuse of materials. The availability and quality of recycled materials can be inconsistent, which can pose challenges for supply chains that depend on these materials. Variability in recycled material quality can affect product quality and reliability. The main aspects of this risk include resource scarcity (e.g., Althaf & Babbitt, 2021), material contamination (e.g., Briassoulis et al., 2021), inconsistent material streams (e.g., Chen et al., 2022), dependency on collection infrastructure (e.g., Kanike, 2023), competition for high-quality resources (e.g., Villalba-Eguiluz et al., 2023), and quality control and traceability (e.g., Wu, 2022).

3.1.2 | Supply chain complexity (R_2)

CSCs can be more complex than linear supply chains, involving additional steps for collection, disassembly, and refurbishment. Complexity can increase the risk of operational disruptions. This organizational complexity is a consequence of multistage operations (e.g., Hazen et al., 2021), diverse material flows (e.g., Centobelli et al., 2022), reverse logistics (e.g., Zatrochová et al., 2021), the need for quality assurance (e.g., de Lima et al., 2022), demanding inventory management (e.g., Awan et al., 2022), keeping track of sustainability metrics (e.g., Chang Chien & Chen, 2023), and the need for extensive collaboration (e.g., Aarikka-Stenroos et al., 2022).

3.1.3 | Regulatory compliance (R_3)

Circular economy practices may be subject to specific regulations related to recycling, waste management, and environmental standards. Companies operating in CSCs need to navigate these regulations, which can vary by region. Main regulatory aspects include environmental regulations (e.g., Kazancoglu et al., 2021), product regulations (e.g., Wilson & Goffnett, 2022), waste management laws (e.g., Hemidat et al., 2022), recycling and material recovery regulations (e.g., de Lima et al., 2022), sustainability reporting (e.g., Opferkuch et al., 2021), consumer protection (e.g., Mak & Terryn, 2020), packaging regulations (e.g., Pascall et al., 2022), extended producer responsibility (EPR) (e.g., Diggle et al., 2023), ethical and labor standards (e.g., Kosanoglu & Kus, 2021), and import and export regulations (e.g., Barrie & Schröder, 2022).

3.1.4 | Consumer acceptance (R_4)

Circular economy initiatives often require changes in consumer behavior, such as returning products for recycling or accepting refurbished goods. Consumer acceptance and willingness to participate can be uncertain, impacting the success of CSCs (Wang et al., 2013). The main factors that influence the acceptance include the following: behavioral change (e.g., Arora & Dhama, 2023), perceived value,

product familiarity, trust and quality assurance (e.g., Zhu et al., 2022), consumer education, convenience and accessibility (e.g., Tunn et al., 2019), pricing and affordability (e.g., Konietzko et al., 2020), and marketing and branding, consumer engagement, and cultural and regional variations (e.g., Minton et al., 2018).

3.1.5 | Technological challenges (R₅)

Implementing circular economy practices often involves advanced technologies for disassembly, recycling, and remanufacturing (Kocabasoglu-Hillmer et al., 2023). These technologies can be expensive and may require significant investments and expertise. The main factors affecting risks associated with the technological challenges are product design for circular practices (e.g., Wang et al., 2022), disassembly and material recovery technologies characteristics (e.g., Agnusdei, Krstić, & Miglietta, 2023), quality control and testing (Akano et al., 2021), data management and traceability requirements (Centobelli et al., 2022), recycling and material sorting (Wilts et al., 2021), energy efficiency, consumer engagement technologies characteristics, supply chain visibility, cross-industry collaboration, regulatory compliance tools requirements, and scalability.

3.1.6 | Economic viability (R₆)

Transitioning to a circular economy can require significant upfront investments, and the economic viability of circular practices may not be immediately evident. Companies need to carefully assess the long-term financial sustainability of CSCs. Most important aspects of this risk refer to upfront investment (e.g., Ozkan-Ozen et al., 2020), operational costs (e.g., Khan, Chowdhury, et al., 2022), pricing challenges, market demand, economies of scale (e.g., Govindan et al., 2020), profit margin pressures, return on investment (ROI) (e.g., Ethirajan et al., 2021), and competitive advantage.

3.1.7 | Social and ethical concerns (R₇)

Circular economy practices may involve labor-intensive processes, such as disassembly and refurbishment. Ensuring fair labor practices and ethical sourcing can be challenging. This risk is affected by labor implications, job creation, and displacement (Schröder, 2020), labor standards, health and safety standards, resource communities (Schröder et al., 2020), consumer equity, product accessibility, global supply chain ethics, consumer awareness, and cultural and social acceptance (Ki et al., 2021).

3.2 | Risk prioritization criteria

Criteria for the evaluation and ranking of the risks are divided into three main groups, namely, preventive measures, protective measures

and corrective measures (Krstić et al., 2023). Preventive measures include the following: possibility of risk prediction, possibility of risk prevention, and possibility of preparation for the risk.

Possibility of risk prediction (C₁) assesses the ability to foresee and anticipate potential risks within a supply chain. It plays a fundamental role in risk management as it enables organizations to prepare for, protect against or correct issues that might otherwise disrupt the supply chain. It involves data collection, analysis, scenario planning, and the integration of predictive insights into decision-making processes to enhance supply chain resilience.

Possibility of risk prevention (C₂) assesses an organization's ability to proactively take measures that prevent the occurrence of risks within the supply chain. It focuses on strategies and actions that reduce the likelihood of risks happening in the first place. It involves a combination of risk assessment, preventive planning, resource allocation, and ongoing monitoring to reduce the likelihood of disruptions.

Possibility of preparation for the risk (C₃) assesses an organization's ability to prepare and plan for potential risks within the supply chain. It focuses on readiness and readiness measures that can help mitigate the effects of a risk should it occur. By identifying potential risks and developing tailored preparedness plans organizations can enhance their ability to respond to risks and minimize their impact on supply chain operations. Effective preparation contributes to greater supply chain resilience and continuity.

