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Evaluation of circular supply chains barriers in the era of Industry 4.0 transition using an extended decision-making approach

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Abstract

Purpose – The poor leadership style is a key obstacle to the effective implementation of Industry 4.0 technologies. To successfully apply the Industry 4.0 technologies, which can enhance the sustainability of firms, senior management needs to be inspiring and transformational. On the other hand, numerous factors can hinder the Industry 4.0 transition and "Circular Supply Chain (CSC)" transformation. Therefore, the main purpose of this study is to evaluate the related barriers of CSCs in the era of Industry 4.0 transition.

Design/methodology/approach – The current study developed an innovative decision-making approach with the help of the "Combined Compromise Solution (CoCoSo)" method and "Criteria Importance Through Intercriteria Correlation (CRITIC)" method on the "q-Rung Orthopair Fuzzy Sets (q-ROFSs)." CRITIC in this combined method was used to predict the importance or weighting degrees of the CSCs barriers in the age of Industry 4.0 transition.

Findings – The results of this study found that the absence of knowledge about the Industry 4.0 technologies and circular approaches was the first barrier followed by the problems associated with data security in relationship management in circular flows, the deficiency of knowledge regarding the data management among stakeholders and the lack of awareness about the potential benefits of autonomous systems in labor-oriented "End-of-Life (EOL)" activities for CSCs in the era of Industry 4.0 transition.

Research limitations/implications – A limitation may be that despite the generalizability of the proposed framework, the results may differ when it is implemented in different sectors. By emphasizing the obstacles to sustainable operations of supply chains (SCs) in the context of circular economy (CE) and Industry 4.0, researchers working in the same domain may be encouraged to find ways to remove such obstacles in different settings. As suggested in this study, the priority of various barriers helps researchers suggest effective strategies for the sustainable development of companies within the current dynamic business atmosphere.

Practical implications – The findings of this paper can aid industry practitioners in fixing their attention on the digitization or automation of their systems in the context of sustainability or resource circularity. Note that within the current context of CE, one of the crucial issues is how to conserve the existing resources; the answer to this question can save the environment.

Originality/value – The current paper proposed a new multi-criteria decision-making method using q-ROFSs to analyze, rank and evaluate the CSC barriers in the age of Industry 4.0 transition. To this end, a new decision-making approach with the help of CRITIC and CoCoSo methods on q-ROFSs called q-ROF-CRITIC-CoCoSo was introduced to evaluate the CSCs barriers in the era of Industry 4.0 transition.

Keywords Circular supply chain, Circular economy, Supply chain, q-Rung orthopair fuzzy sets, MCDM, CoCoSo, Industry 4.0

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1. Introduction

In the present age of global competition, every company is making its efforts to add sustainability to its "*Supply Chain (SC),*" hence being more concentrated on social, environmental and economic perspectives of business (Nosratabadi *et al.*, 2019). Formerly, the systems of production and consumption were based on the linear economy (i.e. "*Take-Make-Consume-Dispose*") (Goyal *et al.*, 2018), which is also recognized as the "*Cradle-to-Grave*" procedure (Gregson *et al.*, 2015). The big problem with this conventional model is that it produces a massive volume of waste and causes the depletion of natural resources, which significantly endangers sustainability (Genovese *et al.*, 2017). The annual rate of worldwide solid waste generation is approximately 1.3 billion tons, which scientists predict to increase up to 2.2 billion tons by 2025 (Masi *et al.*, 2017). Accordingly, the mitigation of waste production and protecting the environment against degradation are two demanding challenges to every manufacturing firm (Braun *et al.*, 2018).

In developing countries, "*Circular Economy (CE)*" can be recognized as an effective strategy for the transformation of the conventional economic systems into a sustainable circular system (Mangla *et al.*, 2018). CE addresses two major problems in the industrial environment, i.e. ecological degradation and resource depletion (Geng *et al.*, 2009). In this new model of the economy, there is no more room for the conventional approach that was using the "*Take-Make-Consume-Dispose (TMCD)*" model (Williams, 2001). As a result, there is a need for the transformation of the entire SC in regard to designing, manufacturing, etc. (Low *et al.*, 2016).

The linear model of the economy, which was based on "the cradle-to-grave" approach, cannot effectively achieve the demand and supply balance in the consumption of natural resources. Such failure can result in the unsustainability of nations, firms and organizations, resulting in environmental/socioeconomic risks and volatility by negatively impacting the global SC. Due to the realization of the challenge of future resource depletion, the currently implemented linear economy model is feeling the necessity of transition to the CE (George *et al.*, 2015; Goyal *et al.*, 2018).

The CE prototype has been portrayed at three levels: (1) eco-enterprises at the small-scale level, (2) eco-industrial parks at the meso-level and (3) eco-regions at the full-scale level (Yuan *et al.*, 2006). These activities aim to incorporate monetary developments with ecological sustainability (Wang *et al.*, 2010; Zhu *et al.*, 2011). In addition, because of the rapid industrial progress and modernization processes, companies globally are encountering problems in relation to the damaging environmental impacts of their business activities. To deal with this situation, companies are making their efforts to develop new effective methods for the management of these challenges. Recently, companies have been attempting to methodically implement the circular supply chain (CSC) models in their businesses in a way to prolong the products' life cycle, manage the waste generation rates, develop the economic sustainability through the inclination of the consumers' preferences toward the use of secondary goods and products. Today, due to the presence of the challenges mentioned above, the application of CE to SCs is becoming more and more widespread (Geng *et al.*, 2012).

For the improvement of business revenues and environmental effects, a proper approach could be the improvement of circularity in the economy, especially in SCs, which can be achieved by adding sustainability to SC operations (Ahi and Searcy, 2013; Seuring and Müller, 2008; Winter and Knemeyer, 2013). Reefke and Sundaram (2017) reviewed the literature on SC operations and, this way, succeeded in the identification of the most important themes of planning, collaboration and coordination. They then introduced the related research opportunities that could be addressed in relation to circularity. On the other hand, the literature still lacks widely accepted theories and practical applications in regard to sustainable SC management (Carter and Liane Easton, 2011; Lambert and Cooper, 2000; Winter and Knemeyer, 2013). According to the relevant literature, CSCs should possess at least four characteristics: (1) The priority of the inner cycles over the outer cycles (e.g. reusing and recovering activities come before recycling); (2) slowed down cycles (i.e. the use of resources for as long as possible); (3) reduction of waste generation rates at every phase of the products' life cycles; and (4) available resources should be reduced, reused, recycled and recovered as much as possible.

CSC refers to a restorative production system in which the available resources are entered into an infinite loop of reusing, remanufacturing and recycling. The objective of CSC is the optimization of the resources used all through the products' life cycle (Genovese *et al.*, 2017). CSC can also effectively solve different problems, e.g. unattainable production and consumption patterns, pollution, resource depletion, climate change, etc. With the implementation of the circular model of the flow of products, materials and waste, companies can decrease the waste generation rates and alleviate the adverse environmental effects in their SC practices (Genovese *et al.*, 2017; Nasir *et al.*, 2017). As a fresh area of study, CSC can help industries develop their approach and find crucial methods and techniques for the effective adoption of CSC models (Govindan *et al.*, 2015). However, the literature lacks efficient circular supply models. Due to the above-mentioned problems, it is difficult to implement CSC practices since there are many obstacles to the execution of these practices (Goyal *et al.*, 2018; Yaduvanshi *et al.*, 2016).

In addition, many obstacles have been identified in the literature to the adoption and implementation of Industry 4.0 and CSCs. The key challenge in this regard is that such obstacles generally act dependently on each other, and they can activate and intensify each other. As a result, many firms have decided to adopt and implement these technologies concurrently instead of using them one after the other. This helps them to take into action the solutions to these problems simultaneously. For that reason, there is a need to address all the obstacles, which are recognized as synchronized barriers, together with their inter-relationships, to accomplish an effective transformation into both Industry 4.0 and CSC at the same time to have resource management of higher sustainability and digitalized structures. Accordingly, it is of high importance to answer two key questions: (1) What are the CSC obstacles to the transition to Industry 4.0? (2) How the relative priorities of these obstacles could be well determined?

According to Baltussen (2019), SC poses noteworthy barriers to a variety of industries such as manufacturing. For that reason, the current paper concentrates on identifying the SC obstacles that may arise in the context of manufacturing firms to the adoption and implementation of CE. It is mainly aimed at understanding the SC obstacles that manufacturing firms may be faced with when applying CSC to the manufacturing industry. This paper contributes to the body of knowledge in this field of study by proposing a conceptual framework revealing the obstacles to CSC from a holistic perspective by taking into account all the stakeholders in SC in the manufacturing sector.

Following the above discussion on the extant literature, the current paper is focused upon the q-ROFSs context. However, CRITC is a widely used tool applied to different fields of study and is an effective tool for estimating the objective weights or significance degree of attributes. Nevertheless, the literature lacks research concentrating on the application of CRITIC to q-ROFSs. Accordingly, the present study is an attempt to develop a q-ROF-CRITIC-CoCoSo model with the help of CoCoSo and CRITIC in a q-ROFSs environment. Moreover, CoCoSo offers a simple implementation procedure with accurate and dependable outcomes that can be applied to analyze and evaluate the obstacles to CSCs in the age of Industry 4.0 transition in the q-ROFSs context. Thus, the current study has the following contributions:

(1) We are designing an innovative decision-making model using q-ROF, CRITIC and CoCoSo (called q-ROF-CRITIC-CoCoSo) to rank the firms and analyze the obstacles to CSC in the age of Industry 4.0 transition.

