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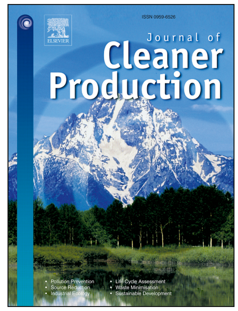

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Hassan Mina, Devika Kannan, Seyed Mohammad Gholami-Zanjani, Mehdi Biuki

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Hassan Mina[2]; Devika Kannan[1a]; Seyed Mohammad Gholami-Zanjani [3]; Mehdi Biuki[4]

[1] Center for Sustainable Supply Chain Engineering, Department of Technology and Innovation, University of Southern Denmark, Odense M, Denmark.

[2] School of Industrial Engineering, College of Engineering, University of Tehran, Tehran, Iran.

[3] School of Industrial Engineering, Iran University of Science and Technology, Tehran, Iran.

[4] Department of Industrial Engineering, Faculty of Industrial and Mechanical Engineering, Qazvin Branch, Islamic Azad University, Qazvin, Iran.

[a] Corresponding author (deka@iti.sdu.dk)

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Abstract

In view of controversial environmental issues and increased public awareness, companies are increasingly under pressure from their beneficiaries and governments to become environmentally friendly. These environmentally competitive conditions have led companies to emphasize green practices in their daily operations, and a critical aspect of environmental operations involves the selection of circular suppliers for collaboration. In this paper, a novel approach is developed by integrating multi-criteria decision-making (MCDM) methods and fuzzy inference system (FIS) to evaluate and rank the suppliers towards the transition in the circular supply chain. In the proposed approach, the weights of sub-criteria are determined based on the fuzzy analytic hierarchy process (FAHP) method and, then, the score of each supplier in terms of each criterion is calculated by the fuzzy technique for order of preference by similarity to the ideal solution (FTOPSIS). At the end, the final score of the suppliers is calculated and the suppliers are ranked using a FIS. Since each method of the above-mentioned suffers some drawbacks in addition to its unique advantages, this study attempts to overcome these disadvantages through the integration of these methods for the first time. This study contributes to the sustainable development goals (SDG's) such as Good Health, and Wellbeing (SDG 3); Clean Water and Sanitation (SDG 6); Decent Work and Economic Growth (SDG 8); Industry, Innovation and Infrastructure (SDG 9); Responsible Consumption and Production (SDG 12) and Climate Action (SDG 13). In this way, a practical approach will be proposed for ranking suppliers in the circular supply chain. This approach was applied to an Iranian petrochemical company with six suppliers involved. The performance of proposed approach is validated through comparing it with two other methods by using the Spearman rank correlation coefficient. The results, obtained through comparisons and experts' opinions, show that the proposed approach is efficient and applicable.

***Keywords*:** Circular supplier selection; Circular supply chain; Fuzzy theory; TOPSIS; Analytic hierarchy process; Fuzzy inference system; Sustainable development goals (SDG's)

1. Introduction

In the current competitive world, most enterprises seek to pursue cost reduction and to enhance their product quality at the same time. In some industries, about 70 percent of costs pertain to details associated with purchases (Mirzaee et al., 2018). Accordingly, a reliable method of supplier selection is a significant issue since this choice has an impact on costs. However, supplier selection is not solely limited to cost criterion; other criteria, such as on-time delivery, product quality, risk, and the like must be weighed during the evaluation process. Supplier selection is regarded as a multi-criteria decision-making (MCDM) problem in which tangible and intangible criteria are considered (Guarnieri and Trojan, 2019). Furthermore, it should be mentioned that some of these criteria may be inconsistent with each other.

It is also noteworthy that, as the main element for the effectiveness and profitability of any supply chain, suppliers have a pivotal role and, thereby, pertinent supplier selection exerts a direct effect on profitability since it may lead to cost reduction, an increase in profit margins, an enhancement in products' quality, and the on-time delivery of products to customers (Chan and Kumar, 2007). In this regard, Sawik (2010) states that supplier selection aims at introducing the optimal supplier who is capable of providing the best possible products or services to customers and can act as some part of the organizational supply chain. Supplier evaluation and selection addresses the strategic problems where the emerging trend aims at selecting suppliers with a lasting relationship (Araz et al., 2007).

In recent years, with concerns raised about environmental degradation, the search for solutions to control and mitigate this damaging trend has been on the agenda for most industries and organizations. The traditional methods of SCMs are mostly based on a linear economy referred to as take-make-consume-dispose, which generates a considerable amount of waste and depletes the environmental resources. It also leads to natural resource scarcity and severely pollutes the environment (Genovese et al., 2017; Goyal et al., 2018). In this line, it is witnessed that the world's community generates 1.3 billion tons of waste per year. It is anticipated to increase up to 2.2 billion tons by 2050, which highlights the urgent need towards incorporating sustainability considerations. The circular economy (CE) is a recent approach to mitigate undesired environmental impacts (Lahane et al., 2020). This approach in the supply chain entitles as circular SCM increase the competitiveness of supply chains and protect the environment. In this regard, in addition to the inner practices, commitments to outside sustainability are considered (Ageron et al., 2012). Accordingly, more business occasions are created and benefited from. Moreover, some newly passed rules and regulations put firms under pressure to assign credit to CE criteria in their decision-making processes (Jabbour et al., 2014).

As the first level of the supply chain network, suppliers have a noteworthy role in reducing environmental degradation and increasing the competitiveness of organizations (Mardan et al., 2019). Therefore, selecting the suppliers and implementing common and circularity criteria at the same time, helps to protect the environmental resources in addition to increasing network efficiency and reducing costs. Supplier selection regarding environmental criteria has concerned many researchers. Progressively, more authors have addressed supplier selection matters in green supply chains from environmental facets (e.g. Gao et al., 2020; Haeri and Rezaei, 2019; Lo et al., 2018; Mousakhani et al., 2017).

Choosing the most effective and appropriate criteria besides an efficient method for evaluating suppliers are the two crucial factors in supplier selection and evaluation approaches. These two factors complement each other so that neglecting either of them would lead to the inefficiency of the evaluation process. For this reason, the two basic questions in supplier selection researches are "Which criteria are suitable for supplier selection process?" and "Which method is most effective in evaluating the suppliers?". It should be noted that the selecting the appropriate criteria and the effective method depend heavily on the business context (Qazvini et al., 2019). Since the purpose of this article is to evaluate and select petrochemical industry suppliers, research questions can be stated as follows:

- What are the most appropriate common and circular criteria for selecting petrochemical industry suppliers?

- What approach is suitable for weighting the criteria using a linear relationship and for calculating the final score using a nonlinear relationship for ranking the petrochemical industry suppliers in the circular supply chain?

This paper seeks to develop an integrated approach through the combination of MCDM methods and FIS for the evaluation and ranking of petrochemical industry suppliers in the circular supply chain to achieve Sustainable development goals (SDG's). In the proposed approach, the weights of the sub-criteria are first calculated using the FAHP method; thereafter, the performance of each supplier is evaluated regarding each criterion by FTOPSIS. Finally, the final score of suppliers is calculated using a FIS and, accordingly, the suppliers are ranked. Since there is a hierarchy structure between goals, criteria, sub-criteria, and alternatives in the proposed approach and the sub-criteria of each criterion are of one category type, there is the possibility of considering a linear relationship between them. Therefore, it is recommended to use FAHP method (Tavana et al., 2019). Moreover, the review of the literature on this subject shows that the TOPSIS method may work whenever the main purpose is to evaluate alternatives by means of a number of criteria (Govindan and Sivakumar, 2016; Wang et al., 2019). Thus, the score of each supplier is calculated with regard to criterion using the combination of FAHP and FTOPSIS. In addition, it is not reasonable to consider a specific and certain weight for each criterion since the importance of each criterion varies under different conditions in calculating the final score of suppliers. Then, it can be concluded that the relationship between the final score and criteria follows a nonlinear relationship and, thereby, it is not possible to use methods such as AHP for this purpose. In such conditions, the application of rule-based methods can be the right decision (Tavana et al., 2019; Govindan et al., 2020a); therefore, an FIS is used in this paper to calculate the final score of the suppliers. In general, the innovations of this study can be stated as follows:

- Identifying the economic and circular criteria suitable for ranking circular suppliers in the petrochemical industry to achieve Sustainable development goals (SDG's);
- Developing a practical novel approach through the combination of FAHP, FTOPSIS, and FIS methods to evaluate and rank the petrochemical industry suppliers in the circular supply chain;
- Implementing the proposed approach in the real world using expert opinion and data of a petrochemical industry in Iran.

The remainder of this paper is organized as follows. In Section 2, we review the literature on supplier selection criteria and supplier selection methods. In Section 3, we present the proposed approach. We present our case study and validation of proposed approach in Sections 4 and 5, respectively, and close with our contribution to SDG's and conclusions in Section 6 and 7.

2. Literature review

Regarding the research questions, the related literature is classified into two groups: supplier selection criteria and supplier selection methods. In the first category, common and circular criteria are reviewed and, in the second category, the related methods are studied.

2.1. Supplier selection criteria

Supplier selection and evaluation problem is a MCDM problem of high complexity and it includes contradictory criteria. Gathering appropriate, effective criteria is a key factor in supplier selection (Mohammed et al., 2019) that strongly depends on the studied business context (Mina et al., 2014b). Haeri and Rezaei (2019) developed an uncertain approach to green supplier selection. They used both economic and environmental criteria for supplier evaluation; they calculated the weights of the criteria by best-worst method (BWM) and the interdependencies between the criteria via grey relational analysis. They considered delivery, price, quality, innovativeness, and technology capability as the economic criteria, and green image, resource consumption, pollution control, pollution production, and management commitment as the environmental criteria. In this vein, Liu et al. (2019) proposed a fuzzy three-stage approach based on MCDM methods for sustainable supplier selection. Using the triple bottom line concept, they extracted the evaluation criteria from three aspects, namely economic, environmental, and social ones available in the related literature. Environmental commitment, emissions, recyclable package, customer friendly, and environmental adaptability constitute the green criteria used in this paper. Ecer and Pamucar (2020) also presented a novel integrated approach using fuzzy BWM for sustainable supplier selection in home appliance manufacturers. They proposed transportation cost, delivery, service, price, and quality as the economic criteria, and environmental management system, environmental cost, green management, pollution control, and environmental competencies as the environmental criteria. A consensus decision-making approach was developed by Gao et al. (2020) for the green supplier selection in the area of electronics manufacturing where technology capability, quality, and cost were regarded as the economic criteria; and emissions, waste management, green product, environmental management certification, and green competitiveness were introduced as the environmental criteria for green supplier evaluation and selection. The review of the literature indicates that a significant number of studies on green supplier selection have been so far conducted in various fields. A number of recent articles in the field of green supplier evaluation and selection are reviewed in Table 1 in order to review and identify common and green or circular criteria, i.e., the economic and environmental criteria.