Protective measures include the following: possible degrees of risk mitigation, flexibility of the supply chain protection, and complexity of the supply chain protection.

Possible degree of risk mitigation (C₄) assesses the extent to which an organization can reduce or minimize the impacts of a risk when it occurs within the supply chain. It focuses on the effectiveness of measures and strategies put in place to mitigate the consequences of a risk. It involves a holistic approach to risk management, including proactive planning, resource allocation, and the implementation of strategies that enable the supply chain to respond effectively when risk events occur. An effective risk mitigation capability contributes to supply chain stability and continuity.

Flexibility of the supply chain protection (C₅) assesses the ability of an organization's supply chain protection strategies to adapt quickly and effectively to changes induced by the occurrence of a risk. It focuses on the supply chain's resilience and capacity to absorb disruptions and continue operations. It involves proactive planning, resource allocation, technology utilization, and collaborative efforts to ensure that the supply chain can quickly adapt to changes and continue to deliver products and services to customers, even when faced with unexpected challenges.

Complexity of the supply chain protection (C₆) assesses the level of complexity involved in an organization's supply chain protection strategies. It focuses on how intricate or challenging it is for the supply chain to adjust to changes induced by the occurrence of a risk. Organizations must carefully consider the balance between the complexity of supply chain protection measures and their effectiveness. While complex strategies may provide robust protection, they can also require significant resources and expertise to manage. Striking the

right balance between complexity and practicality is crucial for building a resilient and adaptive supply chain.

Corrective measures include degrees of possible damage remediation, correction time, and correction resources.

Degree of possible damage remediation (C_7) assesses an organization's ability to address and remedy the consequences of damage caused by the occurrence of a risk within the supply chain. It focuses on the extent to which the supply chain can recover and return to normal operations following a disruption. It involves a combination of damage assessment, development of recovery plans, backup systems, and infrastructure to minimize the impact of damage and expedite the return to normal operations.

Correction time (C_8) assesses the time required to rectify and remedy the consequences of damage or disruptions caused by a risk event within the supply chain. It focuses on the speed and efficiency with which the supply chain can recover and return to normal operations. It involves timely responses, pre-established procedures, alternative sourcing, and post-event evaluation to minimize the duration of disruptions and maintain the stability of the supply chain.

Correction resources (C_9) assesses the resources, primarily financial, but also including human and technological resources, required to rectify and remedy the consequences of damage or disruptions caused by a risk event within the supply chain. It focuses on the allocation and availability of resources to support the correction process effectively. Adequate resources support the efficient execution of corrective actions, minimize the duration of disruptions, and contribute to the overall resilience and stability of the supply chain.

3.3 | Stakeholders

Stakeholders hold varying perspectives on the elements of the defined problem and on the significance of the criteria, aligning with their respective goals and viewpoints. Each stakeholder group has unique perspectives, needs, and goals when it comes to prioritizing CSC risks. This study considers the input from three distinct stakeholders, namely, logistics service providers (LSP), logistics service users (LSU), and government (Gov.).

LSPs are businesses primarily engaged in offering a comprehensive range of services encompassing order processing, transportation, warehousing, inventory management, and packaging, essentially delivering a holistic logistics solution to optimize supply chain performance effectively. They play a critical role in enabling CSCs. They are responsible for the transportation, storage and management of materials and products within the supply chain. They require supply chain protection strategies that can adapt quickly to minimize the impact of risks. Assessing the economic sustainability of circular practices helps LSPs determine the feasibility of providing their services to CSCs. The most important criteria from their perspective are possible degree of risk mitigation (C_4), flexibility of the supply chain protection (C_5), and complexity of the supply chain protection (C_6).

LSUs encompass suppliers, producers, manufacturers, wholesalers, retailers, and processors within supply chains, relying on

logistics services to facilitate the core functions of their operations. They are organizations or companies that rely on logistics services to manage their CSCs. Their perspective centers on achieving their circularity goals while maintaining cost-effectiveness and product quality. The most important criteria for the prioritization of risks are possibility of risk prediction (C_1), possibility of risk prevention (C_2), and degree of possible damage remediation (C_7).

Government includes administration on various levels, national, regional, or local. Government bodies are responsible for regulating and overseeing various aspects of CSCs. They aim to promote sustainability, protect the environment, and ensure compliance with laws and regulations. Governments prioritize environmental protection and sustainability. They want to reduce resource consumption, minimize waste, and lower carbon emissions. The most important criteria from the governmental perspective are possibility of risk prediction (C_1), possible degree of risk mitigation (C_4), and correction resources (C_9).

4 | METHODOLOGY

The proposed hybrid MCDM model combines Delphi, AHP, and ADAM methods in the fuzzy environment. Fuzzy Delphi-based AHP method is used to obtain the criteria weights, while the fuzzy ADAM method is used to obtain the final ranking of the alternatives (Figure 1). Choosing the right MCDM method for a specific problem can be a complex task, and it depends on various factors. Some of the most important ones are the decision context, stakeholder involvement, type of decision, consistency, transparency, and intuitiveness. The decision context implies the structure of the problem, that is, the number and relations between the alternatives and criteria for their evaluation. The choice of method involves various aspects. For example, some methods are more suitable for problems that require involvement of multiple stakeholders. Moreover, different MCDM methods are suitable for different types of decisions. For instance, some methods are better for ranking alternatives, while others are more adapted to selecting the best alternative. There are also methods that provide a clear and structured approach to making decisions, some of which even use visual representation, which makes them more transparent and intuitive. These factors, in addition to the advantages of the methods themselves, affected the selection of the aforementioned MCDM methods.