(2) Implementing the CRITIC procedure is utilized with the aim of evaluating the obstacles to CSC in the age of Industry 4.0 transition.

(3) We are applying CoCoSo to rank the firms in the age of Industry 4.0 transition by analyzing the obstacles to CSC.

(4) We are validating the proposed model by comparing its performance with the extant decision-making approaches.

The remaining of the paper is arranged as follows: Section 2 discusses comprehensive reviews related to this study. Section 3 presents some fundamental concepts of q-ROFSs and proposes a new decision-making model under the q-ROFSs context. Section 4 presents the results and discussion to demonstrate the effectiveness of the proposed model. At last, Section 5 concludes the whole work and recommends further study.

2. Circular supply chain barriers

Since linear economy started to transform into CSC, complexity further increased (Mangla *et al.*, 2018) due to two main reasons: first, the increase in the number of stakeholders within CSC, and their evolution as a result of circular flow and reverse logistics; second, the existence of a variety of business models within CSC, which had not existed in the linear economy. The circular flow of CSC is formed on the 6Rs (i.e. redesign, reuse, refurbish, remanufacture, recycle, recover) of CE. As a result, "*Supply Chain Management (SCM)*" has encountered several complexities because of this transformation. The decision-making arrangement in SCM has been modified according to the increased number of stakeholders the augmented complexity of the processes involved in decision-making (Manuj and Sahin, 2011). Such serious alteration in the decision-making mechanisms can be considered under two different issues: the increased number of decisions and the change to the content of the decision-making problems. With the transformation of SC into its new circular form, the number of stakeholders has increased, which has led to a considerable rise in the number of decisions to be made. Furthermore, the closed-loop concept has brought various objectives for decision makers (DMs), which had not been formerly observed in the linear SCs; circular approaches have provided great conceptual supports for such systems (Tseng *et al.*, 2019).

It is not easy to transform into CSC models because to adopt profoundly innovative business models, several new organizational practices and processes are required to be taken into action. This is particularly the case for inter-organizational collaboration as there is a need for critical skills and resources to develop and adopt CSC practices that have resided outside the organizational restrictions (Lavie, 2006). On the other hand, despite the fact that many studies have been carried out to investigate the incentives to adopt and implement CSC operations, there is still room to examine their real adoption and implementation (Gregson *et al.*, 2015; Wagner and Svensson, 2010) deeply. Moreover, as firms have started to redirect their attention toward CSC operations, there is an increasing need to investigate the transition process together with all challenges that may arise during this process.

As mentioned earlier, the transformation from linear into CSC can be a process full of various challenging for companies (Levering and Vos, 2019; Schraven *et al.*, 2019). In brief, CSC is a recovering production system through which resources are moved into an unbroken loop of end-of-life activities that include recycling, reuse and remanufacturing. It would make several important opportunities for companies to overwhelm a number of global problems such as uncontrollable production and consumption processes, insufficiency of resources, severe changes to climate and air pollution (Mangla *et al.*, 2018; Sehnem *et al.*, 2019). CSC has the potential to keep the resources in use as long as possible, hence reducing the waste generation at every stage of product life (Subramanian and Gunasekaran, 2015). When CSC is being implemented, linear manufacturing chains must be transformed into circular chains so that the business network models could effectively manage the streamlined circular flow of the products and the by-products and/or waste (Loomba and Nakashima, 2012).

The scope of CSC initiatives implementation has been extended considerably among business companies since CSC initiatives can offer a practical linkage between the economic development and the problems regarding resource depletion and community welfare, and this way, these initiatives can provide many opportunities for adding sustainability to business (Park *et al.*, 2010). However, due to the high complexity of the current business environment, adapting and extending the CSC models for sustainability is a difficult task that requires an in-depth inclusive understanding and theory building (Mangla *et al.*, 2018). To this end, there is a need for further work on the concepts of CE and CSC and the role they can play in the improvement of the environmental-economic-social performance of industrial SCs. Across the world, numerous studies have been conducted focusing on different perspectives of CSC models in an SC context (Genovese *et al.*, 2017; Goyal *et al.*, 2018). It has frequently been confirmed that different challenges arise when implementing the CSC concepts, and there is a need for finding effective solutions to these challenges from the industrial perspectives (Su *et al.*, 2013).

According to MacArthur (2013), four elements are required to be addressed well, i.e. circular product design, reverse logistics, serviced business models and enablers. In this regard, Bressanelli *et al.* (2019) believed that it is normally improbable for a firm to redesign its SC suddenly completely; however, it can be concentrated upon CE elements individually; that study attempted to review the challenges associated with SC redesign for CE systematically.

Govindan and Hasanagic developed a multi-perspective CE framework, and Tura *et al.* (2019) with the use of the organized literature review and case study procedures, which involved enablers, barriers and practices. However, they did not systematically prioritize or analyze the interrelationships that exist among the recognized factors. Mangla *et al.* (2018) attempted to determine and analyze different obstacles to CSCs in the context of the Indian automotive industry. According to Mangla *et al.* (2018), adopting and applying Industry 4.0 to sustainable SCs can result in a number of technological, strategic, organizational, legal and ethical threats. They also determined 18 critical challenges a sustainable manufacturing sector may face during its business process. The key problems that can confine the acceptance of Industry 4.0 include the absence of global standards and clear protocols for data sharing, deficiency of governmental supports and effective policies, and limited financial aids. Kirchherr *et al.* (2018) attempted to identify the technological, cultural, market, and regulatory challenges that can delay the adoption of CE. The most important issues in this regard are the high cost required for adopting CE, the low rate of virgin materials within the market and the lack of financial subsidies. Liboni *et al.* (2018) also focused on identifying the challenges that may arise for industries with the acceptance of Industry 4.0 and accomplishment of the goals defined in terms of protecting the natural environment. They highlighted the significance of technology integration in enabling the capacities of remanufacturing, reuse and recycling. The obstacles in this regard were highlighted from cultural, technological, economic and legal perspectives. Rajput and Singh (2021) attempted to identify the obstacles that Industry 4.0 can pose against the acceptance and adoption of CE by making discussions with experts and reviewing the extant literature. They introduced three factors, i.e. process digitalization, semantic interoperability and infrastructure standardization, as the most important barriers affecting the integration of Industry 4.0 with CE. According to Sharma *et al.* (2019), Because of different reasons such as the absence of required technologies and techniques, ineffective government policies and deficiency of farmer's awareness, the application of CE to CSC generally faces many problems. Mangla *et al.* (2019) attempted to identify the financial, infrastructural, environmental, government/political, legal and technological challenges the food SC may encounter when implementing sustainability. Yadav *et al.* (2020a) examined the problems associated with sustainable SC and suggested some solutions to these problems on the basis of Industry 4.0 and CE. The key problems mentioned in their study in this regard were the lack of financial and technological supports, the absence of human resources, conflicting sustainability policies, ineffective management in adopting the sustainability and free trade provisions. Yadav *et al.* (2020b) examined the most important obstacles to implementing blockchain in Indian CSCs and emphasized the following two issues: uncertainty or the absence of governmental regulations and public perception and the nonexistence of trust among stakeholders. In addition, a systematic literature review was carried out by Saroha *et al.* (2018) with the aim of identifying the challenges associated with CSCs. They classified these challenges under seven categories: governmental challenges, knowledge and skill challenges, market challenges, technological challenges, management challenges, social challenges and framework challenges. They were concentrated on introducing an initial framework for understanding the CSC issues. Pan *et al.* (2015) fixed their attention on waste generation in energy SCs and attempted to find the optimum ways for the accomplishment of CE; they concentrated upon several issues, e.g. energy demand, greenhouse gas (GHG) emissions and waste management. The obstacles in this regard were organized and discussed under the financial, technological, institutional and regulatory aspects.

To accomplish sustainability-oriented objectives, CSCs consider sustainable resource management to use available resources more efficiently in such a way that social, environmental and economic achievements could be well protected. As a result, it is necessary to identify the barriers of circularity in SCs so that firms can effectively transform into CSC in regard to the operational, financial, organizational, technological and managerial aspects. In recent years, many studies have been carried out to determine the obstacles to CE, sustainable SCM and green SCM; though, no in-depth research has been conducted into the barriers to "*Circular Supply Chain Management (CSCM)*" for resource management. Investigations on the barriers around CSCs from the macro perspectives have shown that the key challenge is how to transform the entire SC by taking into consideration the key elements of CE. The above discussions and the inclusive review of the existing literature conducted in this study resulted in the identification of the following 13 key barriers: the lack of technology transfers integration, high investments in Industry 4.0 technologies, inefficient training and education, lack of knowledge among stakeholders, data security in relationship management, ineffective management support for Industry 4.0 technologies in research and development (R&D) activities, absence of internet of things (IoT) facilities for recovering and tracking the product already released, deficiency of decentralized organizational structure understanding, absence of governmental supports and protocols for Industry 4.0, not adopting Industry 4.0 technologies for high transparency, deficiency of knowledge regarding the Industry 4.0 technologies, lack of awareness about the "*End-of-Life (EOL)*" activities and lack of organizational trust and willingness in the Industry 4.0 transformation for the application of CSCs in the age of Industry 4.0, which is shown in Figure 1.