Table 1. The common and environmental criteria in supplier selection

Author(s)	Economic (common) criteria	Environmental criteria
Yazdani et al. (2017)	Financial stability, Quality control systems, Manufacturing, Facility, Quality adaptation, Price, Delivery speed, Production planning	Environmental management systems, Waste disposal program, Management commitment, Reverse logistics, Energy and natural resource consumption, Green design, Re-use and recycle rate
Awasthi et al. (2018)	Cost, Dependability, Flexibility, Innovativeness, Speed, Quality	Energy, Materials, Water, Emissions, Effluents and waste, Biodiversity
Banaeian et al. (2018)	Price, Quality, Service level	Environmental management system
Gören (2018)	Price, Productivity, Continuity, Capacity, Lead time, Quality, Responsiveness, Production technology	Environmental management system, Environmentally friendly product design, Resource consumption
Vahidi et al. (2018)	Transportation cost	ISO 14001 certification, Technology level, Usage of toxic substances, Amount of solid wastes, Pollution production, Energy consumption, Green technology
Liou et al. (2019)	-	Green design, Green production, Green purchasing, Collaboration with suppliers, Control of in-process environmental substances, Control of nonconforming environmental production, Warehousing management, Control of outgoing environmental substances
Mishra et al. (2019)	Technological, Quality, Flexibility, Financial capability, Culture innovativeness	Environmental management system, Eco-design, Green technology, Green product, Management commitment
Qazvini et al. (2019)	Quality of product, Capability of handling abnormal quality, Product rejection rate, On-time delivery, Lead time flexibility, Time to solve the complaint	Eco-design, Air emission, Environmental management system, Hazardous wastes, Green packaging, Green technology, Green design and purchasing
Giannakis et al. (2020)	Productivity, Return on equity, Economic value added, Investment in sustainable processes and products	Greenhouse gas emissions, Energy consumption, Water consumption, Amount of waste generated
Amiri et al. (2020)	Delivery lead time, Financial power, Operational cost, Defective rate	Resource consumption, Air pollution emission, Certifications, Pollution production
Govindan et al. (2020b)	On-time delivery, Quality	Air pollution, Environmental standards, Eco-friendly raw material, Eco-design, Eco-friendly transportation, Clean technology
Hendiani et al. (2020)	Cost, Quality, Delivery reliability, Supply capacity, Relationship conditions, Flexibility, Service	Control on pollution, Environmental management and policies, Green involvement, Environmental competencies, Energy conservation
Kannan et al. (2020)	Cost, Quality, Delivery, Reputation, Technology, Flexibility	Air pollution, Eco-friendly raw materials, Environmental standards, Clean technologies, Eco-friendly packaging
Lei et al. (2020)	-	Environmental improvement quality, Transportation cost of suppliers, Environmental competencies, Green image and financial conditions
Mousavi et al. (2020)	-	Staff ecological preparing, Total item life cycle cost, Pollution, Quality administration, Green capabilities, Environment administration, Resource utilization, Green picture, Green item advancement, Use of naturally benevolent innovation

Although the criteria used in the supplier selection problem are strongly influenced by the chain under study, the literature review shows that criteria such as quality, delivery, and capability are among the most important and widely used economic criteria as they are employed in almost all industries. However, they may be different from each other in the sub-criteria. Furthermore, criteria such as environmental management system, eco-friendly raw materials, environmental standards, pollution, and green packaging are the most frequently used environmental criteria at the supplier selection problem in various fields. They are also employed in this paper for circular supplier selection given the nature of the problem under study and expert opinion in this field.

2.2. Supplier selection methods

Several methods have been employed to solve the supplier selection problem. To this aim, researchers have used different tools and models like AHP/FAHP (Unal and Temur, 2020; Hosseini and Al Khaled, 2019; Abdel-Basset et al., 2018; Dweiri et al., 2016), analytic network process (ANP)/fuzzy ANP (Giannakis et al., 2020; Whicher et al., 2019; Mina et al., 2014a), TOPSIS/FTOPSIS (Li et al., 2019; Memari et al., 2019; Bai and Sarkis, 2018; Mousakhani et al., 2017), data envelopment analysis (DEA)/fuzzy DEA (Dobos and Vörösmarty, 2019; Fallahpour et al., 2016; Dotoli et al., 2016 ; Bafrooei et al., 2014), BWM/fuzzy BWM (Amiri et al., 2020; Ecer and Pamucar, 2020; Bai et al., 2019; Rezaei et al., 2016), FIS (Jain and Singh, 2020; Amindoust and Saghafinia, 2017), MCDM methods and FIS (Jain et al., 2020; Amindoust, 2018; Khan et al., 2018), MCDM methods and Mathematical programming approach (Govindan et al., 2020b; Kellner and Utz, 2019; Park et al., 2018; Vahidi et al., 2018) and hybrid MCDM methods (Kannan et al., 2020; dos Santos et al., 2019; Govindan et al., 2018; Parkouhi and Ghadikolaei, 2017).

Büyüközkan and Çifçi (2011) investigated supplier selection problem based on both social and environmental accountabilities, and in their later study, they applied three methods of fuzzy DEMATEL, fuzzy ANP, and FTOPSIS to the proposed problem. Kannan et al. (2014) proposed a new approach based on FTOPSIS for supplier evaluation and selection in a green supply chain management. They implemented their method in an electrical company in Brazil including 12 suppliers. A comprehensive model, based on ANP and improved grey relation analysis (GRA) for evaluating suppliers in automobile industry, was presented by Hashemi et al. (2015). They utilized ANP to consider interdependencies between criteria and used GRA to deal with uncertainties. Kannan et al. (2015) developed a MCDM approach so-called fuzzy axiomatic design to evaluate green suppliers in manufacturing industries. They applied the model on a plastic manufacturing company to validate their proposed approach. Kuo et al. (2015) suggested a hybrid approach consisting of ANP, DEMATEL, and VIKOR methods for prioritizing the green suppliers. In this approach, criteria weights are calculated through ANP and interdependency between weights are considered with DEMATEL method. Then, suppliers are prioritized by VIKOR method. The approach was implemented and validated by applying it in electronic industries. As another hybrid method, Wang Chen et al. (2016) employed FAHP and FTOPSIS methods for evaluating the suppliers regarding economic and environmental criteria.

Efficiency and applicability of the approach was tested on luminance enhancement film. Fallahpour et al. (2017) used fuzzy preference programming for determining the criteria weight and FTOPSIS for prioritizing the suppliers considering uncertainties. Awasthi et al. (2018) developed a two-stage method. First, criteria weights are calculated by FAHP and then fuzzy VIKOR is used to prioritize the suppliers. A hybrid approach based on ANP and VIKOR was presented by Abdel-Baset et al. (2019) to evaluate and select sustainable suppliers. They used ANP to calculate criteria and sub-criteria weights and then applied VIKOR method to prioritize the suppliers. Kannan et al. (2020) developed a practical and integrated approach for sustainable supplier selection in the circular supply chain from the combination of fuzzy BWM and interval VIKOR. They calculated the weights of the criteria via fuzzy BWM method and then benefited from VIKOR interval to rank the suppliers. The efficiency of their approach was validated by its implementation in a wire and cable industry.

The literature review in this domain demonstrates that different methods are used for supplier selection problems, which are determined in certain situations by considering the nature of the problem under study. Since each of these methods suffers some disadvantages besides its advantages, researchers have sought to integrate them to tackle the weaknesses of these methods. In this paper, the combination of FAHP, FIS, and FTOPSIS has also been employed to come to an efficient and effective approach. As there is a hierarchical structure between criteria, sub-criteria, and alternatives, the FAHP method is used to weight the sub-criteria (Tavana et al., 2019). In the same way, since it is aimed to rank a number of alternatives using some criteria, it is desirable to use TOPSIS method (Govindan and Sivakumar, 2016). Accordingly, this study employs the FTOPSIS method to evaluate each supplier in terms of each criterion. Because supplier evaluation criteria (i.e., circular, delivery, capability, quality) are not of same category (type), it is not possible to use a linear function to calculate the suppliers' final score. Hence, it is suggested to employ a method like FIS that establishes a connection between criteria using nonlinear relations (Govindan et al., 2020a). As a conclusion, due to the aforementioned reasons, an integrated approach based on FAHP, FTOPSIS, and FIS will be proposed in this paper for circular supplier evaluation and selection in the petrochemical industry.

3. Methodology

In this section, fuzzy set theory and TOPSIS methods are briefly introduced and then the proposed approach is presented.

3.1. Fuzzy set theory

Uncertain operating conditions such as human's subjective thinking, judgment, imprecision and vagueness, crisp numbered data cannot describe the considered system properly (Shen et al., 2013). Furthermore, comparisons and ratings through weights would never be precise. To overcome the limit of human's judgment with due attention on vagueness, fuzzy set is employed to consider uncertainties for decision making process. Known as fuzzy MCDM, fuzzy set theory uses linguistic terms to cover decision maker's selections in terms of ambiguity, subjectivity, and imprecision (Govindan et al., 2009; Singh and Benyoucef, 2011). Bellman and Zadeh (1970) incorporated fuzzy sets in decision-making problems (Shen et al., 2013). Prior to that, the fuzzy set theory was introduced to address uncertainties in human's judgments in MCDM by Zadeh (1965, 1976).