The AHP method was established by Saaty (1980), and it is one of the most used MCDM methods. It has been applied for solving the problems in various fields (Pereira & Bamel, 2023). AHP provides a structured and systematic approach to decision-making, helping decision-makers break down complex problems into a hierarchical structure of criteria and alternatives. In addition, it provides a built-in mechanism for checking the consistency of decision-maker preferences. It also relies on pairwise comparisons, where decision-makers compare criteria and alternatives in a relative fashion. This simplifies the evaluation process and reduces the need for precise numerical data. AHP also allows for the employment of visual tools like decision matrices and hierarchy diagrams, making it easier for decision-makers

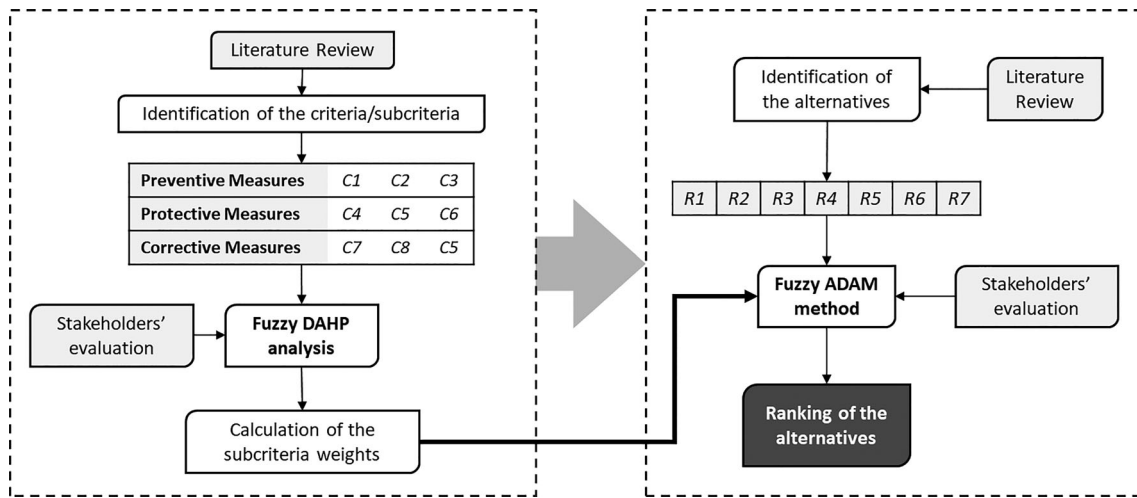


FIGURE 1 Methodological framework.

to understand and communicate complex decisions. AHP is particularly useful for group decision-making scenarios, which was the case in this study. However, this ability of the AHP process is limited, hence the main reason the Delphi method was introduced into the model.

The Delphi method was developed by Dalkey and Helmer (1963), and it is most often used for gathering and distilling the knowledge and opinions of a group of experts to make informed decisions or reach a consensus on a particular issue. It has also found a wide application, especially in combination with the AHP method (Khan, Alam, et al., 2022), primarily due to its main advantages. It has also been identified as one of the most widely used techniques for risk identification (Sharmaa et al., 2022). The Delphi method allows for the integration of diverse expert opinions and knowledge. It is particularly useful when dealing with complex decision-making scenarios where multiple criteria and uncertainties are involved. Participants in the Delphi process typically remain anonymous. This can lead to more honest and unbiased responses as experts are not influenced by social or peer pressure. The Delphi process is iterative, meaning that it involves multiple rounds of feedback and consensus building. This allows experts to refine their opinions and reach a more robust decision over time. The Delphi method is designed to minimize biases and group dynamics that can influence decision-making in traditional group discussions. This makes it particularly useful for sensitive or controversial topics. Delphi helps in building consensus or identifying areas of disagreement among experts. It can result in a more informed and agreeable decision-making process. However, the Delphi-AHP combination is inefficient and resource consuming when dealing with problems consisting of a greater number of criteria and alternatives, due to the need for pairwise comparisons of all elements of the problem structure. This was the main reason for applying another method for the alternatives ranking. In this part of the model, the ADAM method was used.

The ADAM method was developed by Krstić et al. (2023) and despite the fact that it is one of the youngest MCDM methods, it has

TABLE 1 Grades and corresponding fuzzy values.

Grade	Abbreviations	Fuzzy scale
“None”	N	(1, 1, 2)
“Very low”	VL	(1, 2, 3)
“Low”	L	(2, 3, 4)
“Fairly low”	FL	(3, 4, 5)
“Medium”	M	(4, 5, 6)
“Fairly high”	FH	(5, 6, 7)
“High”	H	(6, 7, 8)
“Very high”	VH	(7, 8, 9)
“Extremely high”	EH	(8, 9, 9)

already attracted attention due to its main advantages (Agnusdei, Krstić, Palmi, & Miglietta, 2023; Krstić et al., 2024). The ADAM method is known for its simplicity, user-friendliness, and easy-to-understand approach. It offers a low risk of rank reversal and employs an intuitive graphical representation based on polyhedra volume calculations. The method remains stable even when criteria weights change, ensuring reliable and easily interpretable decision-making for a multitude of criteria. Furthermore, results obtained using the ADAM method exhibit a high level of agreement with other common MCDM methods, with consistently high average correlation indices. The ADAM method in combination with the Delphi and AHP methods provides a unique hybrid MCDM model.

Model application requires the establishment of a problem structure, set of alternatives that need to be evaluated and ranked, and sets of criteria and subcriteria arranged in a hierarchy, used for the alternatives' evaluation. Detailed steps of the model application are presented in the following.

Step 1. Obtain the pairwise comparison matrices in relation to all decision-makers (experts); transform the evaluations into triangular fuzzy numbers (using the relations given in Table 1).