3. Research methodology

3.1 An overview of decision-making methods

"*Decision Makers (DMs)*" fail to achieve precise outcomes in real "*Multi-Criteria Decision-Making (MCDM)*" problems, which is mainly because of the information absence, uncertainty of human beings' thoughts and issues related to time complexity. This challenge was well addressed by Atanassov (1986) through initiating the idea of "*Intuitionistic Fuzzy Set (IFS)*." IFS is designated by two concepts, i.e. "*Belongingness Degree (BD)*" and "*Non-belongingness Degree (ND),*" and fulfills the condition that the sum of its BD and ND is ≤ 1. After that, Yager (2014) attempted to remove the IFS weaknesses by proposing a new concept termed "*Pythagorean Fuzzy Set (PFS)*." Similarly, PFS was depicted by BD and ND and fulfilled a condition that the sum of the squares of BD and ND is ≤ 1. At the moment, PFS is more popular than IFS; it can treat the uncertainty that may arise in MCDM problems in the real

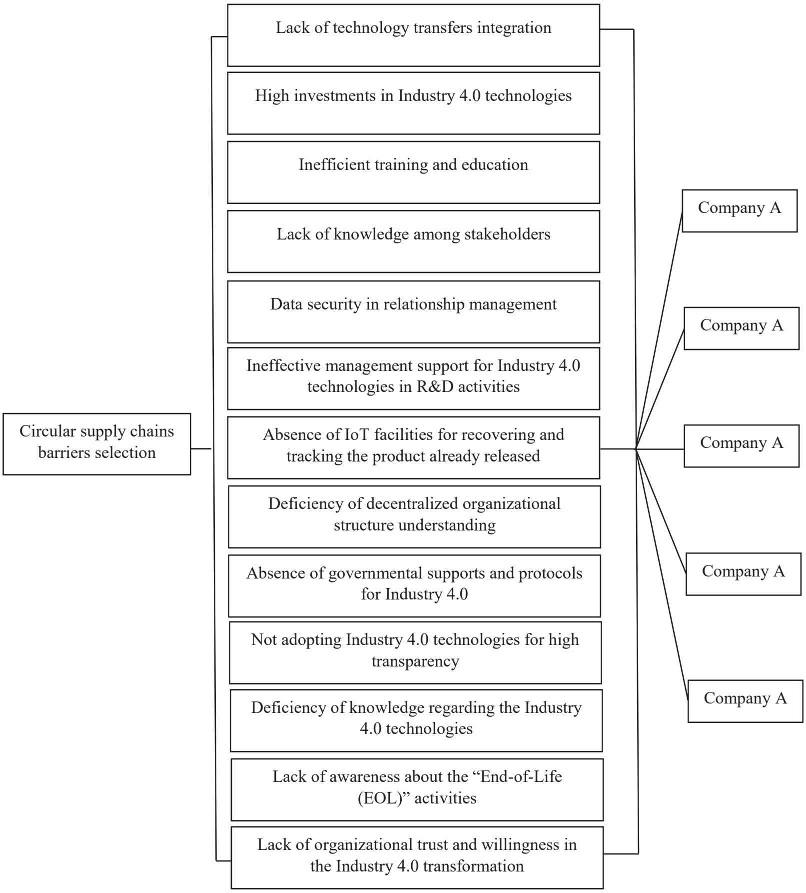

Figure 1.
CSCs barriers selection

world. In recent years, the literature has offered a number of methods, theories and approaches in relation to PFS (Peng, 2019a, b; Rani *et al.*, 2019, 2020a, b).

Nonetheless, in regard to MCDM, a case may appear in which DMs might provide the BD to which an option S_i fulfills the criteria T_j is 0.6 and the degree to which an option S_i invalidates the criteria is 0.9. Consequently, IFS and PFS are incapable to treat these circumstances because $0.6 + 0.9 > 1$ and $0.6^2 + 0.9^2 > 1$. To effectively manage this problem, "*q-Rung Orthopair Fuzzy Sets (q-ROFSs)*" was pioneered by Yager (2017). q-ROFSs is also portrayed by the two concepts of BD and ND. However, the constraint here is that the sum of the qth power of BD and ND is ≤ 1, where $q \geq 1$. This new model is capable of properly handling the above-explained example. In q-ROFSs, the information space is wider than that of PFSs and IFSs corresponding to the variation of the parameter q ($q \geq 1$); it is clear that PFSs and IFSs are in fact two forms of q-ROFSs. Therefore, the q-ROFS is a method of higher flexibility and applicability for handling the higher levels of uncertainty. In recent years, many studies have been carried out in the q-ROFSs environment. For instance, Yager and Alajlan (2017) investigated the essential postulates of q-ROFSs and made use of this concept for the information representation. In another research, Liu and Wang (2018) examined different geometric and arithmetic operators for q-ROFSs. In the study of Liu and Liu (2019), a number of q-ROF-Bonferroni mean operators were defined. Pinar and Boran (2020) designed a hybridized model using the distance measure for q-ROFSs and applied it to the problem of selecting suppliers. A number of neutral aggregation operators were introduced by Garg and Chen (2020) for q-ROFSs. Darko and Liang (2020) investigated a number of q-ROF Hamacher aggregation operators and examined the ways these operators could be applied. Krishankumar *et al.* (2020) presented an MCDM model using the q-ROFSs to obtain an effective solution to the problem of selecting renewable energy resources. Rani and Mishra (2020a, b) introduced an extended WASPAS method to evaluate the fuel technologies with the use of q-ROF-information.

An important challenge of DMs in any MCDM problem is the assessment of the criteria weights. Numerous procedures have been introduced in the literature for the computation of the criteria weights (Diakoulaki *et al.*, 1995; Kersuliene *et al.*, 2010; Mishra and Rani, 2019). To determine the criteria weights, two different approaches can be taken into consideration: objectivity and subjectivity (Peng, 2019a, b). The CRITIC tool was designed in 1995 by Diakoulaki *et al.* (1995) for the calculation of the objective weights of criteria. To implement the CRITIC model, the criteria weight is assessed with the use of the contrast intensity of the criteria, which is determined as the "*Standard Deviation (SD)*"; on the other hand, the conflicts among the criteria are computed with the use of the "*Correlation Coefficient (CRC)*." In different practical MCDM concerns, the CRITIC tool has been productively applied to the computation of the objective criteria weights (Adali and Tus, 2019; Tus and Adali, 2019; Zolfani *et al.*, 2020). For instance, Ghorabaee *et al.* (2017) combined two models, i.e. WASPAS and CRITIC, for the purpose of considering the 3PRLP with IT2FSs. After that, Ghorabaee *et al.* (2018) used the EDAS method together with the SWARA and CRITIC models to evaluate the construction equipment. Peng *et al.* (2020) applied CoCoSo and CRITIC to the evaluation of the 5G industry. In another research, Wei *et al.* (2020) used GRA and CRITIC tools for the solution of the optimum EVCS evaluation. Peng and Huang (2020) made use of CoCoSo with CRITIC procedure to analyze the financial risks. Mishra *et al.* (2021b) combined EDAS and CRITIC to evaluate the sustainable 3PRLP problem using the Fermatean fuzzy information. Mishra and Rani (2021) integrated CoCoSo and CRITIC to solve the sustainable 3PRLPs problem on SVNSs. The present paper discusses the multi-criteria blockchain technology in the problem of SCM selection on PFSs. The review of the relevant literature showed that no study had used the CRITIC approach to assess the criteria weights in the context of blockchain technology in the SCM selection process.

In recent years, an original MCDM model was proposed by Yazdani *et al.* (2019a), which was known as "*Combined Compromise Solution (CoCoSo)*." It incorporates the aggregated compromise algorithm with a variety of aggregation strategies with the aim of obtaining a compromise solution. They developed the method by combining two models, i.e. the weighted product measure (WPM) and simple additive weighting (SAW). Moreover, CoCoSo has been found highly stable and reliable in terms of ranking the available alternatives. Deleting or adding the options has less effects upon the final preference outcomes achieved by this approach compared to those obtained by "*VIKOR (Visekriterijumska optimizacija I Kompromisno Resenje),*" "*TOPSIS (Technique for Order Preference by Similarity to Ideal Solution)*" and other MCDM models (Yazdani *et al.*, 2019b). Pamucar and Cirovic (2015) designed the "*Multi-Attributive Border approximation Area Comparison (MABAC)*" model that is used to originate the distances from the alternatives to the "*Border Approximation Area (BAA)*." The MARCOS model was presented by Stević *et al.* (2019) on the basis of delineating the relationships between alternatives and "*Reference Points (RPs)*." VIKOR, TOPSIS and MARCOS present the preference degree from the "*Ideal Solution (IS)*" and "*Anti-ideal Solution (A-IS)*." The distances in VIKOR, TOPSIS and MABAC are summed up regardless of their relative importance. On the other hand, in decision-making processes, the reference point can be one of the most important concerns, and the human beings' rationale is to be as close as possible to the ideal state. TOPSIS uses an n-dimensional Euclidean distance that can denote some balance between the individual and total satisfaction.