3.2. TOPSIS

TOPSIS was proposed by Hwang and Yoon (1981) for order preference by similarities with ideal solutions (Yu et al., 2012). In TOPSIS method, the positive and negative ideal solutions are defined. Then the distance of each solution is calculated from these two extremes. Based on distances, the ranking can be identified which serves as the cornerstone of TOPSIS method. This method is one of the classical methods for dealing with MCDM problems (Shen et al., 2013). In this technique, the positive ideal solution (PIS) maximizes the benefit and minimizes the cost. Alternatively, the negative ideal solution (NIS) minimizes the benefit and maximizes the cost. The best solution is the nearest to PIS and the furthest away from NIS. This distance is called the closeness coefficient in TOPSIS method and the solutions are selected based on their closeness coefficient (Kahraman et al., 2009; Torlak et al., 2011). Vagueness can be covered in this method by employing fuzzy sets. In FTOPSIS, the ratings and weights are defined as linguistic values and then transformed to fuzzy numbers like triangular fuzzy numbers.

3.3 Proposed approach

This section presents the hybrid approach based on FAHP, FTOPSIS, and FIS for selecting and prioritizing the petrochemical industry suppliers. Because there is a hierarchical structure between goal, criteria, sub-criteria, and alternatives, using the FAHP method is appropriate for weighting the criteria and sub-criteria. But since there is not a linear relationship between the criteria in the studied industry, and unlike other industries, the effect of each criterion on suppliers' final score is highly dependent on the performance of other criteria, using the FAHP method is not appropriate here; it is used only for weighting sub-criteria because the sub-criteria of each criterion are of the same gender and their effect is the same in different conditions. Therefore, rule-based methods should be used to determine the relationships between criteria to calculate suppliers' final scores, since they allow the user to define a rule according to each condition and to calculate nonlinear relationships in calculations. In this way, a hybrid method for ranking the suppliers is developed in which each supplier's score is calculated for each criterion using the FAHP and FTOPSIS method, and the obtained score is provided as FIS input to calculate the final score through nonlinear relationships and defined rules. In Figure 1, the steps of the proposed approach are depicted.

This approach is presented through 9 steps as follows (it is assumed that K number of experts $(D_1, D_2, ..., D_k)$, m number of suppliers $(A_1, A_2, ..., A_m)$, and n number of criteria $(C_1, C_2, ..., C_n)$ are available):

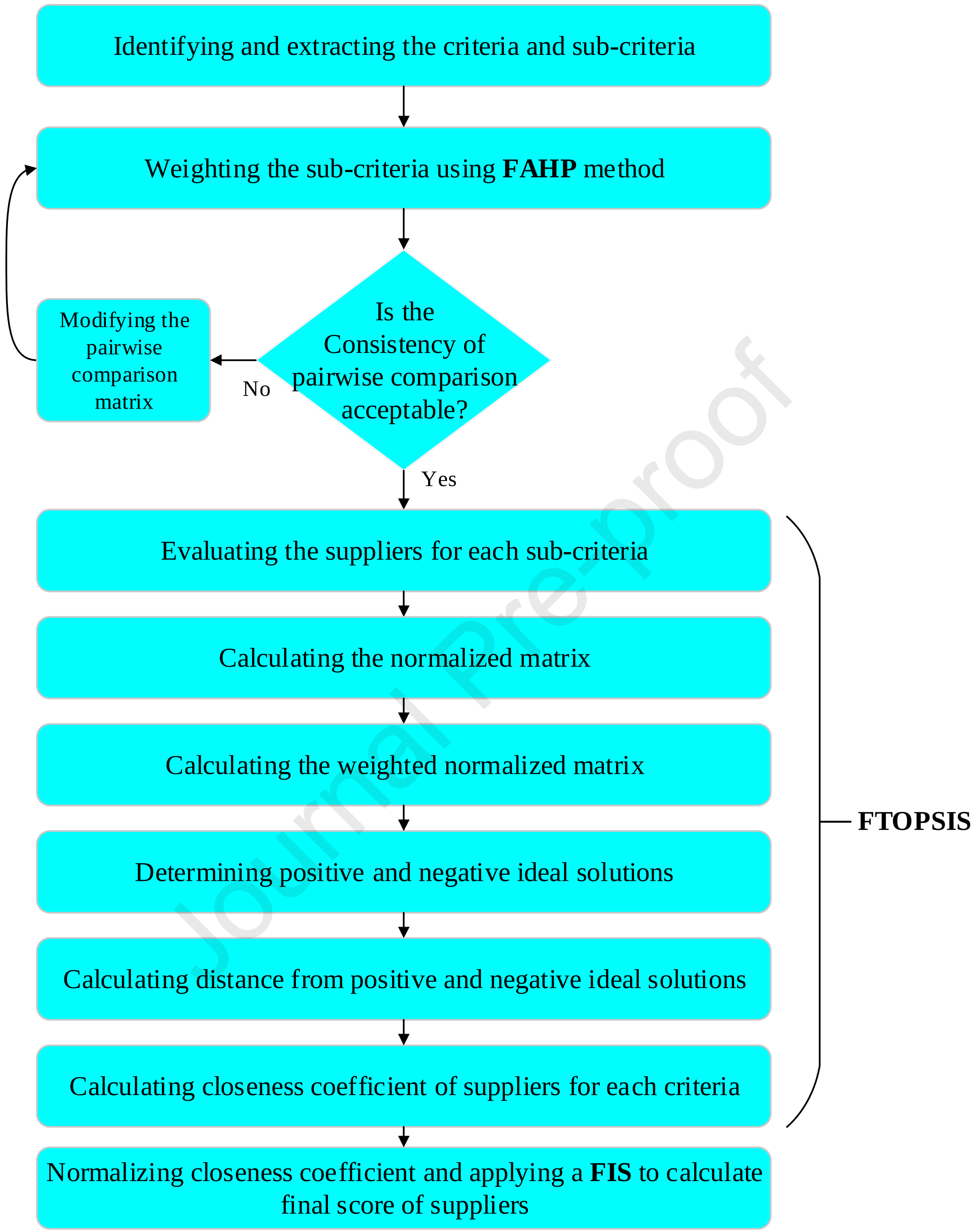


Figure 1. The structure of proposed approach

Step 1: In this step, the criteria for supplier evaluation from both economic and environmental aspects are extracted based on the experts' opinion of the company and the related literature. For this purpose, the experts were provided with the criteria presented in Table 1 and they placed the criteria for supplier evaluation in four categories, including quality, delivery, circular, and capability through brainstorming method. In Table 4, the criteria and sub-criteria for the evaluation of petrochemical industry suppliers are shown.

Step 2: The sub-criteria of each criterion are weighted in this step. Towards this end, pairwise comparison questionnaires are prepared to be filled out by the experts. The experts are asked to make judgments between criteria regarding Table 2. As a consequence of questionnaires and pairwise comparison matrixes and through a non-linear model, presented by Dagdeviren and Yuksel (2010), the weights of sub-criteria are obtained. The mentioned mathematical model is as follows.

$$\begin{aligned}
&Max\,\lambda \\
&Subject\,to: \\
&(m_{ij}-l_{ij})\times\lambda\times w_j - w_i + l_{ij}\times w_j \le 0 \\
&(u_{ij}-m_{ij})\times\lambda\times w_j + w_i - u_{ij}\times w_j \le 0 \\
&\sum_{f=1}^{n} w_f = 1; \qquad w_f > 0; \quad f=1,2,\ldots,n \\
&i=1,2,\ldots,n-1; \quad j=2,3,\ldots,n; \quad j>i
\end{aligned} \tag{1}$$

Table 2. Linguistic scale for difficulty and importance

Linguistic scales for difficulty	Linguistic scales for importance	Triangular fuzzy scale	Triangular fuzzy reciprocal scale
Just equal	Just equal	(1, 1, 1)	(1, 1, 1)
Equally difficult	Equally importance	(1/2, 1, 3/2)	(2/3, 1, 2)
Weakly more difficult	Weakly more importance	(1, 3/2, 2)	(1/2, 2/3, 1)
Strongly more difficult	Strongly more importance	(3/2, 2, 5/2)	(2/5, 1/2, 2/3)
Very strongly more difficult	Very strongly more importance	(2, 5/2, 3)	(1/3, 2/5, 1/2)
Absolutely more difficult	Absolutely more importance	(5/2, 3, 7/2)	(2/7, 1/3, 2/5)

In this nonlinear model, (l_{ij}, m_{ij}, u_{ij}) shows 3 triangular fuzzy numbers in pairwise comparisons and w_f demonstrates weight of *f*th sub-criterion. The optimal value of λ can be either positive or negative ($-1 \le \lambda \le 1$). Positive number means that the pairwise comparisons are consistent; otherwise, the negative number implies that there is not enough consistency in our judgments and in this case the questionnaires are required to be filled out again to reach a specific level of consistency. So, the weights matrix is obtained for each expert and for each sub-criterion (W'_{jt}). The mean value of weights matrix is defined as follows (W_j).

$$W_j = \frac{\sum_{t=1}^{k} W'_{jt}}{k} \tag{2}$$

Step 3: In this step, for constructing the decision matrix, experts are asked to score each alternative for each sub-criterion with regard to linguistics variables of Table 3.

$$D = \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1n} \\ r_{21} & r_{22} & \cdots & r_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ r_{m1} & r_{m2} & \cdots & r_{mn} \end{bmatrix} \tag{3}$$

Where r_{mn} is the rate of alternative A_m with respect to sub-criterion C_n.