Step 2. Unify the assessment using the fuzzy Delphi method (Hsu & Yang, 2000):

$$\tilde{\delta} = (\alpha, \beta, \gamma) \tag{1}$$

$$\alpha = \min_f (l_f), f = 1, \dots, o \tag{2}$$

$$\beta = \left(\prod_{f=1}^o m_f \right)^{1/o}, f = 1, \dots, o \tag{3}$$

$$\gamma = \max_f (u_f), f = 1, \dots, o \tag{4}$$

where α, β , and γ are lower, medium, and upper values of the unified fuzzy evaluation $\tilde{\delta}$, respectively, and $\alpha \leq \beta \leq \gamma$. l_f, m_f , and u_f are lower, medium, and upper values of the triangular fuzzy evaluation, which indicate the importance of the element in relation to the stakeholder f . o is the number of the considered stakeholders.

Step 3. Calculate the relative weights of the elements. Unified fuzzy evaluations of the elements form the fuzzy judgment matrix $\tilde{\Delta}^I$:

$$\tilde{\Delta}^I = \begin{bmatrix} \tilde{\delta}_{11}^I & \dots & \tilde{\delta}_{1n}^I \\ \vdots & \ddots & \vdots \\ \tilde{\delta}_{n1}^I & \dots & \tilde{\delta}_{nn}^I \end{bmatrix} \tag{5}$$

where $\tilde{\delta}_{gj}^I = (\alpha_{gj}, \beta_{gj}, \gamma_{gj})$ indicates the unified fuzzy value of importance of element g over element j , and $g, j = 1, \dots, n$, where n is the number of elements.

The priority vectors for each pairwise comparison matrix must be obtained. The priority vector can be obtained from the fuzzy matrix $\tilde{\Delta}^I$ in various ways. This study uses the ‘‘logarithmic fuzzy preference programming’’ (LFPP) (Wang & Chin, 2011) method, which approximates the triangular fuzzy judgments $\tilde{\delta}_{gj}^I$ using the equation:

$$\ln \tilde{\delta}_{gj}^I \approx (\ln \alpha_{gj}, \ln \beta_{gj}, \ln \gamma_{gj}), g, j = 1, \dots, n \tag{6}$$

To obtain the elements' weights (w_j) the following nonlinear priority model is proposed:

$$\text{Min} J = (1 - \lambda)^2 + M \sum_{g=1}^{n-1} \sum_{j=g+1}^n (\epsilon_{gj}^2 + \eta_{gj}^2) \tag{7}$$

$$\text{s.t.} \begin{cases} x_g - x_j - \lambda \ln \left(\frac{\beta_{gj}}{\alpha_{gj}} \right) + \epsilon_{gj} \geq \ln \alpha_{gj}, g = 1, \dots, n-1; j = g+1, \dots, n \\ -x_g + x_j - \lambda \ln \left(\frac{\gamma_{gj}}{\beta_{gj}} \right) + \eta_{gj} \geq -\ln \gamma_{gj}, g = 1, \dots, n-1; j = g+1, \dots, n \\ \lambda, x_g \geq 0, g = 1, \dots, n \\ \epsilon_{gj}, \eta_{gj} \geq 0, g = 1, \dots, n-1; j = g+1, \dots, n \end{cases} \tag{8}$$

where $x_{gj} = \ln w_{gj}$ for $g = 1, \dots, n, j = g+1, \dots, n$ and M is a specified sufficiently large constant such as $M = 10^3$. ϵ_{gj} and η_{gj} for $g = 1, \dots, n-1$ and $j = g+1, \dots, n$ are the nonnegative deviation variables introduced to avoid membership degree λ from taking a negative value. It is most desirable for the values of the deviation variables to be as small as possible, and they must meet the following inequalities:

$$\ln w_g - \ln w_j - \lambda \ln \left(\frac{\beta_{gj}}{\alpha_{gj}} \right) + \epsilon_{gj} \geq \ln \alpha_{gj}, g = 1, \dots, n-1; j = g+1, \dots, n$$

$$-\ln w_g + \ln w_j - \lambda \ln \left(\frac{\gamma_{gj}}{\beta_{gj}} \right) + \eta_{gj} \geq -\ln \alpha_{gj}, g = 1, \dots, n-1; j = g+1, \dots, n$$

Let $x_g^* (g = 1, \dots, n)$ be the optimal solution to model (7-8). The normalized priorities for fuzzy pairwise comparison matrix $\tilde{\Delta}^I = (\tilde{\delta}_{gj}^I)_{n \times n}$ can then be obtained as follows:

$$w_j^* = \frac{\exp(x_g^*)}{\sum_{j=1}^n \exp(x_g^*)}, g = 1, \dots, n \tag{9}$$

where $\exp()$ is the exponential function, namely, $\exp(x_{gj}^*) = e^{x_{gj}^*}$ for $g = 1, \dots, n-1$ and $j = g+1, \dots, n$. This method results in crisp normalized weights.

In order to control the result of the method, the consistency ratio (CR) for each matrix is calculated as follows (Saaty, 1996):

$$CR = CI / RI \tag{10}$$

where CI is the consistency index and is calculated as follows:

$$CI = (\lambda_{max} - n) / (n - 1) \tag{11}$$

λ_{max} is the Perron root or principal eigenvalue of the matrix $\tilde{\Delta}^I$. RI is the random index whose values for matrices of various sizes can be seen in Saaty (1996). The comparisons are acceptable only if the CR values are less than 0.10.

Step 4. Apply the fuzzy extension of the ADAM method (Krstić et al., 2024) to rank the alternatives.

Step 4.1: Define the matrix.

$$\tilde{E} = [\tilde{e}_{ij}]_{m \times n} \tag{12}$$

where $\tilde{e}_{ij} = (l^e, m^e, u^e)$ are the evaluations of the alternatives i in relation to criteria j , m is the total number of alternatives.

Step 4.2: Define the matrix.

$$\tilde{S} = [\tilde{s}_{ij}]_{m \times n} \tag{13}$$

where $\tilde{s}_{ij} = (f^s, m^s, u^s)$ indicate the sorted evaluations \tilde{e}_{ij} in descending order.