CRITIC and CoCoSo were developed by Biswas *et al.* (2019) to select battery-operated electric vehicles (BEVs). Rani and Mishra (2020b) suggested a CoCoSo model to the evaluation of the WEEE recycling partner on "*Single-Valued Neutrosophic Sets (SVNSs).*" After that, CRITIC and CoCoSo were used by Biswas *et al.* (2020) for the purpose of selecting an automotive passenger vehicle of the highest level of feasibility. Mishra and Rani (2021) hybridized CRITIC and CoCoSo on SVNSs to assess the optimum S3PRLP. In a similar study, Mishra *et al.* (2021a) attempted to hybridize CoCoSo and discrimination measures on HFSs in a way to obtain a solution to the problem of S3PRLP assessment. Liu *et al.* (2021) attempted to assess and choose an appropriate technology for medical waste treatment with the help of a Pythagorean fuzzy CoCoSo approach. Deveci *et al.* (2021) introduced a generalized version of CoCoSo for the purpose of prioritizing the benefits of six real-time methods already proposed for managing traffic. Torkayesh *et al.* (2021) attempted to combine the level-based weight assessment (LBWA) and best–worst method (BWM) to determine the weights of healthcare indicators. Afterward, they applied CoCoSo to the evaluation of the healthcare performance in a number of countries based on the pre-determined indicator weights.

3.2 Basic concept

This section briefly presents elementary conceptions on q-ROFSs and similarity measures.

Definition 1. (Yager, 2017). Let $\Xi = \{z_1, z_2, \ldots, z_n\}$ be a finite discourse set. A q-ROFS "M" in Ξ is described as follows:

$$M = \{(z_i, \mu_M(z_i), \nu_M(z_i)) | z_i \in \Xi\}$$

Here, μ_M and ν_M signify the BD and NBD of $z_i \in \Xi$, respectively, $\mu_M(z_i) \in [0, 1] \nu_M(z_i) \in [0, 1], 0 \le (\mu_M(z_i))^q + (\nu_M(z_i))^q \le 1$, with $q \ge 1$. The "*Hesitancy Degree (HD)*" is defined as $\pi_M(z_i) = \sqrt[q]{1 - (\mu_M(z_i))^q - (\nu_M(z_i))^q}, \ \forall z_i \in \Xi$. The pair $(\mu_M(z_i), \nu_M(z_i))$ is referred as q-ROF number, denoted by $\varphi = (\mu_\varphi, \nu_\varphi)$.

Definition 2. For three q-ROFNs $\varphi = (\mu_\varphi, \nu_\varphi), \varphi_1 = (\mu_{\varphi_1}, \nu_{\varphi_1})$ and $\varphi_2 = (\mu_{\varphi_2}, \nu_{\varphi_2})$, the operations can be given by (Liu and Wang, 2018):

$$\varphi^c = (\nu_\varphi, \mu_\varphi);$$

$$\varphi_1 \oplus \varphi_2 = \left(\sqrt[q]{\mu_{\varphi_1}^q + \mu_{\varphi_2}^q - \mu_{\varphi_1}^q \mu_{\varphi_2}^q}, \nu_{\varphi_1} \nu_{\varphi_2} \right);$$

$$\varphi_1 \otimes \varphi_2 = \left(\mu_{\varphi_1} \mu_{\varphi_2}, \sqrt[q]{\nu_{\varphi_1}^q + \nu_{\varphi_2}^q - \nu_{\varphi_1}^q \nu_{\varphi_2}^q} \right);$$

$$\varsigma \varphi = \left(\sqrt[q]{1 - \left(1 - \mu_\varphi^q\right)^\varsigma}, \nu_\varphi^\varsigma \right), \ \varsigma > 0;$$

$$\varphi^\varsigma = \left(\mu_\varphi^\varsigma, \sqrt[q]{1 - \left(1 - \nu_\varphi^q\right)^\varsigma} \right), \ \varsigma > 0.$$

Definition 3. (Liu and Wang, 2018). Let $\varphi = (\mu_\varphi, \nu_\varphi)$ be a q-ROFN. Then, score and accuracy values of φ are presented as $S(\varphi) = \mu_\varphi^q - \nu_\varphi^q$ and $\hbar(\varphi) = \mu_\varphi^q + \nu_\varphi^q$, respectively, wherein $S(\varphi) \in [-1, 1]$ and $\hbar(\varphi) \in [0, 1]$ (Liu and Wang, 2018).

Definition 4. Assume that $\varphi = (\mu_{\varphi}, \nu_{\varphi})$ be a q-ROFN. Then, the improved score and uncertainty values are defined as:

$$S^{*}(\varphi) = \frac{1}{2}(S(\varphi)+1), \ \ \hbar^{\circ}(\varphi) = 1-\hbar(\varphi) \ \text{ such that } \ S^{*}(\varphi), \ \hbar^{\circ}(\varphi) \in [0,1]. \tag{1}$$

For any two q-ROFNs $\varphi_1 = (\mu_{\varphi_1}, \nu_{\varphi_1})$ and $\varphi_2 = (\mu_{\varphi_2}, \nu_{\varphi_2})$,

(1) If $S^{*}(\varphi_1) > S^{*}(\varphi_2)$, then $\varphi_1 > \varphi_2$,

(2) If $S^{*}(\varphi_1) = S^{*}(\varphi_2)$, then

- if $\hbar^{\circ}(\varphi_1) > \hbar^{\circ}(\varphi_2)$, then $\varphi_1 < \varphi_2$;
- if $\hbar^{\circ}(\varphi_1) = \hbar^{\circ}(\varphi_2)$, then $\varphi_1 = \varphi_2$.

Definition 5. (Liu *et al.*, 2019a). Let $\varphi_1 = (\mu_{\varphi_1}, \nu_{\varphi_1})$ and $\varphi_2 = (\mu_{\varphi_2}, \nu_{\varphi_2})$ be q-ROFNs. Now, the distance measure for φ_1 and φ_2 is discussed as:

$$D(\varphi_1, \varphi_2) = \frac{1}{2}\left(\left|\mu_{\varphi_1}^{q} - \mu_{\varphi_2}^{q}\right| + \left|\nu_{\varphi_1}^{q} - \nu_{\varphi_2}^{q}\right| + \left|\pi_{\varphi_1}^{q} - \pi_{\varphi_2}^{q}\right|\right). \tag{2}$$

3.3 Proposed q-Rung orthopair fuzzy- criteria importance through intercriteria correlation-combined compromise solution (q-ROF-CRITIC-CoCoSo) approach

Yazdani *et al.* (2019a) pioneered CoCoSo to address the MCDM problems. It works on the basis of SAW and the integrated EWP procedures. The present paper extends the capacities of CoCoSo by applying it to a new integrated model called q-ROF-CRITIC-CoCoSo. In this model, CRITIC is used for the description of ambiguous and complicated MCDM problems. The working procedure of q-ROF-CRITIC-CoCoSo is described below in detail:

Step 1: Generate a "*q-ROF-decision matrix (q-ROF-DM)*"

A set of ℓ DMs $A = \{A_1, A_2, ..., A_\ell\}$ determine the sets of m options $X = \{X_1, X_2, ..., X_m\}$ and n criteria $P = \{P_1, P_2, ..., P_n\}$, respectively. Owing to the imprecision of the human's mind, lack of data and imprecise knowledge about the options, the DMs allocate q-ROFNs to assess his/her decision on option X_i over a criterion P_j. Assume that $\mathbb{Z}^{(k)} = (\xi_{ij}^{(k)})_{m\times n}$, $i = 1, 2, ..., m, j = 1, 2, ..., n$ is the suggested decision matrix by DMs, where $\xi_{ij}^{(k)}$ refer to the evaluation of an option X_i over a criterion P_j in form of q-ROFN given by kth DM.

Step 2: Compute the weights of DMs

To determine the DMs' weights, the importance ratings of the DMs are defined as "*Linguistic Terms (LTs)*" and then articulated by q-ROFNs. To compute the kth DM, let $A_k = (\mu_k, \nu_k, \pi_k)$ be the q-ROFN. Now, the expert weight is obtained by:

$$\varpi_k = \frac{\left(\mu_k^q + \pi_k^q \times \left(\frac{\mu_k^q}{\mu_k^q + \nu_k^q}\right)\right)}{\sum_{k=1}^{\ell}\left(\mu_k^q + \pi_k^q \times \left(\frac{\mu_k^q}{\mu_k^q + \nu_k^q}\right)\right)}, \quad k = 1(1)\ell. \tag{3}$$

Here, $\varpi_k \geq 0$ and $\sum_{k=1}^{\ell} \varpi_k = 1$.