Then, the mean value of experts' opinions is calculated through the below formula and it is called as R_{ij} matrix.

$$R_{ij} = (a_{ij}, b_{ij}, c_{ij}) = \frac{\sum_{t=1}^{k} (a_{ijt}, b_{ijt}, c_{ijt})}{k} \quad \forall i, j \tag{4}$$

Table 3. Linguistic variables and fuzzy ratings of the alternatives (Tavana et al., 2020)

Linguistic scales for importance	Triangular fuzzy scale
Very Poor (VP)	(0,0,1)
Poor (P)	(0,1,3)
Medium Poor (MP)	(1,3,5)
Fair (F)	(3,5,7)
Medium Good (MG)	(5,7,9)
Good (G)	(7,9,10)
Very Good (VG)	(9,9,10)

Step 4: In this step, R_{ij} matrix in normalized regarding the following equations.

$$\begin{aligned} r_{ij} &= \left(\frac{a_{ij}}{c_j^*}, \frac{b_{ij}}{c_j^*}, \frac{c_{ij}}{c_j^*}\right), j \in B \\ c_j^* &= \max c_{ij}, j \in B \\ r_{ij} &= \left(\frac{a_j^-}{c_{ij}}, \frac{a_j^-}{b_{ij}}, \frac{a_j^-}{a_{ij}}\right), j \in C \\ a_j^- &= \min a_{ij}, j \in C \end{aligned} \tag{5}$$

In Eq. 5, *B* and *C* show desirable and undesirable criteria sets, respectively, and r_{ij} illustrates fuzzy normalized matrix.

Step 5: The normalized weighted decision matrix (ν_{ij}) is established, in this step. To this aim, according to Eq. 6, the normalized decision matrix is multiplied by criteria weights.

$$\nu_{ij} = r_{ij}.W_j \quad , \begin{matrix} i = 1, 2, ..., m \\ j = 1, 2, ..., n \end{matrix} \tag{6}$$

Step 6: In this step, fuzzy Positive Ideal Solution (PIS) and Negative Ideal Solution (NIS) are determined. These terms are calculated as follows:

$$\begin{aligned} &(A^*) = (\nu_1^*, \nu_2^*, ..., \nu_n^*) \\ &(A^-) = (\nu_1^-, \nu_2^-, ..., \nu_n^-) \\ &where \\ &\nu_j^* = \max_i \{\nu_{ij}\} \ \forall i, j \\ &\nu_j^- = \min_i \{\nu_{ij}\} \ \forall i, j \end{aligned} \tag{7}$$

Step 7: This step is designated to calculate each alternative's distance from fuzzy PIS and NIS.

$$\begin{matrix} d_i^* = \sum_{j=1}^{n} d_\nu(\nu_{ij}, \nu_j^*) \\ d_i^- = \sum_{j=1}^{n} d_\nu(\nu_{ij}, \nu_j^-) \end{matrix} \quad , i = 1, 2, ..., m \tag{8}$$

where $d_i^* = \sum_{j=1}^{n} d_\nu(\nu_{ij}, \nu_j^*)$ and $d_i^- = \sum_{j=1}^{n} d_\nu(\nu_{ij}, \nu_j^-)$ are applied to calculate the distance of alternatives from PIs and NIS, respectively.

$$d_\nu(\nu_{ij}, \nu_j^*) = \sqrt{\frac{1}{3}[(a_j^* - a_{ij})^2 + (b_j^* - b_{ij})^2 + (c_j^* - c_{ij})^2]} \tag{9}$$

Step 8: In this step, the closeness coefficient (*CC*) is calculated through the following formula.

$$CC_i = \frac{d_i^-}{d_i^- + d_i^*} \quad , i = 1, 2, ..., m \tag{10}$$

Step 9: In this step, a FIS is proposed to calculate the final score of suppliers. To develop a FIS, the input and output variables, their membership functions, and fuzzy inference rules should be determined. In the proposed FIS, the *CC* of criteria for suppliers obtained from step 8 is defined as the input variables and the final score of suppliers is defined as the output variable. It is noteworthy that the input variables are normalized via Eq.11. In this paper, three membership functions, namely low, mid, and high are considered for the input and output variables, as depicted in Figure 2. Fuzzy inference rules, which are the engine of FIS, are determined through questionnaire based on the knowledge of the company experts (See Appendix-Table A). To form

FIS, the input and output variables, their membership functions, and the fuzzy inference rules are defined in the FIS Editor GUI toolbox in MATLAB R2012a software. To calculate the final score of the suppliers, it suffices to enter the values of the input variables in the rule reviewer section. Then, the final score is displayed as the output variable.

$$CC_i^{Normalized} = \begin{cases} \dfrac{CC_i}{Max\{CC_i\}}, & for\ desirable\ criteria \\ \dfrac{Min\{CC_i\}}{CC_i}, & for\ undesirable\ criteria \end{cases} \quad (11)$$

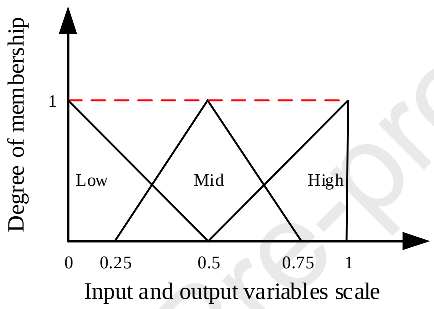


Figure 2. The triangular fuzzy number to define linguistic variables

3.4. Data collection

The data of this study are collected in three separate steps through a questionnaire designed based on experts' knowledge. The first set of data pertains to the pairwise comparisons questionnaire, which is obtained through expert knowledge in step 2 using the mentioned process. In Table 5, an example of a pairwise comparisons questionnaire completed by one of the experts is presented. The second set of data relates to supplier evaluation for each sub-criterion, which has been described in step 3. These data have also been reported in Table 7. Finally, the last set of data is related to the determination of fuzzy inference rules, which determine the relationship between the criteria and the final score. This information is presented in Table A inserted in the Appendix.

4. Case study

To evaluate accuracy and effectiveness of the proposed approach, it is implemented in a petrochemical company in Iran. With more than 10 years of experience in the field of petrochemical production, this company, located in an area of 30,000 m^2 in northern Iran, is one of the largest manufacturers of expandable polystyrene (EPS). 4,200 employees work in the company and it has a production capacity of 5,000 tons of EPS per year. EPS is made of styrene-monomer and is used in the production of acoustic and thermal insulation in buildings as well as the production of refrigerant insulation in cold storage and the packaging industry. In this research, the knowledge of five experts, including health, safety, and environmental manager;

quality control manager; production manager; procurement manager; and human resources manager, is used to evaluate and rank the six suppliers of this company. In the following, the implementation process of the proposed approach in the company has been presented step by step:

Step 1: In this step, the evaluation criteria of suppliers are determined. In the literature review section, a set of criteria for supplier evaluation in economic and environmental aspects was extracted from the literature and was submitted to the company experts. The experts subdivided the supplier evaluation criteria into four aspects, including delivery, quality, circular, and capability. The evaluation criteria and sub-criteria of circular suppliers in the industry under study are presented in Table 4.

Table 4. Criteria and sub-criteria of supplier evaluation

Criteria	Sub-criteria	Description	References
Delivery	Order lead time (D1)	Appropriate mechanisms for receiving and processing orders	Dobos and Vörösmarty (2014); Gören (2018); Qazvini et al. (2019)
	On-time delivery (D2)	Applying methods based on scheduling problem to reduce the processing time	Amindoust et al. (2012); Kannan et al. (2013); Kannan et al. (2015); yazdani et al. (2017); Qazvini et al. (2019); Govindan et al. (2020b)
	Delivery reliability (D3)	Ratio of the number of deliveries made without any error to the total number of deliveries in a period	Mina et al. (2014a); Parkouhi et al. (2017); Cavalcante et al. (2019)
	Distribution network quality (D4)	Applying methods based on routing problems in order to increase distribution network quality	Parkouhi et al. (2017); Parkouhi et al. (2019)
Quality	Quality control system (Q1)	Applying proper systems to increase products quality	Mina et al. (2014a), Yazdani et al. (2017) ; Govindan et al. (2020b)
	After-sale services (Q2)	Providing conditions to return defective products and utilization of grantee	Kuo et al. (2010), Amindoust et al. (2012), Kannan et al. (2015); Wu et al. (2019)
	Previous customers satisfaction (Q3)	Providing conditions to demonstrate customers' satisfaction	Mina et al. (2014a); Govindan et al. (2020b)
	Sustainability longevity (Q4)	Appropriate mechanisms for reducing manufacturing efforts and saves a large amount of energy and new materials	Luthra et al. (2017); Fallahpour et al. (2017)
Circular	Greenhouse gas emissions from production and recycling activities (CR1)	Consideration of decreased air pollution in procedure of recycling the products	Vahidi et al. (2018), Azimifard et al. (2018);

			Kannan et al. (2020)
	Environmental regulations and standards (CR2)	Respecting environmental standards in production and recycling activities	Govindan et al. (2020b); Kannan et al. (2020)
	Green packaging (CR3)	Employing recyclable materials in packaging products	Awasthi and Govindan (2016); Liu et al. (2019); Qazvini et al. (2019); Kannan et al. (2020)
	Eco-friendly and recyclable raw material (CR4)	Utilizing recyclable and eco-friendly raw materials for producing the products	Gupta and Barua (2017); Govindan et al. (2020b); Kannan et al. (2020)
	Clean technology (CR5)	Applying green and clean technology in production and recycling procedures	Yazdani et al. (2017); Banaeian et al. (2018); Gören (2018); Ecer and Pamucar (2020)
Capability	Executive capability (C1)	Supporting capabilities similar to the components of a value chain	Mina et al. (2014a); Kannan (2018)
	Technology capability (C2)	A set of managerial and technical skills for exploiting a technology	Hashemi et al. (2015); Gören (2018); Vahidi et al. (2018); Haeri and Rezaei (2019); Gao et al. (2020)
	production facilities and capacity (C3)	Capacity of facilities for producing and recycling the products	Amindoust et al. (2012); Gören (2018)
	Financial capability (C4)	Profitability and cash reserves	Amindoust et al. (2012), Yazdani et al. (2017); Mishra et al. (2019)
	Flexibility (C5)	Ability of suppliers for responding the changing demand (volume, delivery, and modification)	Awasthi et al. (2018); Mishra et al. (2019); Qazvini et al. (2019); Kannan et al. (2020)
	Research and Development (C6)	Applying up-to-date knowledge in the process of supply, production and distribution	Amindoust et al. (2012); Luthra et al. (2017); Kannan (2018); Stević et al. (2020)

Step 2: In this step, the sub-criteria, defined in the previous step, are weighted. Once the questionnaires are filled out by experts and linguistic scales are substituted by triangular fuzzy numbers, a nonlinear mathematical model, presented by Dagdeviren and Yuksel (2010), is employed to derive the weights of sub-criteria. In Table 5, the pairwise comparisons are presented for delivery criterion, done by an expert, and the weights are calculated through the nonlinear mathematical model, which is described in the following model. The extended

nonlinear model is run in GAMS 23.6 software using BARON solver. Therefore, the related weights for sub-criteria are resulted. Table 6 shows the mean values for sub-criteria weights.