Step 4.3: Find the fuzzy coordinates $(\tilde{x}_{ij}, \tilde{y}_{ij}, \tilde{z}_{ij})$ of the fuzzy reference \tilde{R}_{ij} and fuzzy weighted reference \tilde{P}_{ij} points:

$$\tilde{x}_{ij} = (f^{x_{ij}}, m^{x_{ij}}, u^{x_{ij}}) = (f^{s_{ij}} \times \sin \alpha_j, m^{s_{ij}} \times \sin \alpha_j, u^{s_{ij}} \times \sin \alpha_j), \forall j = 1, \dots, n; \quad (14)$$

$$\forall i = 1, \dots, m$$

$$\tilde{y}_{ij} = (f^{y_{ij}}, m^{y_{ij}}, u^{y_{ij}}) = (f^{s_{ij}} \times \cos \alpha_j, m^{s_{ij}} \times \cos \alpha_j, u^{s_{ij}} \times \cos \alpha_j), \forall j = 1, \dots, n; \quad (15)$$

$$\forall i = 1, \dots, m$$

$$\tilde{z}_{ij} = (f^{z_{ij}}, m^{z_{ij}}, u^{z_{ij}}) = \begin{cases} (0, 0, 0), & \text{for } \tilde{R}_{ij} \\ (f^{w_j}, m^{w_j}, u^{w_j}), & \text{for } \tilde{P}_{ij} \end{cases}, \forall j = 1, \dots, n; \forall i = 1, \dots, m \quad (16)$$

where α_j is obtained as follows:

$$\alpha_j = (j-1) \frac{90^\circ}{n-1}, \forall j = 1, \dots, n \quad (17)$$

Step 4.4: Obtain the fuzzy values:

$$\tilde{V}_i^C = \bigoplus_{k=1}^{n-1} \tilde{V}_k, \forall i = 1, \dots, m \quad (18)$$

where \tilde{V}_k is obtained as follows:

$$\tilde{V}_k = \frac{1}{3} \tilde{B}_k \otimes \tilde{h}_k, \forall k = 1, \dots, n-1 \quad (19)$$

where \tilde{B}_k is obtained as follows:

$$\tilde{B}_k = \tilde{c}_k \otimes \tilde{a}_k \oplus \frac{\tilde{a}_k \otimes (\tilde{b}_k \ominus \tilde{c}_k)}{2} \quad (20)$$

where $\tilde{a}_k = (f^{a_k}, m^{a_k}, u^{a_k})$ in which

$$\begin{aligned} f^{a_k} &= \min \left(\sqrt{(u^{x_{j+1}} - f^{x_j})^2 + (u^{y_{j+1}} - f^{y_j})^2}, \sqrt{(f^{x_{j+1}} - u^{x_j})^2 + (f^{y_{j+1}} - u^{y_j})^2} \right) \\ m^{a_k} &= \sqrt{(m^{x_{j+1}} - m^{x_j})^2 + (m^{y_{j+1}} - m^{y_j})^2} \\ u^{a_k} &= \max \left(\sqrt{(u^{x_{j+1}} - f^{x_j})^2 + (u^{y_{j+1}} - f^{y_j})^2}, \sqrt{(f^{x_{j+1}} - u^{x_j})^2 + (f^{y_{j+1}} - u^{y_j})^2} \right) \end{aligned} \quad (21)$$

$\tilde{b}_k = (f^{b_k}, m^{b_k}, u^{b_k})$ and $\tilde{c}_k = (f^{c_k}, m^{c_k}, u^{c_k})$ are equal to

$$\tilde{b}_k = \tilde{z}_j \quad (22)$$

$$\tilde{c}_k = \tilde{z}_{j+1} \quad (23)$$

Following Equations (16)–(18), Equation (20) can be expressed as $\tilde{B}_k = (f^{B_k}, m^{B_k}, u^{B_k})$ in which

$$\begin{aligned} f^{B_k} &= f^{c_k} \times f^{a_k} + \frac{f^{a_k} \times (f^{b_k} - u^{c_k})}{2} \\ m^{B_k} &= m^{c_k} \times m^{a_k} + \frac{m^{a_k} \times (m^{b_k} - m^{c_k})}{2} \\ u^{B_k} &= u^{c_k} \times u^{a_k} + \frac{u^{a_k} \times (u^{b_k} - f^{c_k})}{2} \end{aligned} \quad (24)$$

$$\tilde{h}_k = \frac{2 \sqrt{\tilde{s}_k (\tilde{s}_k - \tilde{a}_k) (\tilde{s}_k - \tilde{d}_k) (\tilde{s}_k - \tilde{e}_k)}}{\tilde{a}_k} \quad (25)$$

where

$$\tilde{s}_k = \frac{\tilde{a}_k \oplus \tilde{d}_k \oplus \tilde{e}_k}{2} \quad (26)$$

where \tilde{d}_k can be expressed as $\tilde{d}_k = (f^{d_k}, m^{d_k}, u^{d_k})$ in which

$$\begin{aligned} f^{d_k} &= \sqrt{(f^{x_j})^2 + (f^{y_j})^2} \\ m^{d_k} &= \sqrt{(m^{x_j})^2 + (m^{y_j})^2} \\ u^{d_k} &= \sqrt{(u^{x_j})^2 + (u^{y_j})^2} \end{aligned} \quad (27)$$

and \tilde{e}_k can be expressed as $\tilde{e}_k = (f^{e_k}, m^{e_k}, u^{e_k})$ in which

$$\begin{aligned} f^{e_k} &= \sqrt{(f^{x_{j+1}})^2 + (f^{y_{j+1}})^2} \\ m^{e_k} &= \sqrt{(m^{x_{j+1}})^2 + (m^{y_{j+1}})^2} \\ u^{e_k} &= \sqrt{(u^{x_{j+1}})^2 + (u^{y_{j+1}})^2} \end{aligned} \quad (28)$$