Step 3: Aggregate all q-ROF-DMs

To obtain the aggregated q-ROF-DM (A-q-ROF-DM), the "*q-ROF Weighted Averaging (q-ROFWA)*" operator is used and then $A = (\xi_{ij})_{m\times n}$, where:

$$\xi_{ij} = q - ROFWA_{\varpi}\left(\xi_{ij}^{(1)}, \xi_{ij}^{(2)}, \dots, \xi_{ij}^{(\ell)}\right) = \left(\sqrt[q]{1 - \prod_{k=1}^{\ell}\left(1 - \mu_k^q\right)^{\varpi_k}}, \prod_{k=1}^{\ell}(\nu_k)^{\varpi_k}\right). \quad (4)$$

Step 4: Employ the CRITIC tool for the assessment of criteria weights

Assume that $\omega = (\omega_1, \omega_2, \dots, \omega_n)^T$ is the criteria weight, where $\omega_j \in [0, 1]$ and $\sum_{j=1}^{n}\omega_j = 1$. This method tends to make the intensity contrast of every attribute and conflicts among the attributes completely unified. The steps involved in CRITIC on q-ROFSs are presented as:

Step 4-A: Obtain the score matrix $S = (\xi_{ij})_{m\times n}$, $i = 1(1)m$, $j = 1(1)n$, where

$$\xi_{ij} = \frac{1}{2}\left(\left(\mu_{ij}^q - \nu_{ij}^q\right) + 1\right), \quad (5)$$

Step 4-B: Create the standard q-ROF-DM $\tilde{S} = (\tilde{\xi}_{ij})_{m\times n}$, where

$$\tilde{\xi}_{ij} = \begin{cases} \dfrac{\xi_{ij} - \xi_j^-}{\xi_j^+ - \xi_j^-}, & j \in s_b \\[2ex] \dfrac{\xi_j^+ - \xi_{ij}}{\xi_j^+ - \xi_j^-}, & j \in s_n \end{cases} \quad (6)$$

wherein $\xi_j^+ = \max_i \xi_{ij}$ and $\xi_j^- = \min_i \xi_{ij}$.

Step 4-C: Estimate the SDs with equation (7):

$$\sigma_j = \sqrt{\frac{\sum_{i=1}^{m}\left(\tilde{\xi}_{ij} - \overline{\xi}_j\right)^2}{m}}, \quad \text{Wherein } \overline{\xi}_j = \sum\nolimits_{i=1}^{m}\tilde{\xi}_{ij}\Big/m. \quad (7)$$

Step 4-D: Measure the CRC between the criteria:

$$r_{jt} = \frac{\sum_{i=1}^{m}\left(\tilde{\xi}_{ij} - \overline{\xi}_j\right)\left(\tilde{\xi}_{it} - \overline{\xi}_t\right)}{\sqrt{\sum_{i=1}^{m}\left(\tilde{\xi}_{ij} - \overline{\xi}_j\right)^2 \sum_{i=1}^{m}\left(\tilde{\xi}_{it} - \overline{\xi}_t\right)^2}}. \quad (8)$$

Step 4-E: Define the amount of information of criteria and is given by:

$$c_j = \sigma_j \sum_{t=1}^{n}(1 - r_{jt}). \quad (9)$$

Step 4-F: Compute the criteria weight as follows:

$$\omega_j = \frac{c_j}{\sum_{j=1}^{n} c_j}. \quad (10)$$

Step 5: Create the normalized A-q-ROF-DM (NA-q-ROF-DM)

The NAPF-DM $\mathbb{R} = [\varsigma_{ij}]_{m\times n}$ is obtained from $A = (\xi_{ij})_{m\times n}$, and is presented by:

$$\varsigma_{ij} = \left(\overline{\mu}_{ij},\ \overline{\nu}_{ij}\right) = \begin{cases} \xi_{ij} = \left(\mu_{ij},\ \nu_{ij}\right), & \text{for benefit criterion,} \\ \left(\xi_{ij}\right)^{c} = \left(\nu_{ij},\ \nu_{ij}\right), & \text{for cost criterion.} \end{cases} \tag{11}$$

Step 6: Assess the "*Weighted Sum Measure (WSM)*" and "*Weighted Product Measure (WPM)*"

The WSM $\mathbb{C}_i^{(1)}$ and WPM $\mathbb{C}_i^{(2)}$ for each option are obtained as:

$$\alpha_i^{(1)} = \bigoplus_{j=1}^{n} w_j\, \varsigma_{ij}. \tag{12}$$

$$\alpha_i^{(2)} = \bigotimes_{j=1}^{n} w_j\, \varsigma_{ij}. \tag{13}$$

Step 7: Assess the balanced compromise degrees of alternatives

At this step, the relative degrees are defined to evaluate the options' balanced compromise degree as:

$$\beta_i^{(1)} = \frac{S^*\left(\alpha_i^{(1)}\right) + S^*\left(\alpha_i^{(2)}\right)}{\sum_{i=1}^{m}\left(S^*\left(\alpha_i^{(1)}\right) + S^*\left(\alpha_i^{(2)}\right)\right)}, \tag{14}$$

$$\beta_i^{(2)} = \frac{S^*\left(\alpha_i^{(1)}\right)}{\min_i S^*\left(\alpha_i^{(1)}\right)} + \frac{S^*\left(\alpha_i^{(2)}\right)}{\min_i S^*\left(\alpha_i^{(2)}\right)}, \tag{15}$$

$$\beta_i^{(3)} = \frac{\vartheta\, S^*\left(\alpha_i^{(1)}\right) + (1-\vartheta) S^*\left(\alpha_i^{(2)}\right)}{\vartheta \max_i S^*\left(\alpha_i^{(1)}\right) + (1-\vartheta)\max_i S^*\left(\alpha_i^{(2)}\right)}. \tag{16}$$

Here, ϑ is the decision parameter, and $\vartheta \in [0, 1]$. Generally, we take $\vartheta = 0.5$.

Step 8: Estimate the overall compromise degree

The final degree β_i is computed to express the importance rating of the option as:

$$\beta_i = \frac{1}{3}\left(\beta_i^{(1)} + \beta_i^{(2)} + \beta_i^{(3)}\right) + \left(\beta_i^{(1)}\, \beta_i^{(2)}\, \beta_i^{(3)}\right)^{1/3}. \tag{17}$$

The prioritization of options is obtained by increasing the order of the overall compromise degree β_i.

4. Results

4.1 Case study

The current paper attempts to identify the obstacles to adopting CSCs in the age of Industry 4.0 transition with the use of a hybrid research methodology. First, the extant literature was reviewed and analyzed using a survey approach to identify essential barriers influencing CSCs in the era of Industry 4.0 transition. In total, this study 13 barriers are including lack of technology transfers integration, inefficient training and education, high investments in

Industry 4.0 technologies, data security in relationship management, lack of knowledge among stakeholders, lack of IoT facilities for product recovery and tracking, poor management support for Industry 4.0 technologies in R&D activities, lack of decentralized organizational structure understanding, lack of Industry 4.0 adoption technologies for high transparency, lack of governmental support and protocols for Industry 4.0, lack of awareness EOL activities, lack of knowledge in Industry 4.0 technologies and lack of organizational trust and willingness in the Industry 4.0 transformation are identified to implement CSC in the era of Industry 4.0. In the second stage, a comprehensive framework has been developed to identify the adoption barriers of CSC in the Industry 4.0 era. Data collection was done with a focus group study held in 2020 based on seven decision-makers (DMs) who work on the CE in the manufacturing industry. The present paper made use of a simple sampling technique. In sampling, the experts were selected by considering the criterion that the experts should have a minimum of ten years of working experience in sustainable development, SC and CE in the manufacturing sector. Then, the selected ones were contacted via telephone or their LinkedIn accounts. Nine experts were asked to participate in our research, but only six could participate in this study, and three had to reject our request because of their time limitations. For that reason, the opinions received from three experts were utilized to list the barriers. These DMs discussed the barriers in "*Sustainable Circular Supply Chain (SCSC)*" for the selected manufacturing companies. In the focus group study, four DMs came from the selected manufacturing companies, who had the SC perspective, one DM was from the production sector and one academic was from the production and manufacturing engineering departments in a university, who have the theoretical perspective and practical information in the SCM and sustainable development CE.

Step 1–2: Assume that the DMs' weights are given in terms of q-ROFNs, presented by {(0.85, 0.50, 0.6390), (0.70, 0.65, 0.7258), (0.75, 0.60, 0.7128), (0.80, 0.55, 0.6851)}. Now, Table 1 defines the ratings of DMs to evaluate the options over related criteria. Table 2 presents the q-ROF-DM $\mathbb{Z}^{(k)} = (\xi_{ij}^{(k)})_{m\times n}$, $k = 1, 2, 3$. DMs' importance degrees, as provided by the DMs, are in terms q-ROFNs. Now, the crisp weights λ_k: 1, 2, 3, 4 of DMs are evaluated by employing equation (3) and given as $\{\varpi_1 = 0.2965,\ \varpi_2 = 0.1982,\ \varpi_3 = 0.2360,\ \varpi_4 = 0.2693\}$.

Step 3: Using equation (4) to obtain an A-q-ROF-DM $A = (\xi_{ij})_{m\times n}$ for different CSCs barriers in the era of Industry 4.0 transition and is presented in Table 3.