Table 5. The pairwise comparison matrix and weights of delivery sub-criteria based on expert 1

	D1	D2	D3	D4	Weight
D1	(1,1,1)	(1,3/2,2)	(1,3/2,2)	(1/2,1,3/2)	0.308
D2	(1/2,2/3,1)	(1,1,1)	(1/2,1,3/2)	(2/3,1,2)	0.232
D3	(1/2,2/3,1)	(2/3,1,2)	(1,1,1)	(1/2,2/3,1)	0.198
D4	(2/3,1,2)	(1/2,1,3/2)	(1,3/2,2)	(1,1,1)	0.262

$\lambda^* = 0.653$

$$\begin{array}{ll}
\frac{1}{2}\times\lambda\times w_2 - w_1 + w_2 \le 0 & \frac{1}{2}\times\lambda\times w_3 - w_2 + \frac{1}{2}w_3 \le 0 \\
\frac{1}{2}\times\lambda\times w_2 + w_1 - 2w_2 \le 0 & \frac{1}{2}\times\lambda\times w_3 + w_2 - \frac{3}{2}w_3 \le 0 \\
\frac{1}{2}\times\lambda\times w_3 - w_1 + w_3 \le 0 & \frac{1}{3}\times\lambda\times w_4 - w_2 + \frac{2}{3}w_4 \le 0 \\
\frac{1}{2}\times\lambda\times w_3 + w_1 - 2w_3 \le 0 & \lambda\times w_4 + w_2 - 2w_4 \le 0 \\
\frac{1}{2}\times\lambda\times w_4 - w_1 + \frac{1}{2}w_4 \le 0 & \frac{1}{6}\times\lambda\times w_4 - w_3 + \frac{1}{2}w_4 \le 0 \\
\frac{1}{2}\times\lambda\times w_4 + w_1 - \frac{3}{2}w_4 \le 0 & \frac{1}{3}\times\lambda\times w_4 + w_3 - w_4 \le 0 \\
w_1 + w_2 + w_3 + w_4 = 1 & \\
w_1, w_2, w_3, w_4 > 0 &
\end{array} \tag{12}$$

Table 6. Final weights of sub-criteria

Criteria	Sub-criteria	Weight
Delivery	Order lead time	0.319
	On-time delivery	0.245
	Delivery reliability	0.168
	Distribution network quality	0.268
Quality	Quality control system	0.371
	After-sale services	0.152
	Previous customers satisfaction	0.294
	Sustainability longevity	0.183
Circular	Greenhouse gas emissions from production and recycling activities	0.284
	Environmental regulations and standards	0.222
	Green packaging	0.179
	Eco-friendly and recyclable raw material	0.152
	Clean technology	0.163
Capability	Executive capability	0.277
	Technology capability	0.197
	production facilities and capacity	0.152

	Financial capability	0.179
	Flexibility	0.083
	Research and Development	0.112

Step 3: In this step, experts score each supplier's sub-criteria according to Table 3. The results are shown in Table 7.

Table 7. The fuzzy aggregated decision matrix

	D1	D2	D3	D4	Q1	Q2	Q3	Q4	CR1	CR2
Supplier1	(5,8.33,10)	(0,3,7)	(9,10,10)	(1,5,9)	(0,1.33,5)	(3,5.67,9)	(0,3,7)	(5,7,9)	(0,0.667,3)	(7,9.33,10)
Supplier2	(9,10,10)	(0,2.33,7)	(9,10,10)	(5,8.33,10)	(0,3,7)	(0,3,7)	(0,2.33,7)	(0,2.33,7)	(0,0.333,3)	(0,0.333,3)
Supplier3	(3,7,10)	(1,5.67,9)	(5,8.33,10)	(3,7,10)	(3,5.67,9)	(7,9.67,10)	(0,0.333,3)	(1,5,9)	(0,2,5)	(0,1,5)
Supplier4	(5,9,10)	(5,7,9)	(7,9.67,10)	(0,2,5)	(5,8.33,10)	(3,7.67,10)	(5,8.33,10)	(5,8.33,10)	(5,8.33,10)	(0,1.33,5)
Supplier5	(9,10,10)	(0,2.33,7)	(9,10,10)	(0,3,7)	(0,2.33,7)	(0,6.67,10)	(0,3,7)	(3,7,10)	(0,2.33,7)	(0,2.33,7)
Supplier6	(7,9.33,10)	(5,9,10)	(7,9,10)	(5,8.33,10)	(1,5.67,9)	(9,10,10)	(3,5.67,9)	(0,2,5)	(0,0.333,3)	(0,1.33,5)

	CR3	CR4	CR5	C1	C2	C3	C4	C5	C6
Supplier1	(0,0.333,3)	(9,10,10)	(0,0,1)	(3,6.33,10)	(9,10,10)	(5,8.33,10)	(3,7,10)	(3,7,10)	(3,7,10)
Supplier2	(1,5.67,9)	(0,0.333,3)	(0,0.333,3)	(1,5,9)	(0,1,5)	(1,5,9)	(3,6.33,10)	(3,5.67,9)	(1,5,9)
Supplier3	(0,3,7)	(0,1.33,5)	(0,1,5)	(5,7,9)	(1,5.67,9)	(3,6.33,10)	(9,10,10)	(1,5,9)	(7,9.67,10)
Supplier4	(5,9,10)	(0,0.333,3)	(0,2.33,7)	(1,5.67,9)	(1,5,9)	(5,8.33,10)	(5,7,9)	(5,7,9)	(5,7,9)
Supplier5	(0,3,7)	(0,1.33,5)	(5,8.33,10)	(3,6.33,10)	(5,8.33,10)	(9,10,10)	(7,9.67,10)	(0,6.67,10)	(5,7,9)
Supplier6	(0,1.33,5)	(1,5.67,9)	(5,7,9)	(1,5.67,9)	(1,5,9)	(0,1.33,5)	(0,2.33,7)	(1,5,9)	(0,3,7)

Step 4: This step determines normalizing fuzzy aggregated decision matrix through Eq. 5. The outcome of this process is shown in Table 8.

Table 8. Normalized matrix

	D1	D2	D3	D4	Q1	Q2	Q3	Q4	CR1	CR2
Supplier1	(0.5,0.833,1)	(0,0.3,0.7)	(0.9,1,1)	(0.1,0.5,0.9)	(0,0.133,0.5)	(0.3,0.567,0.9)	(0,0.3,0.7)	(0.5,0.7,0.9)	(0,0.0667,0.3)	(0.7,0.933,1)
Supplier2	(0.9,1,1)	(0,0.233,0.7)	(0.9,1,1)	(0.5,0.833,1)	(0,0.3,0.7)	(0,0.3,0.7)	(0,0.233,0.7)	(0,0.233,0.7)	(0,0.0333,0.3)	(0,0.0333,0.3)
Supplier3	(0.3,0.7,1)	(0.1,0.567,0.9)	(0.5,0.833,1)	(0.3,0.7,1)	(0.3,0.567,0.9)	(0.7,0.967,1)	(0,0.0333,0.3)	(0.1,0.5,0.9)	(0,0.2,0.5)	(0,0.1,0.5)
Supplier4	(0.5,0.9,1)	(0.5,0.7,0.9)	(0.7,0.967,1)	(0,0.2,0.5)	(0.5,0.833,1)	(0.3,0.767,1)	(0.5,0.833,1)	(0.5,0.833,1)	(0.5,0.833,1)	(0,0.133,0.5)
Supplier5	(0.9,1,1)	(0,0.233,0.7)	(0.9,1,1)	(0,0.3,0.7)	(0,0.233,0.7)	(0,0.667,1)	(0,0.3,0.7)	(0.3,0.7,1)	(0,0.233,0.7)	(0,0.233,0.7)
Supplier6	(0.7,0.933,1)	(0.5,0.9,1)	(0.7,0.9,1)	(0.5,0.833,1)	(0.1,0.567,0.9)	(0.9,1,1)	(0.3,0.567,0.9)	(0,0.2,0.5)	(0,0.0333,0.3)	(0,0.133,0.5)

	CR3	CR4	CR5	C1	C2	C3	C4	C5	C6
Supplier1	(0,0.0333,0.3)	(0.9,1,1)	(0,0,0.1)	(0.3,0.633,1)	(0.9,1,1)	(0.5,0.833,1)	(0.3,0.7,1)	(0.3,0.7,1)	(0.3,0.7,1)
Supplier2	(0.1,0.567,0.9)	(0,0.0333,0.3)	(0,0.0333,0.3)	(0.1,0.5,0.9)	(0,0.1,0.5)	(0.1,0.5,0.9)	(0.3,0.633,1)	(0.3,0.567,0.9)	(0.1,0.5,0.9)
Supplier3	(0,0.3,0.7)	(0,0.133,0.5)	(0,0.1,0.5)	(0.5,0.7,0.9)	(0.1,0.567,0.9)	(0.3,0.633,1)	(0.9,1,1)	(0.1,0.5,0.9)	(0.7,0.967,1)
Supplier4	(0.5,0.9,1)	(0,0.0333,0.3)	(0,0.233,0.7)	(0.1,0.567,0.9)	(0.1,0.5,0.9)	(0.5,0.833,1)	(0.5,0.7,0.9)	(0.5,0.7,0.9)	(0.5,0.7,0.9)
Supplier5	(0,0.3,0.7)	(0,0.133,0.5)	(0.5,0.833,1)	(0.3,0.633,1)	(0.5,0.833,1)	(0.9,1,1)	(0.7,0.967,0.1)	(0,0.667,1)	(5,7,9)
Supplier6	(0,0.133,0.5)	(0.1,0.567,0.9)	(0.5,0.7,0.9)	(0.1,0.567,0.9)	(0.1,0.5,0.9)	(0,0.133,0.5)	(0,0.233,0.7)	(0.1,0.5,0.9)	(0,0.3,0.7)

Step 5: In this step, weighted normalized decision matrix is resulted from multiplication of normalized matrix and criteria weights. Table 9 illustrates weighted normalized decision matrix.