Following Equations (25) and (28), Equation (26) can be expressed as $\tilde{s}_k = (f^{s_k}, m^{s_k}, u^{s_k})$ in which

$$\begin{aligned} f^{s_k} &= \frac{f^{d_k} + f^{e_k} + f^{a_k}}{2} \\ m^{s_k} &= \frac{m^{d_k} + m^{e_k} + m^{a_k}}{2} \\ u^{s_k} &= \frac{u^{d_k} + u^{e_k} + u^{a_k}}{2} \end{aligned} \quad (29)$$

and Equation (27) can be expressed as $\tilde{h}_k = (f^{h_k}, m^{h_k}, u^{h_k})$ in which

$$\begin{aligned} f^{h_k} &= \frac{2 \sqrt{f^{s_k} |f^{s_k} - u^{d_k}| |f^{s_k} - u^{d_k}| |f^{s_k} - u^{e_k}|}}{u^{d_k}} \\ m^{h_k} &= \frac{2 \sqrt{m^{s_k} |m^{s_k} - m^{d_k}| |m^{s_k} - m^{d_k}| |m^{s_k} - m^{e_k}|}}{m^{d_k}} \\ u^{h_k} &= \frac{2 \sqrt{u^{s_k} |u^{s_k} - f^{d_k}| |u^{s_k} - f^{d_k}| |u^{s_k} - f^{e_k}|}}{f^{d_k}} \end{aligned} \quad (30)$$

According to the transformed equations (24) and (30), Equation (19) can be expressed as $\tilde{V}_k = (f^{V_k}, m^{V_k}, u^{V_k})$ in which

$$\begin{aligned} f^{V_k} &= \frac{f^{B_k} \times f^{h_k}}{3} \\ m^{V_k} &= \frac{m^{B_k} \times m^{h_k}}{3} \\ u^{V_k} &= \frac{u^{B_k} \times u^{h_k}}{3} \end{aligned} \quad (31)$$

and Equation (18) as $\tilde{V}_i^C = (l^{V_i^C}, m^{V_i^C}, u^{V_i^C})$ in which

$$\begin{aligned} l^{V_i^C} &= \sum_{k=1}^{n-1} l^{V_k} \\ m^{V_i^C} &= \sum_{k=1}^{n-1} m^{V_k} \\ u^{V_i^C} &= \sum_{k=1}^{n-1} u^{V_k} \end{aligned} \tag{32}$$

Step 5. Rank the alternatives by the crisp values (adapted from Rahmani et al., 2016)

$$\text{Crisp}(\tilde{V}_i^C) = (4 \times m^{V_i^C} + u^{V_i^C} - 2l^{V_i^C}) / 3(u^{V_i^C} - 2l^{V_i^C}) \tag{33}$$

5 | RESULTS

The defined problem was solved by applying the methodology described in Section 4. Questionnaires concerning the evaluations of the criteria and risks were given to the 53 stakeholder representatives with different backgrounds, experience, and specialties. Using the grades given in Table 1, they made pairwise comparisons of criteria and subcriteria. These grades were then unified using Equations (1)–(4). Afterward, by applying Equations (5)–(9), subcriteria weights were obtained (Table 2) and the consistency of the evaluations was checked using Equations (10) and (11).

Stakeholder representatives then evaluated risks against the defined criteria. By applying Equations (12)–(33), the values were obtained, based on which the final ranking of the risks was performed (Table 3). Results indicate that the most important risk is supply chain complexity (R₂), followed by resource availability and quality (R₁), and technological challenges (R₅).

The sensitivity analysis was performed by creating 12 scenarios (Sc.1–12). In the first nine scenarios, the weight of one of the three

most important subcriteria was reduced by 30%, 60%, and 90%, respectively. The last three scenarios were created by reducing the weights of all three most important criteria by the same percentages. Results (Figure 2) indicate that, although the final values vary, the final rankings of the risks remain the same in almost all scenarios. This implies that the results obtained in the basic scenario (Sc.0) are stable enough and can thus be adopted as the final one.

Validating the results of the MCDM model ensures the reliability and robustness of the model, detects potential biases, and provides a more comprehensive and balanced perspective on the decision problem, ultimately leading to more informed and defensible decisions. To validate the results obtained in this study, we compared the results with the results obtained using some other relevant MCDM methods on the same set of input data (Figure 3). To quantify the similarity of the obtained results, we calculated the Spearman correlation coefficients. The average value of 0.89 indicates high conformity with other MCDM methods, additionally confirming the validity of the obtained rank.

6 | DISCUSSIONS

Since the goal of this study was to evaluate and rank the main risks associated with the CSCs, the most important contribution is the identification of the most relevant risks, which allows stakeholders to allocate resources and concentrate their efforts on the most vital areas, ultimately bolstering the resilience and sustainability of their CSC operations. By identifying the most important risks, they can try to prevent or mitigate them by applying various measures.

Supply chain complexity (R₂), as the most important risk, can be addressed by taking various measures. In addition to the measures already established in the literature (Bier et al., 2020), this study proposes the adoption of advanced technology, the establishment of

TABLE 2 Obtained criteria and sub-criteria weights.

Criterion	Weight	Sub-criterion	Weight	Overall weight
Preventive measures	0.4126	C ₁	0.1429	0.059
		C ₂	0.5714	0.236
		C ₃	0.2857	0.118
Protective measures	0.3275	C ₄	0.5714	0.187
		C ₅	0.2857	0.094
		C ₆	0.1429	0.047
		C ₇	0.3439	0.089
Corrective measures	0.2599	C ₈	0.2229	0.058
		C ₉	0.4333	0.113

TABLE 3 Final ranking of the CSC risks.