Step 4. To obtain the barrier's weights, the CRITIC tool is utilized on q-ROFSs. Using equations (5) and (6) and Table 4, the score matrix $S = (\chi_{ij})_{p\times q}$. standard q-ROF-DM $\tilde{S} = (\tilde{\chi}_{ij})_{p\times q}$ are obtained. Then, by equations (7)–(9), the SD, CRC and amount of

LVs	q-ROFNs
Absolutely high (AH)	(0.95, 0.20)
Very high (VVH)	(0.90, 0.35)
Very high (VH)	(0.85, 0.50)
High (H)	(0.80, 0.60)
Medium high (MH)	(0.70, 0.65)
Average (A)	(0.60, 0.70)
Medium low (ML)	(0.50, 0.75)
Low (L)	(0.40, 0.80)
Very low (VL)	(0.30, 0.90)
Absolutely low (AL)	(0.20, 0.95)

Table 1.
Performance ratings of options and CSCs barriers

Table 2. LTs of options over different CSCs barriers by DMs

	C_1	C_2	C_3	C_4	C_5
s_1	(VH, A, MH, VVH)	(A, ML, ML, A)	(MH, H, A, A)	(A, ML, ML, MH)	(MH, MH, A, A)
s_2	(ML, A, VVH, H)	(ML, MH, VH, VH)	(VH, VH, A, MH)	(MH, ML, MH, VH)	(A, VH, A, MH)
s_3	(MH, VH, VH, H)	(H, VH, H, VVH)	(VH, MH, A, H)	(A, VH, H, VVH)	(A, MH, A, H)
s_4	(MH, ML, A, MH)	(MH, VH, A, H)	(MH, ML, ML, MH)	(VH, VH, A, H)	(A, ML, ML, MH)
s_5	(MH, ML, MH, VH)	(MH, ML, H, H)	(A, MH, ML, A)	(H, ML, H, H)	(H, MH, ML, A)
s_6	(ML, VL, MH, L)	(L, A, VL, ML)	(L, VL, MH, A)	(A, L, VL, ML)	(VL, L, MH, A)
s_7	(MH, ML, MH, L)	(ML, L, ML, L)	(ML, A, ML, A)	(VL, L, ML, L)	(ML, A, ML, A)
s_8	(VH, H, VVH, VH)	(H, A, VVH, VH)	(MH, ML, A, MH)	(H, A, VVH, VH)	(ML, ML, A, MH)
s_9	(MH, MH, A, H)	(H, A, VH, H)	(VH, A, MH, H)	(MH, A, VH, H)	(VH, A, MH, H)
s_{10}	(ML, ML, L, A)	(ML, L, VL, VL)	(ML, L, A, ML)	(L, L, VL, VL)	(ML, L, A, ML)
s_{11}	(ML, ML, L, L)	(A, MH, ML, L)	(ML, MH, H, A)	(A, MH, ML, L)	(ML, MH, H, A)
s_{12}	(L, A, ML, ML)	(ML, L, A, ML)	(MH, H, MH, A)	(ML, L, A, ML)	(MH, H, MH, A)
s_{13}	(H, H, A, VH)	(MH, MH, ML, A)	(MH, VH, MH, A)	(H, MH, ML, A)	(MH, VH, MH, ML)

Table 3.
A-q-ROF-DM for different CSCs barriers

	C_1	C_2	C_3	C_4	C_5
s_1	(0.812, 0.517, 0.273)	(0.561, 0.721, 0.407)	(0.683, 0.664, 0.304)	(0.642, 0.692, 0.329)	(0.654, 0.675, 0.342)
s_2	(0.754, 0.582, 0.304)	(0.761, 0.594, 0.260)	(0.776, 0.581, 0.246)	(0.730, 0.623, 0.281)	(0.700, 0.642, 0.313)
s_3	(0.802, 0.568, 0.185)	(0.844, 0.501, 0.193)	(0.769, 0.599, 0.224)	(0.812, 0.524, 0.259)	(0.690, 0.662, 0.293)
s_4	(0.647, 0.680, 0.343)	(0.752, 0.615, 0.238)	(0.630, 0.692, 0.353)	(0.798, 0.569, 0.198)	(0.596, 0.707, 0.381)
s_5	(0.730, 0.623, 0.281)	(0.734, 0.642, 0.222)	(0.604, 0.701, 0.379)	(0.764, 0.627, 0.152)	(0.682, 0.670, 0.295)
s_6	(0.512, 0.765, 0.391)	(0.454, 0.787, 0.418)	(0.533, 0.752, 0.387)	(0.476, 0.777, 0.412)	(0.528, 0.761, 0.377)
s_7	(0.609, 0.707, 0.360)	(0.457, 0.773, 0.440)	(0.551, 0.726, 0.411)	(0.403, 0.816, 0.414)	(0.551, 0.726, 0.411)
s_8	(0.856, 0.477, 0.200)	(0.822, 0.519, 0.234)	(0.647, 0.557, 0.520)	(0.822, 0.519, 0.234)	(0.591, 0.710, 0.384)
s_9	(0.714, 0.647, 0.266)	(0.788, 0.593, 0.168)	(0.771, 0.597, 0.221)	(0.761, 0.607, 0.229)	(0.771, 0.597, 0.221)
s_{10}	(0.512, 0.747, 0.424)	(0.393, 0.833, 0.390)	(0.511, 0.747, 0.425)	(0.354, 0.849, 0.392)	(0.511, 0.747, 0.425)
s_{11}	(0.454, 0.775, 0.440)	(0.563, 0.727, 0.394)	(0.663, 0.679, 0.315)	(0.563, 0.727, 0.394)	(0.663, 0.679, 0.315)
s_{12}	(0.498, 0.754, 0.428)	(0.511, 0.747, 0.425)	(0.703, 0.653, 0.283)	(0.511, 0.747, 0.425)	(0.703, 0.653, 0.283)
S_{13}	(0.785, 0.592, 0.183)	(0.637, 0.686, 0.351)	(0.721, 0.615, 0.320)	(0.682, 0.670, 0.295)	(0.695, 0.653, 0.302)

Barriers	C_1	C_2	C_3	C_4	C_5	σ_j	c_j	w_j
s_1	1.000	0.000	0.386	0.234	0.299	0.334	3.636	0.0600
s_2	0.816	0.799	1.000	0.357	0.000	0.365	4.008	0.0662
s_3	0.669	1.000	0.459	0.817	0.000	0.344	4.538	0.0749
s_4	0.220	0.725	0.138	1.000	0.000	0.381	5.531	0.0913
s_5	0.855	0.797	0.000	1.000	0.450	0.359	5.133	0.0848
s_6	0.687	0.000	1.000	0.279	0.857	0.372	4.188	0.0691
s_7	1.000	0.308	0.748	0.000	0.748	0.358	3.909	0.0645
s_8	1.000	0.851	0.399	0.851	0.000	0.370	4.647	0.0767
s_9	0.000	1.000	0.823	0.673	0.823	0.348	5.081	0.0839
s_{10}	1.000	0.187	0.998	0.000	0.998	0.447	4.952	0.0818
s_{11}	0.000	0.489	1.000	0.489	1.000	0.375	5.086	0.0840
s_{12}	0.000	0.059	1.000	0.059	1.000	0.471	6.113	0.1009
S_{13}	1.000	0.000	0.626	0.243	0.369	0.342	3.750	0.0619

Table 4. Implementation of CRITIC method for CSCs barrier's weight

information of each barrier are evaluated. At last, the weight values of the CSCs barriers in the era of Industry 4.0 transition are computed using equation (10) and given in Table 4.

Figure 2 demonstrates the significance degree or weights of various CSCs barriers in the age of Industry 4.0 transition in line with the objectives of the present study. The most important obstacle to CSCs in this era was found to be the absence of knowledge about the Industry 4.0 technologies and circular approaches (s_{12}), with a rating of 0.1009. It was followed by the problems associated with data security in relationship management in circular flows (s_4), with a rating of 0.0913. Then, the third significant barrier was the deficiency of knowledge regarding the data management among stakeholders (s_5), with a rating of 0.0848. The next significant barrier was found to be the lack of awareness about the potential benefits of autonomous systems in labor-oriented EoL activities (s_{11}), with the weight value of 0.0840. The fifth item in this ranking was the problem of not adopting the Industry 4.0 technologies for higher transparency in circular flows (s_9), with the weight value of 0.0839.

Step 5: Since all risk factors values are beneficial, there is no requirement to obtain the NA-ROF-DM.

Steps 6–8: Utilizing equations (11) and (12) to obtain the WPM and WSM degrees for the different companies over different CSCs barriers in the era of Industry 4.0 transition. From equations (13)–(17), the outcomes of the q-ROF-CRITIC-CoCoSo method are obtained and are mentioned in Table 5. Corresponding to the compromise degree β_i, the prioritization of companies over different CSCs barriers is $C_3 \succ C_1 \succ C_2 \succ C_4 \succ C_5$, and thus, Company III (C_3) is the ideal option over different CSCs barriers in the era of Industry 4.0 transition.

4.2 Comparative study

The result of the q-ROF-CRITIC-CoCoSo method was compared with the results of another approach. To demonstrate the efficacy and the unique advantages of the introduced method, the q-ROF-WASPAS (Rani and Mishra, 2020a, b), q-ROF-TOPSIS (Liu *et al.*, 2019) are employed to tackle the same problem.

4.2.1 q-Rung orthopair fuzzy-weighted aggregated sum product assessment (q-ROF-WASPAS) method.