Table 9. Weighted normalized decision matrix

	D1	D2	D3	D4	Q1
Supplier1	(0.1595,0.2657,0.319)	(0,0.0735,0.1715)	(0.1512,0.168,0.168)	(0.0268,0.134,0.2412)	(0,0.0493,0.1855)

Supplier2	(0.2871,0.319,0.319)	(0,0.0571,0.1715)	(0.1512,0.168,0.168)	(0.134,0.2232,0.268)	(0,0.1113,0.2597)
Supplier3	(0.0957,0.2233,0.319)	(0.0245,0.1389,0.2205)	(0.084,0.1399,0.168)	(0.0804,0.1876,0.268)	(0.1113,0.2104,0.3339)
Supplier4	(0.1595,0.2871,0.319)	(0.1225,0.1715,0.2205)	(0.1176,0.1625,0.168)	(0,0.0536,0.134)	(0.1855,0.309,0.371)
Supplier5	(0.2871,0.319,0.319)	(0,0.0571,0.1715)	(0.1512,0.168,0.168)	(0,0.0804,0.1876)	(0,0.0864,0.2597)
Supplier6	(0.2233,0.2976,0.319)	(0.1225,0.2205,0.245)	(0.1176,0.1512,0.168)	(0.134,0.2232,0.268)	(0.0371,0.2104,0.3339)

	Q2	**Q3**	**Q4**	**CR1**	**CR2**
Supplier1	(0.0456,0.0862,0.1368)	(0,0.0882,0.2058)	(0.0915,0.1281,0.1647)	(0,0.0189,0.0852)	(0.1554,0.2071,0.222)
Supplier2	(0,0.0456,0.1064)	(0,0.0685,0.2058)	(0,0.0426,0.1281)	(0,0.0095,0.0852)	(0,0.0074,0.0666)
Supplier3	(0.1064,0.147,0.152)	(0,0.0098,0.0882)	(0.0183,0.0915,0.1647)	(0,0.0568,0.142)	(0,0.0222,0.111)
Supplier4	(0.0456,0.1166,0.152)	(0.147,0.2449,0.294)	(0.0915,0.1524,0.183)	(0.142,0.2366,0.284)	(0,0.0295,0.111)
Supplier5	(0,0.1014,0.152)	(0,0.0882,0.2058)	(0.0549,0.1281,0.183)	(0,0.0662,0.1988)	(0,0.0517,0.1554)
Supplier6	(0.1368,0.152,0.152)	(0.0882,0.1667,0.2646)	(0,0.0366,0.0915)	(0,0.0095,0.0852)	(0,0.0295,0.111)

	CR3	**CR4**	**CR5**	**C1**	**C2**
Supplier1	(0,0.0059,0.0537)	(0.1368,0.152,0.152)	(0,0,0.0163)	(0.0831,0.1753,0.277)	(0.1773,0.197,0.197)
Supplier2	(0.0179,0.1015,0.1611)	(0,0.0051,0.0456)	(0,0.0054,0.0489)	(0.0277,0.1385,0.2493)	(0,0.0197,0.0985)
Supplier3	(0,0.0537,0.1253)	(0,0.0202,0.076)	(0,0.0163,0.0815)	(0.1385,0.1939,0.2493)	(0.0197,0.1117,0.1773)
Supplier4	(0.0895,0.1611,0.179)	(0,0.0051,0.0456)	(0,0.038,0.1141)	(0.0277,0.1571,0.2493)	(0.0197,0.0985,0.1773)
Supplier5	(0,0.0537,0.1253)	(0,0.0202,0.076)	(0.0815,0.1358,0.163)	(0.0831,0.1753,0.277)	(0.0985,0.1641,0.197)
Supplier6	(0,0.0238,0.0895)	(0.0152,0.0862,0.1368)	(0.0815,0.1141,0.1467)	(0.0277,0.1571,0.2493)	(0.0197,0.0985,0.1773)

	C3	**C4**	**C5**	**C6**
Supplier1	(0.076,0.1266,0.152)	(0.0537,0.1253,0.179)	(0.0249,0.0581,0.083)	(0.0336,0.0784,0.112)
Supplier2	(0.0152,0.076,0.1368)	(0.0537,0.1133,0.179)	(0.0249,0.0471,0.0747)	(0.0112,0.056,0.1008)
Supplier3	(0.0456,0.0962,0.152)	(0.1611,0.179,0.179)	(0.0083,0.0415,0.0747)	(0.0784,0.1083,0.112)
Supplier4	(0.076,0.1266,0.152)	(0.0895,0.1253,0.1611)	(0.0415,0.0581,0.0747)	(0.056,0.0784,0.1008)
Supplier5	(0.1368,0.152,0.152)	(0.1253,0.1731,0.179)	(0,0.0554,0.083)	(0.056,0.0784,0.1008)
Supplier6	(0,0.0202,0.076)	(0,0.0417,0.1253)	(0.0083,0.0415,0.0747)	(0,0.0336,0.0784)

Step 6: In this step, fuzzy NIS and PIS are calculated through Eq. 7 for each criterion and the corresponding results are presented in Table 10.

Table 10. Fuzzy PIS and NIS

	v^*	v^-
D1	(0.319,0.319,0.319)	(0.0957,0.0957,0.0957)
D2	(0.245,0.245,0.245)	(0,0,0)
D3	(0.168,0.168,0.168)	(0.084,0.084,0.084)
D4	(0.268,0.268,0.268)	(0,0,0)
Q1	(0.371,0.371,0.371)	(0,0,0)
Q2	(0.152,0.152,0.152)	(0,0,0)
Q3	(0.294,0.294,0.294)	(0,0,0)
Q4	(0.183,0.183,0.183)	(0,0,0)
CR1	(0.284,0.284,0.284)	(0,0,0)
CR2	(0.222,0.222,0.222)	(0,0,0)
CR3	(0.179,0.179,0.179)	(0,0,0)
CR4	(0.152,0.152,0.152)	(0,0,0)
CR5	(0.163,0.163,0.163)	(0,0,0)
C1	(0.277,0.277,0.277)	(0.0277,0.0277,0.0277)
C2	(0.197,0.197,0.197)	(0,0,0)
C3	(0.152,0.152,0.152)	(0,0,0)
C4	(0.179,0.179,0.179)	(0,0,0)
C5	(0.083,0.083,0.083)	(0,0,0)
C6	(0.112,0.112,0.112)	(0,0,0)

Step 7: The distance of suppliers from the fuzzy PIS and NIS considering each criterion is calculated in this step using Eq. 8. Results are depicted in Table 11.

Table 11. Distance from fuzzy PIS and NIS

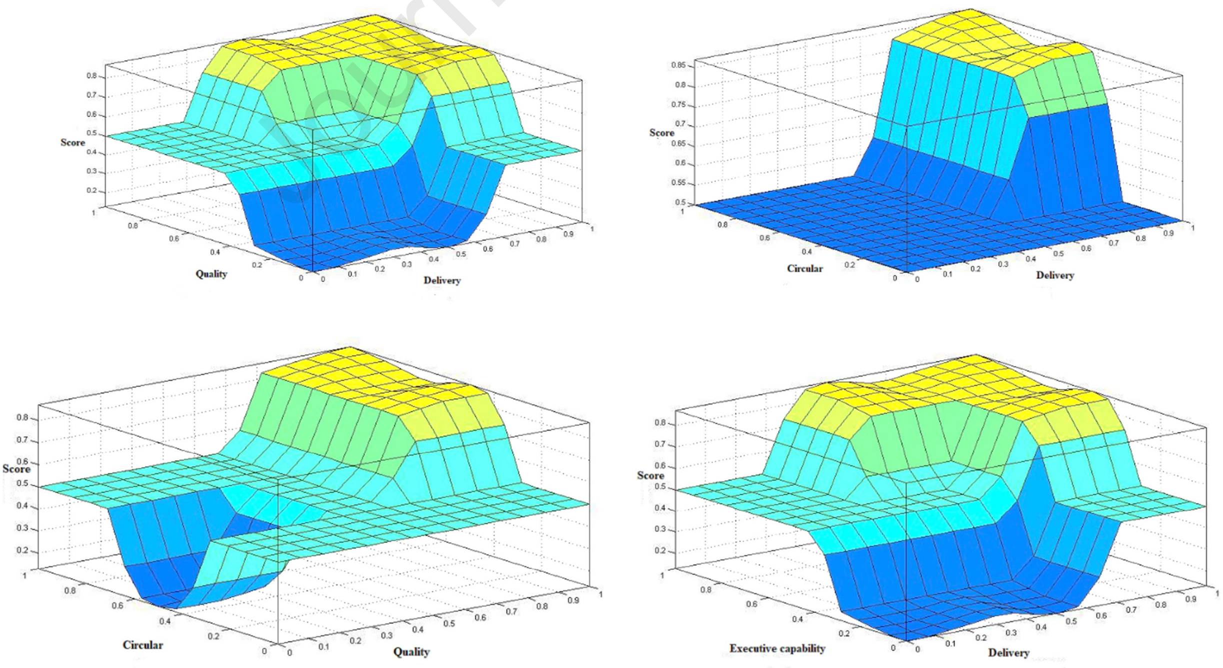
	Delivery		**Quality**		**Circular**		**Capability**	
	d^*	d^-	d^*	d^-	d^*	d^-	d^*	d^-
Supplier1	0.4446	0.5127	0.6517	0.4686	0.6188	0.435	0.3485	0.7547
Supplier2	0.2929	0.6121	0.7363	0.4331	0.8418	0.2535	0.6077	0.5378
Supplier3	0.4512	0.5524	0.5777	0.5339	0.7985	0.3257	0.3576	0.7244
Supplier4	0.4196	0.5023	0.3228	0.7963	0.579	0.5392	0.4522	0.657
Supplier5	0.4058	0.5141	0.6638	0.5256	0.6821	0.4708	0.3151	0.775
Supplier6	0.241	0.6726	0.5097	0.6205	0.7266	0.3802	0.6671	0.4863

Step 8: Closeness coefficient of suppliers are calculated for each criterion using Eq. 10 and it is presented in Table 12.