	R ₁	R ₂	R ₃	R ₄	R ₅	R ₆	R ₇
$\text{Crisp}(\tilde{V}_i^C)$	0.417	0.424	0.364	0.380	0.394	0.384	0.351
Rank	2	1	6	5	3	4	7

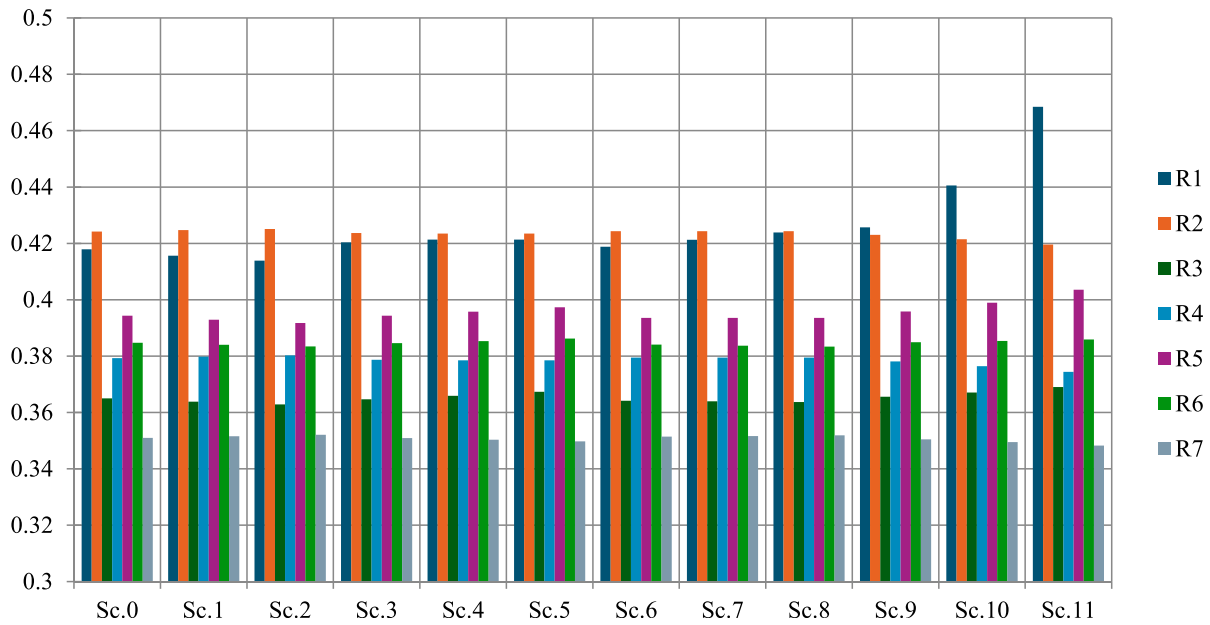


FIGURE 2 Sensitivity analysis.

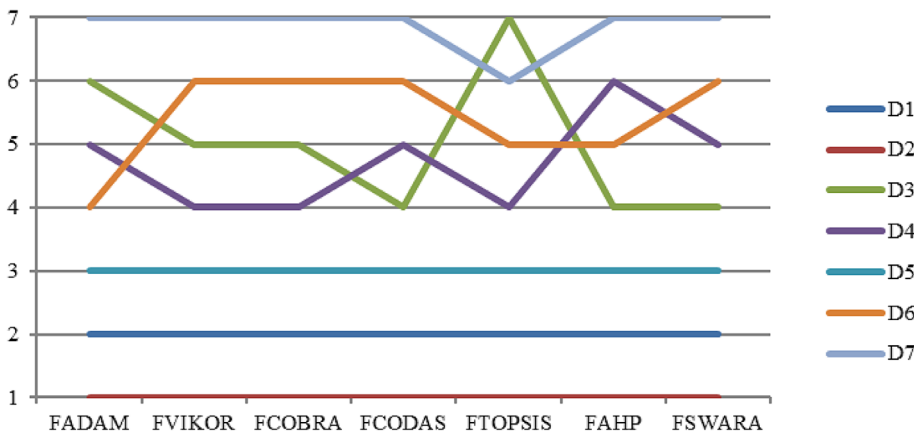


FIGURE 3 Validation of results.

collaboration and partnerships, the embracement of a culture of continuous improvement, training and education to supply chain professionals and partners, fostering transparency in the supply chain, and being informed about evolving regulations and standards to ensure compliance.

Other risks can also be addressed by various measures and practices (El Baz & Ruel, 2021). Some of the measures for addressing resource availability and quality (R_1), ranked as the second most important risk, are the diversification of material sources, investments in quality assurance, collaboration with suppliers, and innovations in material recovery. On the other hand, technological challenges (R_5) can be addressed by greater investment in research and development, pilot projects, skill development, and continuous improvement; economic viability (R_6) by incentives, better pricing strategies, and collaboration; regulatory compliance (R_3) by regulatory monitoring, legal expertise, documentation and reporting, third-party audits, and engagement with regulatory bodies; consumer acceptance (R_4) by

education and awareness campaigns, greater transparency, convenience, and engagement of consumers; social and ethical concerns (R_7) by better labor practices, community engagement, equity considerations, and cultural sensitivity.

Another important contribution of this study is the establishment of a framework for the evaluation and ranking of risks. This framework implies identification of the main risks and criteria for their evaluation. The risks and criteria are not case sensitive; that is, the same risks are present in most CSCs and they can be evaluated using the established set of criteria. Previous studies have mainly dealt with individual CSC risks (Ada et al., 2021; Fofou et al., 2021; Mancheri et al., 2019; Marcos et al., 2021), while this study, instead, intends to comprehensively analyze and prioritize multiple risks and single out the most important ones.

One of the most important contributions of this study is the development of a novel hybrid MCDM model that combines the Delphi, AHP, and ADAM methods in a fuzzy environment. Although

these methods are already known (Agnusdei, Krstic, Palmi & Miglietta, 2023; Khan, Alam, et al., 2022; Pereira & Bamel, 2023), they have never been used together, either in their conventional form or in the fuzzy environment.