Steps 1–6: Similar to the aforementioned model

Step 7: For each alternative, compute the aggregated measure of WASPAS with the use of equation (18):

Figure 2.
Significance values/
weight of different
CSCs barriers

Table 5. Results of different companies over different CSCs barriers using q-ROF-CRITIC-CoCoSo

Options	$\alpha_i^{(1)}$	$\alpha_i^{(2)}$	$S^*(\alpha_i^{(1)})$	$S^*(\alpha_i^{(2)})$	$\beta_i^{(1)}$	$\beta_i^{(2)}$	$\beta_i^{(3)}$	β_i	Ranking
C_1	(0.681, 0.660, 0.318)	(0.634, 0.685, 0.360)	0.5143	0.4663	0.2025	2.1122	0.9832	1.8485	2
C_2	(0.683, 0.661, 0.310)	(0.623, 0.689, 0.371)	0.5153	0.4566	0.2007	2.0925	0.9744	1.8316	3
C_3	(0.666, 0.663, 0.342)	(0.646, 0.673, 0.359)	0.5018	0.4822	0.2032	2.1211	0.9865	1.8556	1
C_4	(0.683, 0.664, 0.304)	(0.619, 0.695, 0.366)	0.5127	0.4500	0.1988	2.0724	0.9651	1.8141	4
C_5	(0.651, 0.684, 0.331)	(0.636, 0.689, 0.348)	0.4781	0.4650	0.1948	2.0333	0.9454	1.7785	5

$$\alpha_i = \lambda \alpha_i^{(1)} + (1-\lambda) \alpha_i^{(2)}, \tag{18}$$

where λ stands for the decision parameter. It was proposed with the aim of estimating the WASPAS accuracy level based on the initial attributes precision and when $\lambda \in [0, 1]$.

Step 8: Prioritize the options based on the decreasing degrees (i.e. score values) of α_i.

Steps 5–8: Applying equation (18), the WASPAS (α_i) measures for each company option are obtained and depicted in Table 6. Therefore, the prioritization of companies is assessed as $C_3 \succ C_1 \succ C_2 \succ C_4 \succ C_5$ and C_3, i.e. Company III, is the most desirable option.

4.2.2 q-Rung orthopair fuzzy-technique for order preference by similarity to ideal solution (q-ROF-TOPSIS) method. The q-ROF-TOPSIS tool involves the steps as:

Steps 1–4: Same as aforementioned model

Step 5: Define "*q-ROF-IS*" and "*q-ROF-A-IS*", given as:

$\alpha^+ = \{$(0.812, 0.517, 0.273), (0.776, 0.581, 0.246), (0.844, 0.501, 0.193), (0.798, 0.569, 0.198), (0.764, 0.627, 0.152), (0.533, 0.752, 0.387), (0.609, 0.707, 0.360), (0.856, 0.477, 0.200), (0.788, 0.593, 0.168), (0.512, 0.747, 0.424), (0.663, 0.679, 0.315), (0.703, 0.653, 0.283), (0.785, 0.592, 0.183)$\}$

$\alpha^- = \{$(0.561, 0.721, 0.407), (0.700, 0.642, 0.313), (0.690, 0.662, 0.293), (0.596, 0.707, 0.381), (0.604, 0.701, 0.379), (0.454, 0.787, 0.418), (0.403, 0.816, 0.414), (0.591, 0.710, 0.384), (0.714, 0.647, 0.266), (0.354, 0.849, 0.392), (0.454, 0.775, 0.440), (0.498, 0.754, 0.428), (0.637, 0.686, 0.351)$\}$.

Next, we measure the discrimination between the alternative C_i and the "*q-ROF-IS*" as well as "*q-ROF-A-IS*."

Step 6: Obtain the "*Closeness Index (CI)*" of each option as:

$$CI(C_i) = \frac{\Upsilon_i^-}{\Upsilon_i^+ + \Upsilon_i^-},$$

where

$$\Upsilon_i^+ = D(\xi_{ij}, \alpha^+) = \sum_{j=1}^{n} w_j \sqrt{\tfrac{1}{2}\left[\left((\mu_{ij})^q - (\mu_j^+)^q\right)^2 + \left((\nu_{ij})^q - (\nu_j^+)^q\right)^2 + \left((\pi_{ij})^q - (\pi_j^+)^q\right)^2\right]}$$

and $\Upsilon_i^- = D(\xi_{ij}, \alpha^-) = \sum_{j=1}^{n} w_j \sqrt{\tfrac{1}{2}\left[\left((\mu_{ij})^q - (\mu_j^-)^q\right)^2 + \left((\nu_{ij})^q - (\nu_j^-)^q\right)^2 + \left((\pi_{ij})^q - (\pi_j^-)^q\right)^2\right]}$.

Therefore, we get $CI(C_1) = 0.6004$, $CI(C_2) = 0.4972$, $CI(C_3) = 0.5708$, $CI(C_4) = 0.5187$ and $CI(C_5) = 0.4520$.

Step 7: Rank the companies as $C_1 \succ C_3 \succ C_4 \succ C_2 \succ C_5$, i.e. the most effective manufacturing firm-I (C_1) for the CSCs barriers in the era of Industry 4.0 transition. Apparently, the outcomes are slightly different with introduced and extant methods.

Table 6.
Results of q-ROF-WASPAS model

	WSM		WPM			
Options	$\alpha_i^{(1)}$	$S^*(\alpha_i^{(1)})$	$\alpha_i^{(2)}$	$S^*(\alpha_i^{(2)})$	WASPAS $\alpha_i(\lambda)$	Ranking
C_1	(0.681, 0.660, 0.318)	0.5143	(0.634, 0.685, 0.360)	0.4663	0.4903	2
C_2	(0.683, 0.661, 0.310)	0.5153	(0.623, 0.689, 0.371)	0.4566	0.4859	3
C_3	(0.666, 0.663, 0.342)	0.5018	(0.646, 0.673, 0.359)	0.4822	0.4920	1
C_4	(0.683, 0.664, 0.304)	0.5127	(0.619, 0.695, 0.366)	0.4500	0.4813	4
C_5	(0.651, 0.684, 0.331)	0.4781	(0.636, 0.689, 0.348)	0.4650	0.4715	5

So far, the q-ROF-SWARA-CoCoSo approach is more resilient and stable than the q-ROF-TOPSIS and q-ROF-WASPAS approaches and thus has wider applicability.

As compared to the above-discussed methods, the q-ROF-CRITIC-CoCoSo approach is more robust and thus has a broader range of implementation. The main benefits of the q-ROF-CRITIC-CoCoSo method are the following (Figure 3):

(1) The q-ROFSs can reveal the DM's indecision more accurately than other traditional generalizations of "*Fuzzy Sets (FSs).*" Consequently, the implementation proposed q-ROF-CRITIC-CoCoSo framework provides a more flexible model to discuss the uncertainty and evaluate sustainable CSCs barriers in manufacturing companies.

(2) The CRITIC tool is implemented to assess the weights of the sustainable CSCs barriers in manufacturing companies, which creates the proposed q-ROF-CRITIC-CoCoSo framework more consistent, effective and sensible.

(3) The introduced q-ROF-CRITIC-CoCoSo can describe the q-ROF-information in a more effective and appropriate manner and from diverse viewpoints, namely, benefit and non-benefit attributes.

4.3 Sensitivity investigation

Here, a sensitivity investigation was carried out to examine how the method proposed in this paper could perform the tasks defined. In this sense, the effects of changing the parameter ϑ on the rankings of the organizations are discussed. Figure 4 displays the analysis of the effect of the value of the coefficient ϑ ($0 \le \vartheta \le 1$) upon the ratings of the main CSCs barriers in the age of Industry 4.0 transition and the utility degrees of the firms. For each company, the overall compromise indexes were measured based on different values of the parameter ϑ. The obtained results are depicted graphically in Figure 4. Accordingly, it can be noticed that the firm options under different CSCs barriers in the age of Industry 4.0 transition are dependent upon and are sensitive to different parameter ϑ values. As a result, q-ROF-CRITIC-CoCoSo was confirmed to be of acceptable stability with various values of ϑ. According to the

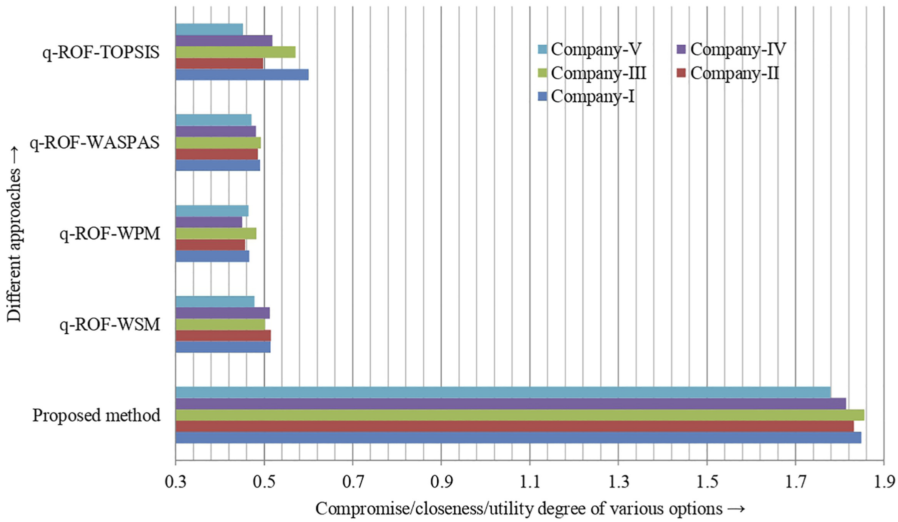

Figure 3.
Utility degree of each company over different sustainable CSCs barriers with extant methods

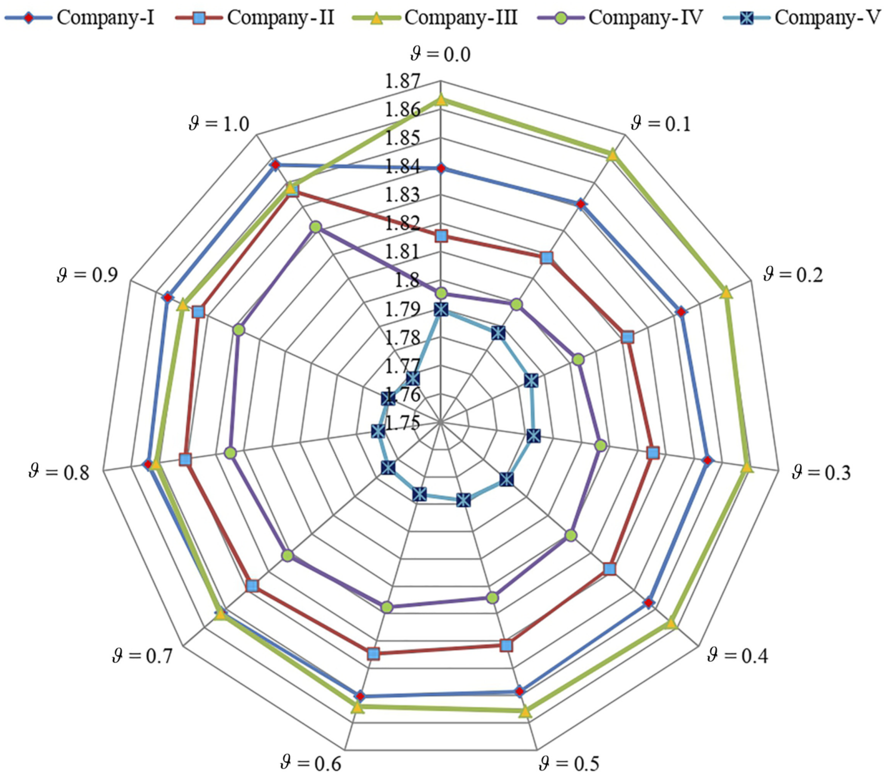

Figure 4.
The compromise degree of the company over parameter (ϑ)

data presented in Table 7 and Figure 4, option C_1 obtained the first rank, while C_3 obtained the last one. As can be observed in Table 7 and Figure 4, changes in the parameter ϑ in the interval [0, 1] minimally affected a change in the value of the main CSCs barriers in the age of Industry 4.0 transition. The analyses results showed that q-ROF-CRITIC-CoCoSo does not depend on any bias, and the results gained in this study are stable in nature.

5. Conclusions

With such a dynamic business environment of Industry 4.0 and CE, businesses have to be exposed to the digitization of processes to remain competitive. For making sure of sustainability of operations, digitization should link Industry 4.0 technologies with CE dimensions. However, companies generally encounter several obstacles hindering the full exploitation of the CE and Industry 4.0 benefits. The most important challenge to the extant production systems is finding the best way to adopt these technological changes to be completely effective and integrated. Today, to effectively handle these sustainability barriers, firms require to adopt a holistic approach. The current paper proposed a new MCDM method with the use of q-ROFSs to analyze, rank and evaluate the CSCs barriers in the age of Industry 4.0 transition. To this end, an extended MCDM approach with the help of CRITIC and CoCoSo methods on q-ROFSs called q-ROF-CRITIC-CoCoSo was introduced to evaluate the CSCs barriers in the era of Industry 4.0 transition. For computing each CSCs barriers' weight in the era of Industry 4.0 transition using CRITIC, the DMs' role is highly important in measuring and computing the weights. To compute the preference order of manufacturing firm over

Options	$\vartheta = 0.0$	$\vartheta = 0.1$	$\vartheta = 0.2$	$\vartheta = 0.3$	$\vartheta = 0.4$	$\vartheta = 0.5$	$\vartheta = 0.6$	$\vartheta = 0.7$	$\vartheta = 0.8$	$\vartheta = 0.9$	$\vartheta = 1.0$
C_1	1.8391	1.8410	1.8429	1.8448	1.8467	1.8485	1.8503	1.8521	1.8539	1.8556	1.8574
C_2	1.8155	1.8188	1.8221	1.8253	1.8285	1.8316	1.8347	1.8378	1.8408	1.8437	1.8466
C_3	1.8635	1.8619	1.8603	1.8587	1.8571	1.8556	1.8540	1.8525	1.8511	1.8496	1.8481
C_4	1.7953	1.7992	1.8030	1.8068	1.8105	1.8141	1.8177	1.8213	1.8248	1.8282	1.8316
C_5	1.7896	1.7873	1.7851	1.7829	1.7807	1.7785	1.7764	1.7743	1.7722	1.7702	1.7682

Table 7. Compromise degree of company over different value of parameter (ϑ)

different CSCs barriers in the era of Industry 4.0 transition, the CoCoSo method is applied. To validate the results of this study, a comparison using the q-ROF-WASPAS, q-ROF-WPM q-ROF-WSM, q-ROF-TOPSIS methods is conducted.

The majority of employees currently working in business firms are unfamiliar with developing technologies such as Industry 4.0. Because of such deficiency in knowledge, companies cannot adopt these technologies to satisfy the CE objectives effectively. Another important obstacle in this regard is the short-term goals of managers; this causes managers not to be focused on the integration of Industry 4.0-based technologies into sustainability criteria in performance evaluation. Companies generally delay making a decision about making substantial monetary investments in Industry 4.0 technologies, and conventional performance frameworks are not relevant in the current business setting. Companies need to provide a performance framework taking into account the present business environment of Industry 4.0 and CE. Three important barriers to the use of sustainability are (1) mis-investment, (2) inadequacy of legislation and control, and (3) resistance of employees to change in the existing production system.

The transformation of businesses toward CE would create value through closed-loop systems, eco-design, reverse logistics, clean production, product life cycle management and a climate-neutral economy. Though, many types of obstacles exist, which can hinder the transition of firms to CE. A significant barrier in this regard is the policy-related obstacles that need to be further studied. In consequence, the present research was aimed at filling such gaps by depicting the policy-related obstacles that may obstruct the path of firms toward the transition to CE in the corporate environmental management context in SCs. The findings of this paper can aid industry practitioners in fixing their attention to the digitization or automation of their systems in the context of sustainability or resource circularity. Note that within the current context of CE, one of the crucial issues is how to conserve the existing resources; the answer to this question can save the environment.

The findings of this research can also enhance our knowledge regarding different barriers to the sustainable operations of the entire SC. After recognizing the priority ranking of various barriers, managers need to provide an operative action plan for sustainable operations in the current business setting of CE and Industry 4.0. Companies must integrate the principles of CE and Industry 4.0 in their manufacturing processes to be both sustainable and competitive. Some efficient performance frameworks are needed to be constructed, taking into account the CE and Industry 4.0 requirements. The present paper contributes to the body of knowledge by, first, proposing a framework that recognizes the policy-related barriers to transition to CE in the context of SCs; second, identifying the cause and effect relationships among different barriers recognized in this study; and finally, applying the research to the manufacturing sector focusing on India as a developing economy. The literature shows that in developing economies, companies do not show enthusiasm for the adoption of sustainability and technological innovations. For that reason, policymakers need to provide the necessary guidelines to hone the workforce skills and encourage them to accept and use novel changes in the age of Industry 4.0 and CE. The government needs to find a way to promote the acceptance and implementation of new technologies in business and manufacturing operations. Those companies that adopt the concepts of CE and Industry 4.0 would demonstrate higher levels of sustainability and competitiveness in global markets. The framework designed in this paper is completely generic and applicable to SCs of the different sectors, e.g. durable goods and food.

A limitation may be that despite the generalizability of the proposed framework, the results may differ when it is implemented in different sectors. By emphasizing the obstacles to sustainable operations of SCs in the context of CE and Industry 4.0, researchers working in the same domain may be encouraged to find possible ways to remove such obstacles in different settings. As suggested in this study, the priority of various barriers helps researchers suggest effective strategies for the sustainable development of companies within the current dynamic business atmosphere. They also could explore the need for newer knowledge/skills according to the current requirements of the industry. The findings of this study could also aid in preparing and validating an inclusive performance framework to ensure sustainable operations. Future studies can be focused upon the evaluation of the barriers identified in the present paper, and they can discuss priorities offered here and interdependencies with the use of various decision-making techniques. In addition, future research can be focused on the development of critical implications to remove the barriers. Furthermore, other obstacles in this regard, e.g. organizational, financial, social, technological, market-based, logistics-based and policy-related obstacles, can be taken into account as a large barrier set for the manufacturing industry. Finally, future research can also be concentrated on the large set of policy-related barriers and the identification of specific requirements and considerations in the context of various industries.

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