Table 12. Closeness coefficient of each supplier

	$CC^{Delivery}$	$CC^{Quality}$	$CC^{Circular}$	$CC^{Capability}$
Supplier1	0.53556	0.4183	0.41278	0.68411
Supplier2	0.67632	0.37036	0.23145	0.4695
Supplier3	0.55038	0.48033	0.28974	0.66953
Supplier4	0.54488	0.71152	0.48219	0.59233
Supplier5	0.55888	0.44189	0.40838	0.71096
Supplier6	0.73621	0.54898	0.34351	0.42162

Step 9: In this step, the proposed FIS is used to determine the final score of the suppliers. As it was discussed in step 9 of the proposed approach section, the *CC*s pertaining to quality, delivery, circular, and capability criteria have been defined as the input variables while the final score has been defined as the output variable of this system, and each of these input and output variables includes three membership functions. The proposed FIS consists of four input variables and each input variable consists of three membership functions. Thus, the number of $3^4 = 81$ fuzzy inference rules should be defined for this system to fully establish the relationship between input and output variables. In Figure 3, the fuzzy inference rules are shown in three dimensions. To calculate the suppliers' final score, the *CC* obtained from step 8 is first normalized by Eq.11 whose result is shown in Table 13. Then, in the rule reviewer section, the normalized *CC* is given as the input to the proposed FIS and the final score is calculated as the output. The final score and rank of suppliers are presented in Table 14.



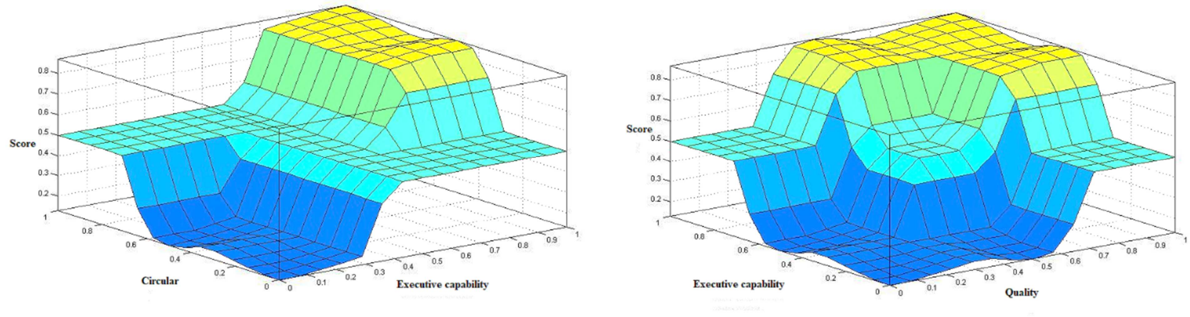


Figure 3. FIS rules in three dimensions

Table 13. The normalized closeness coefficients

	$NCC^{Delivery}$	$NCC^{Quality}$	$NCC^{Circular}$	$NCC^{Capability}$
Supplier1	0.727455	0.587896	0.856053	0.962234
Supplier2	0.918651	0.520519	0.479998	0.660375
Supplier3	0.747586	0.675076	0.600883	0.941727
Supplier4	0.740115	1	1	0.833141
Supplier5	0.759131	0.621051	0.846928	1
Supplier6	1	0.771559	0.712396	0.593029

Table 14. Final score and rank of suppliers

Supplier	Supplier 1	Supplier 2	Supplier 3	Supplier 4	Supplier 5	Supplier 6
Score	0.803	0.781	0.794	0.822	0.839	0.796
Rank	3	6	5	2	1	4

Based on the obtained results in Table 14, supplier 5 with a final relative score of 0.839 is rated as the best supplier, and supplier 2 with a relative score of 0.781 is rated as the worst supplier. According to Table 13, although supplier 4 scored the highest relative score in both quality and circular criteria, overall it performed poorer than supplier 5, indicating the high importance of the capability criterion. On the other hand, although supplier 6 performs lower on capability criterion than supplier 2, they perform better on delivery criterion, which suggests that delivery criterion also plays a crucial role in determining final suppliers. As stated, while there is no linear relationship between the criteria for determining final suppliers, the results and the fuzzy inference rules demonstrate clearly that the capability and delivery criteria have a significant impact on determining final suppliers.

4.1. Discussion and interpretation

The review of the related literature shows that a large number of techniques/approaches have been so far proposed for the supplier selection problem, some of which have used classical methods and some others have employed a combination of two or more methods. The integration of methods was considered when researchers found that they could cover the weaknesses or disadvantages of one method through other methods. In this paper, a practical hybrid approach based on this logic was developed with the aim of selecting worthy circular suppliers by integrating MCDM methods and FIS. In general, the structure of the proposed approach can be divided into two parts from the computational point of view. In the first part, the performance of suppliers is evaluated for each criterion using linear relationships, while, in the second part, the final score of suppliers is calculated using nonlinear relationships. In the proposed approach, the sub-criteria for supplier evaluation were weighed using the FAHP method, and then, the performance of the six suppliers regarding each criterion was evaluated by five experts. At the end, the suppliers' score for each criterion was calculated using FTOPSIS technique. The calculations carried out so far were based on linear relations. Since the relationship between the criteria and the final score does not follow linear functions, the nonlinear and logical relationship between the criteria and the final score was established using a set of fuzzy inference rules and a FIS was developed for this purpose. The results obtained from the proposed FIS show that the two criteria of circular and capability have a considerable effect on suppliers' final score. For example, in the comparison of suppliers 1 and 6, as observed in Tables 13 and 14, although supplier 6 outperforms supplier 1 in terms of delivery and quality criteria, it has a lower final score than supplier 1 due its non-superiority in the circular and capability criteria. Similarly, with the comparison of the obtained results for supplier 5 with those obtained for supplier 6, it is inferred that the two criteria of circular and capability play an important role in the final score. Comparing the performance of supplier 4 with that of supplier 5 reveals that these two suppliers have almost the same performance in the delivery criterion, but supplier 5 has a higher final score despite the superiority of supplier 4 in both circular and quality criteria compared to supplier 5 because supplier 5 has a larger score in the capability criterion. In general, the results obtained from the comparison of suppliers' performance show that circular and capability criteria are more important than the other two criteria, i.e., quality and delivery in the proposed FIS.

4.2. Practical implications

MCDM problems involve multiple and often conflicting criteria. Real-world supplier selection problems are complex multi-criteria problems that are difficult to solve because they require a careful analysis of dominance between the suppliers and a trade-off between the competing criteria. The method proposed in this study is comprehensive and considers a large number of measures. The model is structured and systematic but remains flexible since there is practically no limit on the number of criteria or the number of suppliers. The proposed method is composed of several analytical modules, and it is also intuitive since it utilizes expert opinions. The proposed model is generic and applicable to a wide range of real-world multi-criteria problems, from manufacturing to healthcare and from non-profit to tourism. The model can handle precise data or uncertainty using fuzzy sets. The proposed model can also help managers synthesize data to make effective and informed decisions. The application studied in this paper also addresses an important and common problem in circular supply chain management, which is of great interest to the researchers and practicing managers. The flexibility feature of the proposed model also allows for enhancing the proposed model by incorporating social criteria, including human rights and occupational health and safety systems, among others. In summary, the proposed approach is comprehensive, structured, flexible, analytical, intuitive, and adaptable to a wide range of applications.

4.3. SDGs potential achievements

The developed approach for the petrochemical industry suppliers' evaluation and selection in the circular supply chain helps to achieve six Sustainable development goals (SDG's) intotal out of seventeen goals. The execution of proposed circular based supplier selection decision model will help the company to contributes to SDG 3 for human good health and wellbeing through controlling emission issues, SDG 6 by improving the water-use efficiency, SDG 8 for decent work and economic growth goal by promoting circular training, SDG 9 for Industry, Innovation and Infrastructure by implementing clean and environmental technologies, SDG 12 for responsible consumption and production by reducing the hazardous waste & increasing the recycling rate, and SDG 13 for climate change by reducing CO_2 emissions.

5. Validation of proposed approach

When we are using different MCDM methods to find final rankings, Spearman rank correlation coefficient can be valuable to determine the association among those ranks (Gibbons, 1971; Raju and Kumar, 1999). Here we used three different FTOPSIS methods for our case study to determine the ranks. Those methods are graded mean integration FTOPSIS, geometric mean based FTOPSIS (Chen et al., 2011), and proposed approach based on FTOPSIS. However, we cannot make a final decision unless we ensure the accuracy of the results (Kahraman et al., 2009).

To find out how much difference occurs among the results obtained by three different FTOPSIS methods (proposed FTOPSIS, graded mean integration FTOPSIS, and geometric mean based FTOPSIS) and if those differences are statistically significant, Spearman's rank-correlation test was applied in this paper.

The definition of Spearman coefficient is (Raju and Kumar, 1999):

$$R = 1 - \frac{6\sum_{a=1}^{A} D_a^2}{A(A^2-1)} \tag{13}$$

where a is the number of alternatives; A is the total number of alternatives; D_a is the difference between ranks determined by different methods. If Spearman rank correlation coefficient is equal to one, then there is perfect association between two ranks resulted from two different methods. There is no association if Spearman rank correlation coefficient is zero and perfect disagreement is when it equals -1.