Contributions of this study provide significant theoretical and practical (managerial) implications. The theoretical implications of this study improve the academic understanding of CSC risk management, while the practical implications provide valuable insights and tools for managers and decision-makers to enhance the resilience and sustainability of their supply chain operations. This research contributes to both the theoretical and applied aspects of the field, promoting a more robust and practical approach to managing risks in CSCs.

Previous research has primarily focused on individual risks, whereas this study takes a holistic approach by considering and prioritizing multiple risks. This contributes to a deeper understanding of the complex dynamics within CSCs. The identification of a common set of risks and evaluation criteria that are not case-sensitive holds important theoretical implications. It suggests that the findings of this study can be applied to a wide range of CSCs. This generalizability enhances the theoretical foundation of CSC risk management. The development of a novel hybrid MCDM model provides significant theoretical implications. While these methods individually are well established, their combination in this study contributes to the field of decision-making in complex, uncertain environments, thus expanding the body of literature.

The identification of the most critical risks in CSCs enables organizations to allocate their resources and efforts strategically. By concentrating resources on addressing these high-priority risks, companies can enhance the resilience and sustainability of their CSC operations. The establishment of a framework for evaluating and ranking risks provides an approach that can be applied across various CSC scenarios, simplifying risk assessment. This can be particularly valuable for organizations looking to assess their risk exposure and prioritize mitigation efforts efficiently. Lastly, the novel hybrid MCDM model introduced in the study offers a structured approach to evaluating and prioritizing risks in real-world applications. Organizations can use the findings and methodologies from this study to gain a competitive advantage on the market by reducing disruptions and operational costs and enhancing overall performance. This, in turn, can contribute to better market positioning and financial performance.

The study's findings may be limited by the size and diversity of the sample or data used. Since the research is based on a specific region, it might not be fully representative of the broader landscape of CSCs, limiting the generalizability of the results. The fuzzy MCDM model, while innovative, can be complex to implement in practice. Its applicability may be limited by the availability of suitable software, expertise in implementing fuzzy logic and the computational resources required. This issue could be addressed by using some less complex methods such as weighted product model (WPM) (Miller & Starr, 1969) or the simple weighted sum product method WISP (Stanujkic et al., 2021), for example. The Delphi method, which involves gathering expert opinions, but also the application of the

AHP and ADAM methods to obtain criteria weights and alternatives ranking, are subject to potential biases and the varying perspectives of experts. Although sensitivity analysis is performed, the study might not fully eliminate subjectivity in the evaluation and ranking of risks, affecting the model's reliability. In order to do so, some semiobjective MCDM methods that obtain the criteria weights based on the evaluations of criteria in relation to them could be applied, such as ITARA (Hatefi, 2019), WENSLO (Pamucar et al., 2023). Another important aspect of the applied model, especially for the application of the ADAM method, is the normalization of evaluations. The model uses linear sum-based normalization, which does not necessarily reflect the original information. This issue could be addressed by combining the mixed aggregation by comprehensive normalization technique (MACONT) (Wen et al., 2020). CSC risks are dynamic and can change over time due to various factors such as market conditions, technology advancements, and geopolitical events. The study may not capture the evolving nature of these risks, making the findings relevant only to a specific time frame. Although the study aims to provide a general framework, certain CSC scenarios may have unique variables or circumstances that are not accounted for in the generic risk assessment, limiting its applicability in those specific cases.

7 | CONCLUSIONS

CSCs, a shift from traditional linear models, aim to reduce waste and maximize resource efficiency by continually reusing, remanufacturing and recycling products and materials. This sustainable approach offers environmental benefits, cost savings, and a competitive edge. However, managing risks in the transition is crucial for long-term sustainability, and accordingly, the study main objective was to identify key risks and introduce a prioritization model to help organizations proactively manage and implement CSC strategies. Obtained results indicate that the most important risks are supply chain complexity, resource availability and quality, and technological challenges.

The main contributions of the study include the identification and ranking of key risks in CSCs, enabling stakeholders to allocate resources and focus on critical areas to enhance the resilience and sustainability of their operations (Brandon-Jones et al., 2014; Wieland & Durach, 2021). Additionally, the study proposes specific measures to address these risks. The study also establishes a framework for evaluating and ranking risks, providing a standardized approach applicable to most CSCs. This is a departure from previous studies that have typically focused on individual risks. Furthermore, the study introduces a novel hybrid MCDM model that combines the Delphi, AHP, and ADAM methods in a fuzzy environment, offering a unique approach to risk assessment that has not been previously utilized.

The study offers both theoretical and practical implications. Theoretical advancements include a holistic framework for risk management in CSCs and the development of a novel decision-making model, enhancing the theoretical understanding of the field. On a practical level, the study enables organizations to strategically manage risks,

standardize risk assessment, and gain a competitive edge through improved risk management, reduced disruptions, and lower operational costs. This enhances their resilience and sustainability while simplifying decision-making and prioritizing risk mitigation efforts.

Furthermore, the need to include organizational perspectives for the development and management of CSCs is highlighted: This could provide timely indications to managers and entrepreneurs who want to address the circular evolution of their companies, especially concerning the aspects linked to collaboration, coordination and new technologies within the supply chain.

Future research directions could focus on addressing the identified limitations. Sample size and diversity of data could be expanded to enhance the generalizability of findings across different regions and contexts. The fuzzy MCDM model could be made more accessible and practical for a wider range of applications by streamlining its implementation. Future research could also deal with reducing subjectivity in expert opinions and criteria weighting, potentially by incorporating AI or machine learning techniques. Another important direction would also be to investigate the dynamic nature of risks, that is, to investigating how CSC risks evolve over time and explore methods to adapt risk assessment models to changing conditions. Risk assessment framework could also be tailored to account for unique variables and circumstances in specific CSC scenarios.

ORCID

Leonardo Agnusdei  <https://orcid.org/0000-0002-8867-8857>

Tomas Baležentis  <https://orcid.org/0000-0002-3906-1711>

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