Table 15 shows final ranking for all three methods. In addition, to find the statistical difference between ranks resulted by all three methods, Spearman rank correlation coefficient was calculated. Table 16 shows the Spearman coefficient among three methods. It is obvious that the value of Spearman rank correlation coefficient is from 0.8857 to 0.9429 and it indicates that the three mentioned methods have great association. Table 16 shows that there is no remarkable difference between the proposed approach and the geometric mean based FTOPSIS. In addition to validating the proposed approach through Spearman rank correlation coefficient, the obtained results are authorized by expert panel. They endorsed the resulting rankings of the suppliers.

Table 15. Final Ranks of the different FTOPSIS approaches

Alternatives	Graded mean	Geometric mean	Proposed approach
Supplier 1	3	3	3
Supplier 2	5	5	6
Supplier 3	6	6	5
Supplier 4	1	2	2
Supplier 5	2	1	1
Supplier 6	4	4	4

Table 16. The Spearman coefficient between three methods

	Proposed approach	Graded mean	Geometric mean
Proposed approach	1	0.8857	0.9429
Graded mean		1	0.9429
Geometric mean			1

6. Conclusion

The sustainable/circular supplier selection problem is of particular importance to organizations on the one hand because of its competitive advantage and, on the other hand, due to environmental concerns and social issues. With the increase of organizations in size, supplier selection assumes significant importance more than ever. Petrochemical industries are among the major industries wherein the supplier selection problem is especially important since a significant portion of the costs of these industries, cleaner production, and the chain sustainability in general are related to supplier selection. Therefore, the improper selection of suppliers in such industries has destructive environmental impacts and significantly reduces the chain efficiency and sustainability in addition to imposing huge costs on the chain. In this regard, a new perspective was developed in the form of a practical approach for the petrochemical industry suppliers' evaluation and selection in the circular supply chain for the first time in this study to achieve Sustainable development goals (SDG's). In the proposed approach, the performance of each supplier per criterion (i.e., circular, capability, delivery, and quality) was calculated using the integrated FAHP and FTOPSIS methods. Then, a FIS was proposed using the knowledge of experts in order to develop a nonlinear relationship between the final score of suppliers and the mentioned criteria. Then, to investigate the effectiveness of the proposed approach, the proposed approach was implemented in a petrochemical industry in Iran.

For this purpose, the knowledge of five industry experts was used and the six suppliers were evaluated and ranked by the proposed approach. The results indicated the effectiveness of the proposed approach and were approved by experts. Also, the results of the presented approach were validated by comparing it with two other methods, which showed the accuracy of its performance.

In this paper, social criteria have not been considered in the supplier selection procedure; therefore, it is suggested that an approach to sustainable supplier selection be developed by considering social criteria. In addition, this paper benefits from FAHP for the assignment of weights to the sub-criteria. The application of the fuzzy BWM method can lead to the acceleration of the proposed approach due to the lower number of pairwise comparisons. Thus, researchers interested in this are recommended to use fuzzy BWM rather than FAHP method in future research. In this study, the interdependency between sub-criteria has been overlooked. Accordingly, it is suggested that interdependency among sub-criteria be calculated in future research using the fuzzy decision-making trial and evaluation laboratory (DEMATEL) method and be applied to the weights of the sub-criteria.

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Appendix

Table A. The extracted FIS rules from expert panel by questionnaire

If **D** is **high** and **Q** is **high** and **CR** is **high** and **C** is **high** then **Score** is **high**
If **D** is **high** and **Q** is **high** and **CR** is **high** and **C** is **medium** then **Score** is **high**
If **D** is **high** and **Q** is **high** and **CR** is **high** and **C** is **low** then **Score** is **medium**
If **D** is **high** and **Q** is **high** and **CR** is **medium** and **C** is **high** then **Score** is **high**
If **D** is **high** and **Q** is **high** and **CR** is **medium** and **C** is **medium** then **Score** is **high**
If **D** is **high** and **Q** is **high** and **CR** is **medium** and **C** is **low** then **Score** is **medium**
If **D** is **high** and **Q** is **high** and **CR** is **low** and **C** is **high** then **Score** is **high**
If **D** is **high** and **Q** is **high** and **CR** is **low** and **C** is **medium** then **Score** is **high**
If **D** is **high** and **Q** is **high** and **CR** is **low** and **C** is **low** then **Score** is **medium**
If **D** is **high** and **Q** is **medium** and **CR** is **high** and **C** is **high** then **Score** is **high**
If **D** is **high** and **Q** is **medium** and **CR** is **high** and **C** is **medium** then **Score** is **high**
If **D** is **high** and **Q** is **medium** and **CR** is **high** and **C** is **low** then **Score** is **medium**
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If **D** is **high** and **Q** is **medium** and **CR** is **medium** and **C** is **low** then **Score** is **medium**
If **D** is **high** and **Q** is **medium** and **CR** is **low** and **C** is **high** then **Score** is **high**
If **D** is **high** and **Q** is **medium** and **CR** is **low** and **C** is **medium** then **Score** is **medium**
If **D** is **high** and **Q** is **medium** and **CR** is **low** and **C** is **low** then **Score** is **medium**
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If **D** is **high** and **Q** is **low** and **CR** is **medium** and **C** is **medium** then **Score** is **medium**
If **D** is **high** and **Q** is **low** and **CR** is **medium** and **C** is **low** then **Score** is **low**
If **D** is **high** and **Q** is **low** and **CR** is **low** and **C** is **high** then **Score** is **medium**
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If **D** is **medium** and **Q** is **medium** and **CR** is **high** and **C** is **low** then **Score** is **medium**
If **D** is **medium** and **Q** is **medium** and **CR** is **medium** and **C** is **high** then **Score** is **high**
If **D** is **medium** and **Q** is **medium** and **CR** is **medium** and **C** is **medium** then **Score** is **medium**
If **D** is **medium** and **Q** is **medium** and **CR** is **medium** and **C** is **low** then **Score** is **low**
If **D** is **medium** and **Q** is **medium** and **CR** is **low** and **C** is **high** then **Score** is **medium**
If **D** is **medium** and **Q** is **medium** and **CR** is **low** and **C** is **medium** then **Score** is **medium**
If **D** is **medium** and **Q** is **medium** and **CR** is **low** and **C** is **low** then **Score** is **low**
If **D** is **medium** and **Q** is **low** and **CR** is **high** and **C** is **high** then **Score** is **medium**
If **D** is **medium** and **Q** is **low** and **CR** is **high** and **C** is **medium** then **Score** is **medium**
If **D** is **medium** and **Q** is **low** and **CR** is **high** and **C** is **low** then **Score** is **low**
If **D** is **medium** and **Q** is **low** and **CR** is **medium** and **C** is **high** then **Score** is **medium**
If **D** is **medium** and **Q** is **low** and **CR** is **medium** and **C** is **medium** then **Score** is **low**

If **D** is **medium** and **Q** is **low** and **CR** is **medium** and **C** is **low** then **Score** is **low**
If **D** is **medium** and **Q** is **low** and **CR** is **low** and **C** is **high** then **Score** is **medium**
If **D** is **medium** and **Q** is **low** and **CR** is **low** and **C** is **medium** then **Score** is **medium**
If **D** is **medium** and **Q** is **low** and **CR** is **low** and **C** is **low** then **Score** is **low**
If **D** is **low** and **Q** is **high** and **CR** is **high** and **C** is **high** then **Score** is **medium**
If **D** is **low** and **Q** is **high** and **CR** is **high** and **C** is **medium** then **Score** is **medium**
If **D** is **low** and **Q** is **high** and **CR** is **high** and **C** is **low** then **Score** is **medium**
If **D** is **low** and **Q** is **high** and **CR** is **medium** and **C** is **high** then **Score** is **high**
If **D** is **low** and **Q** is **high** and **CR** is **medium** and **C** is **medium** then **Score** is **medium**
If **D** is **low** and **Q** is **high** and **CR** is **medium** and **C** is **low** then **Score** is **low**
If **D** is **low** and **Q** is **high** and **CR** is **low** and **C** is **high** then **Score** is **high**
If **D** is **low** and **Q** is **high** and **CR** is **low** and **C** is **medium** then **Score** is **medium**
If **D** is **low** and **Q** is **high** and **CR** is **low** and **C** is **low** then **Score** is **low**
If **D** is **low** and **Q** is **medium** and **CR** is **high** and **C** is **high** then **Score** is **high**
If **D** is **low** and **Q** is **medium** and **CR** is **high** and **C** is **medium** then **Score** is **medium**
If **D** is **low** and **Q** is **medium** and **CR** is **high** and **C** is **low** then **Score** is **low**
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If **D** is **low** and **Q** is **medium** and **CR** is **medium** and **C** is **medium** then **Score** is **medium**
If **D** is **low** and **Q** is **medium** and **CR** is **medium** and **C** is **low** then **Score** is **low**
If **D** is **low** and **Q** is **medium** and **CR** is **low** and **C** is **high** then **Score** is **medium**
If **D** is **low** and **Q** is **medium** and **CR** is **low** and **C** is **medium** then **Score** is **medium**
If **D** is **low** and **Q** is **medium** and **CR** is **low** and **C** is **low** then **Score** is **low**
If **D** is **low** and **Q** is **low** and **CR** is **high** and **C** is **high** then **Score** is **medium**
If **D** is **low** and **Q** is **low** and **CR** is **high** and **C** is **medium** then **Score** is **low**
If **D** is **low** and **Q** is **low** and **CR** is **high** and **C** is **low** then **Score** is **low**
If **D** is **low** and **Q** is **low** and **CR** is **medium** and **C** is **high** then **Score** is **medium**
If **D** is **low** and **Q** is **low** and **CR** is **medium** and **C** is **medium** then **Score** is **low**
If **D** is **low** and **Q** is **low** and **CR** is **medium** and **C** is **low** then **Score** is **low**
If **D** is **low** and **Q** is **low** and **CR** is **low** and **C** is **high** then **Score** is **low**
If **D** is **low** and **Q** is **low** and **CR** is **low** and **C** is **medium** then **Score** is **low**
If **D** is **low** and **Q** is **low** and **CR** is **low** and **C** is **low** then **Score** is **low**

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Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: