Journal of Future Sustainability 3 (2023) 167–182

Contents lists available at GrowingScience

Journal of Future Sustainability

homepage: www.GrowingScience.com/jfs

Selection of sustainable and green suppliers using a fuzzy R-method in group decision-making situations

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C H R O N I C L E

Article history:
Received: October 10, 2022
Received in revised format: October 28, 2022
Accepted: January 20, 2023
Available online:
January 20, 2023

Keywords:
Sustainability
Green supplier selection
Fuzzy scale
Multi-criteria decision making
R-method

A B S T R A C T

A growing number of companies treat "sustainability" as an important objective in their strategy. Sustainable and green suppliers increase efficiency by reducing costs and waste in industries. Sustainable and green supplier selection is a critically important factor in moving forward along the path of sustainability. A fuzzy R-method is proposed in this paper based on ranking the fuzzy numbers of alternative suppliers and criteria. Triangular fuzzy membership function and different fuzzy scales are presented to demonstrate and validate the proposed method. Fuzzy composite scores are generated, and these scores are converted into crisp forms to evaluate the alternative suppliers. The novelty of the proposed method is that it is simple, can deal with qualitative and quantitative criteria of supplier selection, and requires less computational effort for evaluating and ranking the green and sustainable suppliers in fuzzy group decision-making situations. The weights of the criteria and alternative suppliers are generated using a simple equation and hence there is no need to apply different methods for weights generation and ranking. Furthermore, this method does not require normalization of the data. Two realistic group decision-making problems of green and sustainable supplier selection to test the method. Sensitivity analysis for the proposed method is also conducted to check the consistency of the proposed method to different weights of the criteria. The proposed method is effective, robust, and competitive to the existing multi-criteria decision making (MCDM) methods of sustainable supplier selection.

1. Introduction

Nowadays, large industrialization is a major source of environmental pollution. Many government agencies and many activists all over the globe critically think about this concern (Garg et al., 2017). Due to this issue, green supply chain management and sustainable development systems are forcing many organizations to improve their sustainability and environmental issues in the manufacturing environment. There is no exact definition of sustainable and green supply chains. We may define sustainable supply chains as consuming existing resources without compromising future generations' needs. A sustainable supply chain involves integrating socially, environmentally, and financially feasible performs into an organization. Sustainable supply chain integrates the industry's social, environmental, and economic aspects (Li et al., 2021). Management of sustainable and green supply chains is capturing the attention of academic researchers and industry people. With growing customer demand and various government policies, it is necessary to think about sustainable supply chain management (Nasr et al., 2021). External stakeholders such as consumers, public, and investors impact companies in their economic, social, and environmental aspects. Negative impacts, such as high pollution, bad working environment, and unethical behavior of employees may damage the organization's reputation. A sustainable supply chain management system can help organizations reduce waste and achieve cost savings and net profit. The target of sustainable supply chain management is to produce a relationship between social, economic, and environmental dimensions. From 2016 onwards, there is an enormous rise in the scientific studies on sustainable supply chain management. To maintain sustainability in the organization, selecting suppliers and the decision-makers is the most crucial aspect. A sustainable goal may threaten the traditional supply chain management system to either establish a new policy or disengage from the field.

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ISSN 2816-8151 (Online) - ISSN 2816-8143 (Print)

doi: 10.5267/j.jfs.2023.1.005

Sustainable supplier selection is a significant issue and challenge for managerial people due to the inclusion of many complex and unpredicted factors. Any improper choice may lead to a considerable loss economically. There is no question that the sustainable supplier's selection directly affects the performance of sustainable supply chain management. The wrong selection of sustainable suppliers may reduce the efficiency and effectiveness of the organization. Therefore, this problem is considered a complex MCDM problem for managerial people. Supplier selection, in the past, was only based on the economy and performance criteria (Badi & Ballen, 2018). Nowadays due to the increase in the demand for sustainability in supply chain management, only economic criterion is not sufficient to estimate the performance of suppliers. It is a necessity to include social and environmental factors in addition to economic and performance requirements. Economic sustainability concentrates on maximizing the output while minimizing the investment. Economic criteria include the cost of transportation, service price, and quantity of product (Liu et al., 2019). Environmental sustainability helps to fulfill the product and service demand without harming nature. Environmental criteria include pollution control, green management, Environmental cost, etc. The social criteria's main aim is to provide training, health, safety, and fundamental rights. Due to pressure from the government and private sectors, sustainable supplier selection is utmost important (Singh et al., 2022). The selection of one supplier from a large and a wide variety having different potentials and capabilities is a complex task that requires an MCDM solution approach.

The research questions (RQs) related to supplier selection using MCDM methods are:

- RQ1: Is there any suitable MCDM method to weigh the supplier selection criteria as well as to evaluate and rank the sustainable and green suppliers in the management of supply chain?
- RQ2: Can the qualitative and quantitative criteria be dealt with by such MCDM method (which provides answer to RQ1)? If so, what about the practical applicability of such MCDM methods in group decision-making situations with a number of decision-makers?
- RQ3: If there is any such MCDM method (which provides answers to RQ1 and RQ2), will it be simple to understand and convenient to solve the problem in fuzzy decision-making situations involving ambiguity in the available information?
- RQ4: Is it possible to have a suitable MCDM method that is effective and robust to the changes in the criteria weights?

The present study proposes a fuzzy R-method as a novel MCDM method to address the above RQs positively.

2. Literature review

Supplier selection is an MCDM problem including social, ethical, and environmental criteria. A novel approach based on a Fuzzy Analytic Network Process (FANP) within a group decision-making scheme involving incomplete preference relations was developed by Büyüközkan and Çifçi (2011). Su et al. (2016) proposed a hierarchical grey DEcision-Making Trial and Evaluation Laboratory (DEMATEL) method and the option of recycle/reuse/reduce was presented to increase the percentage of material savings. Verma et al. (2017) analyzed and proposed the impact of emerging markets on existing diversified firm practices. Krishankumar et al. (2017) extended the Preference Ranking Organization Method for Enrichment of Evaluations (PROMETHEE) method to solve supplier selection problems in the automobile industry. A new aggregation method to aggregate the linguistic terms was proposed considering six criteria. The authors considered 3 decision-makers to rate 4 suppliers according to the performance of each supplier under each criterion. Lu et al. (2018) combined Elimination and Choice Translating Reality (ELECTRE) and rough set theory to solve the MCDM problem of sustainable supplier selection. they considered 4 experts and 8 alternatives. They considered three main criteria and these three main criteria were divided into ten sub-criteria. Zarbakhshnia and Jaghdani (2018) proposed a two-stage Data Envelopment Analysis (DEA) model, considering the intermediate elements between two stages to select the best sustainable supplier. Demir et al. (2018) applied the VlseKriterijumska Optimizacija I Kompromisno Resenje (VIKOR) method to rank the suppliers based on environmental performance. Diba and Xie (2019) evaluated, analyzed, and selected the best suppliers for a Senegal-based milk company considering social, economic, and environmental aspects of sustainable supply chain management using different models of grey relational analysis (GRA). Giannakis et al. (2019) used the Analytic Network Process (ANP) technique to create a sustainable framework for supplier selection. Tirkolaee et al. (2020) developed a fuzzy analytic network process (FANP), fuzzy DEMATEL, fuzzy TOPSIS, and weighted goal programming method for supplier selection. Maximization of the products' weighted value, maximization of the reliability of the supply chain, and minimization of the total cost of the chain were considered as the objectives. Chen et al. (2020) used DEMATEL method for determining the criteria weights, and TOPSIS method for supplier ranking. Kannan et al. (2020) used a fuzzy best-worst method (BWM) to weigh the criteria and an interval VIKOR technique to rank the sustainable suppliers in circular supply chains. Stevic et al. (2020) considered 21 criteria and 8 alternative suppliers and used the Measurement Alternatives and Ranking according to the COmpromise Solution (MARCOS) method for supplier selection in the healthcare industry. Sharma et al. (2021) presented a thorough review of sustainability indicators, performance measurement methods, and challenges. In another work, Sharma et al. (2021) highlighted the prerequisites, impediments, and prospects while transiting to circular economy from the linear economy (LE) of SMEs. Nasr et al. (2021) presented a two-stage fuzzy supplier selection and order allocation model in a closed-loop supply chain. The fuzzy BWM was used to select the most suitable suppliers keeping in view of the social, economic, environmental, and circular criteria. Ho et al. (2021) used a fuzzy AHP method to solve the MCDM problem. Qualitative and quantitative criteria like energy consumption, cost, brand, area, and credit reputation for supplier selection were considered. Liou et al. (2021) applied three different methods to solve the MCDM problem. Initially, they screened out criteria from 25 to 13. After obtaining the criteria, they used fuzzy BWM for generation of weights for these 13 criteria. The suppliers were ranked using the Fuzzy TOPSIS method. Yazdi et al. (2021) applied two methods to solve a decision-making problem in the oil and gas industry. They used a z-number to deal with uncertainty in data. The researchers used the Complex Proportional Assessment (COPRAS) method to generate ranks of alternatives and then the Stepwise Weight Assessment Ratio Analysis (SWARA) method was applied to generate the criteria weights. Singh et al. (2022) identified indicators for economic, environmental and social criteria, and prioritized these based on their significance for sustainable supplier selection in the Indian construction industry. The BWM was presented for sustainable supplier selection.

2.1 Research gaps

Literature review reveals that several MCDM techniques were applied for the selection of suppliers such as ANP (Giannakis et al., 2019; Tirkolaee et al., 2020); FAHP (Buyukozkan & Cifci, 2011; Khoshfetrat et al., 2019; Ho et al., 2021); TOPSIS (Shalke et al., 2018; Do et al., 2019); FTOPSIS (Liou et al., 2021; Tirkolaee et al., 2020); ELECTRE (Lu et al., 2018); PROMETHEE; GRA (Diba & Xie, 2019); DEMATEL and its fuzzy versions (Su et al., 2016; Chen et al., 2020; Tirkolaee et al., 2020); MARCOS (Stevic et al., 2020); SWARA (Yazdi et al., 2021); VIKOR (Demir et al.,2018; Kannan et al., 2020); WASPAS (Mishra et al., 2019); DEA (Zarbakhshnia & Jaghdani, 2018); COPRAS (Yazdi et al., 2021); Basic or fuzzy BWM (Badi & Ballem, 2018; Kannan et al. 2020; Liou et al., 2021; Nasr et al., 2021; Singh et al., 2022), etc. Most of the MCDM methods are very difficult to understand and sometimes researchers apply combined MCDM methods and weight generation methods. This combination process increases the complexity and results in more efforts to evaluate the performance of the supplier. For example, the PROMETHEE method involves the comparison of one alternative with other alternatives for each criterion. Each criterion needs a large matrix computation, which becomes more complicated as the alternatives and criteria increases. Different MCDM methods like TOPSIS, VIKOR, ELECTRE, GRA, etc. require normalization of data and different methods are available for normalizing the data. If the normalization method is changed then the result obtained by the MCDM method also changes. Furthermore, the TOPSIS, VIKOR, ELECTRE, and GRA methods involve more computation. The GRA method gives different rankings for different values of distinguishing coefficients and choosing a proper distinguishing coefficient itself is mostly arbitrary. AHP or ANP and their fuzzy versions require too many matrices for pairwise comparisons and involve more computation. Furthermore, different ways of calculating the weights (i.e., arithmetic mean, geometric mean, etc.) may lead to different decision results. In ANP method, verification of results due to feedback loops and interrelations is very difficult and it is too complex for implementation as a tool for practical decision making in an organization. The COPRAS method involves many parameter calculations for each alternative like maximizing and minimizing index, relative weight, priority order, and performance index. These parameters' calculations increase the complexity. In MARCOS methodology we need to calculate the normalized data, weightage matrix, normalized weighting matrix, utility degree, and utility function which makes the method more computational. The DEMATEL method involves many computations to accurately analyze the complicated interrelations between the factors, and this aspect limits its applications. Furthermore, the unfair arguments' influence on the decision result is to be reduced. In the case of DEA, the results are sensitive to the selection of inputs and outputs. The decision maker must also be familiar with the linear programming technique. In the BWM method, the best criteria and worst criteria need to be identified and this is to be done by the experts. As experts change, the best and worst criteria alter as well and it may lead to the wrong conclusion. The BWM method involves pairwise comparisons between the worst criteria and other criteria which is more computational. The fuzzy versions of the MCDM methods involve large computation and these versions violate the basic rule of fuzzy logic that the available quantitative values of the attributes should not be converted into fuzzy terms.

Literature review reveals that there are only a few studies on sustainable supplier selection regarding environmental, economic, and social aspects. There is no single method used for weight generation and ranking simultaneously. There is a research gap considering three aspects of sustainability in the existing strategy. Despite several proposals, the sustainable supplier selection problem poses numerous challenges, as seen by the prior studies. Most of the approaches are not accurate or successful so far due to the difficulties of sustaining supplier selection activities. The supplier selection problem deals simultaneously with quantitative and qualitative data. Hence a correct and effective MCDM method is needed to tackle this problem.

This paper tries to address the above research questions by presenting a simple, systematic, and logical method named fuzzy R-method. R-method is a simple MCDM method based on ranking of criteria and alternatives. The ranks assigned to the criteria and the ranks assigned to the alternatives with respect to each of the criteria are converted to appropriate weights and the final composite scores of the alternatives are computed using these weights. The fuzzy R-method is used for assigning the weights to the criteria based on their importance and is also used to rank various suppliers using these criteria. The proposed fuzzy R-method can assign the weights and rank the alternatives simultaneously and there is no need to apply another method for computing the criteria weights.

The contributions of the present study are as follows:

- Developing and presenting a simple, logical, practical, and straightforward MCDM method for best suitable supplier selection based on their green and sustainable innovation capabilities and capacities.
- Identifying the qualitative and quantitative criteria to evaluate the performance of green and sustainable suppliers, distinguishing and ranking the criteria based on their importance, and assigning the importance weights to the sustainable and green supplier selection criteria more logically and accurately.
- Evaluating the performance of the suppliers and suggesting the most efficient supplier among various alternative suppliers under fuzzy group decision-making situations.
- Evaluating the methodology on real case studies and demonstrating the robustness of the proposed MCDM method.

This work is an initial attempt to use fuzzy numbers with the R-method. The R-method is a simple and logical method to identify the best and worst alternatives among the different alternatives. R-method is a recently developed method to solve MCDM problems (Rao & Lakshmi, 2021a, b). To demonstrate the suggested methodology for selecting suppliers, one demonstration example and two case studies of supplier selection are considered. This paper answers the research questions RQ1-RQ4 and fills the research gaps to a significant extent. We believe that the methodology for sustainable and green supplier selection is new and was not applied previously to this problem.

3. Proposed decision-making methodology

To understand the proposed methodology, we need to understand the properties of a triangular fuzzy number.

3.1 Properties of triangular fuzzy numbers

Fig. 1 shows a triangular fuzzy membership function.

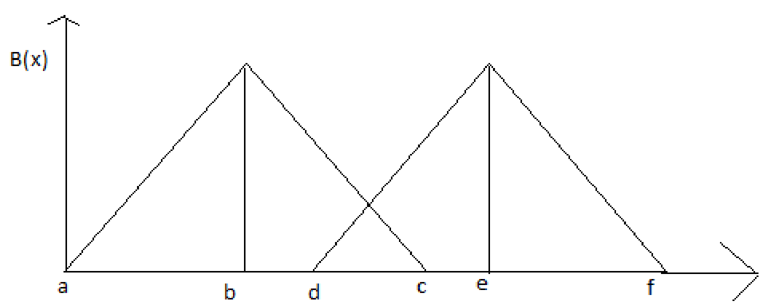

Fig. 1. A triangular fuzzy membership function.

Property 1: the arithmetic operation on two fuzzy numbers TFN1=(a,b,c) and TFN2=(d,e,f) are as follows (Tong et al., 2020).

$$\text{TFN 1} + \text{TFN2} = (a + d, b + e, c + f) \tag{1}$$
$$\text{TFN 1} - \text{TFN2} = (a - d, b - e, c - f) \tag{2}$$
$$\text{TFN 1} \times \text{TFN2} = (a \times d, b \times e, c \times f) \tag{3}$$
$$\text{TFN 1} \div \text{TFN2} = (a \div d, b \div e, c \div f) \tag{4}$$
$$K \times \text{TFN 1} = (K \times a, K \times b, K \times c) \tag{5}$$

Property 2: Suppose we have m number of decision-maker and each decision-maker gives a rating to each alternative for each criterion, then aggregating fuzzy rating for each alternative for corresponding criteria is calculated as follows.

$$A = \text{Min}_m(a), \qquad B = \left(\frac{1}{m}\right)\sum_{1}^{m} b, \qquad C = \text{Max}_m(c) \tag{6}$$

where, (A, B, C) is aggregated fuzzy rating. Suppose, two decision makers DM1 and DM2 are there. To calculate the aggregated fuzzy rating for criterion (C1) and alternative (A1) we consider two fuzzy numbers (0.8, 0.9, 1) and (0.8, 0.9, 1) so that A=min (0.8,0.8) =0.8, B= ((0.9+0.9)/2) =0.9 and C= max (1,1) =1. Table 1 shows the aggregated fuzzy numbers. Similarly, for criterion (C1) and alternative (A2) we consider two fuzzy numbers (0.8, 0.9, 1) and (0.5, 0.7, 0.9) so that A=min (0.8,0.5) =0.5, B= ((0.9+0.7)/2) =0.8 and C= max (1,0.9) =1. Similarly, we calculate aggregate fuzzy rating of criterion (C2) and its alternatives.

Table 1
Aggregated fuzzy number

Criteria	Alternatives	DM1	DM2	Aggregated fuzzy rating
C1	A1	(0.8, 0.9, 1)	(0.8, 0.9, 1)	(0.8,0.9,1)
	A2	(0.8, 0.9, 1)	(0.5, 0.7, 0.9)	(0.5,0.8,1)
C2	A1	(0.3, 0.5, 0.7)	(0.5, 0.7, 0.9)	(0.3,0.6,0.9)
	A2	(0.5, 0.7, 0.9)	(0.8, 0.9, 1)	(0.5,0.8,1)

Property 3: Defuzzification to convert a fuzzy number to a crisp number is as follows, Suppose a fuzzy number is TFN= (a, b, c) then the crisp number is obtained by Eq. (7) using the Centroid method for defuzzification of fuzzy number.

$$\text{Crisp TFN} = \frac{a + 4 \times b + c}{6} \tag{7}$$

3.2. Proposed fuzzy R-method

The proposed method requires a decision matrix, a fuzzy scale, and the weights of different criteria. Triangular membership function is used to conveniently deal with uncertainty in data and to obtain more effective results. The steps are given below.

Step 1: Define the fuzzy scale, define the linguistic terms and corresponding triangular fuzzy numbers.
Step 2: Choose the group of decision-makers. Obtain fuzzy rating of each decision-maker as the positive TFN or linguistic term and evaluate the aggregated fuzzy number.
Step 3: Determine the ranks of the criteria based on their importance and assign the weights developed by the R-method. The weight generation equation is given below.

$$w_j = \frac{\left(\frac{1}{\sum_{k=1}^{j}\left(\frac{1}{r_k}\right)}\right)}{\sum_{j=1}^{n}\left(\frac{1}{\sum_{k=1}^{j}\left(\frac{1}{r_k}\right)}\right)} \tag{8}$$

w_j = weight of criterion j (j = 1, 2, 3, ….., n)
r_k = rank of criterion k (k = 1, 2, 3, ….., j)
n = number of criteria

Step 4: Determine the performance of each alternative under each criterion and obtain the aggregated fuzzy number and obtain the decision table in terms of fuzzy numbers. Generalized decision table is shown below.

Table 2
Generalized decision table.

Alternatives	Criteria				
	C1	C2	C3	C4	C5
A1	TFN 11	TFN 12	TFN 13	TFN 14	TFN 15
A2	TFN 21	TFN 22	TFN 23	TFN 24	TFN 25
A3	TFN 31	TFN 32	TFN 33	TFN 34	TFN 35
A4	TFN 41	TFN 42	TFN 43	TFN 44	TFN 45

where, TFN is a triangular fuzzy number.

Step 5: Assign the rank of each number based on the type of criterion (beneficial (e.g., quality management) or non-beneficial (e.g., transportation cost)) and the importance of each alternative.

Table 3 demonstrates how to rank the alternatives for non-beneficial and beneficial criteria. Suppose we have four triangular fuzzy numbers as (0.8, 0.9, 1), (0.8, 0.9, 1), (0.3, 0.5, 0.7), and (0.5, 0.5, 0.7) for non-beneficial criterion (C1) as well as for the beneficial criterion (C2) for Alternatives A1, A2, A3, and A4, then the fuzzy numbers are ranked as explained.

Table 3
Demonstration to rank the alternatives for non-beneficial/beneficial criteria.

Alternatives	Non-beneficial criterion		Beneficial criterion	
	C1	Ranking	C2	Ranking
A1	(0.8, 0.9, 1)	(3.5,3.5,3.5)	(0.8, 0.9, 1)	(1.5,1.5,1.5)
A2	(0.8, 0.9, 1)	(3.5,3.5,3.5)	(0.8, 0.9, 1)	(1.5,1.5,1.5)
A3	(0.3, 0.5,0.7)	(1,1.5,1.5)	(0.3, 0.5,0.7)	(4,3.5,3.5)
A4	(0.5, 0.5,0.7)	(2,1.5,1.5)	(0.5, 0.5,0.7)	(3,3.5,3.5)

First, we consider cost criterion for which the minimum value is considered more important. We considered the left column of fuzzy number (0.8,0.8,0.3,0.5) then A3 is minimum among all the alternatives. Assign rank 1 to alternative A3 and A4 has 0.5 value which is the second minimum and hence alternative A4 obtains rank 2. A1 and A2 have the same value of 0.8 then we take an average of the rank of 3 and 4 as 3.5 and rank of 3.5 to assign A1 and A2. Now, consider a middle column of fuzzy number (0.9,0.9,0.5,0.5) then 0.5 is the minimum value but A3 and A4 have the value of 0.5 so an average of ranks 1 and 2 is taken as 1.5 and the alternatives A3 and A4 are assigned rank of 1.5. The alternative A1 and A2 also have the same value of 0.9 so we assign an average rank of 3.5 to A1 and A2. Similarly, we obtain ranks for the right column (1,1,0.7,0.7) of the above fuzzy numbers.

Now, we consider beneficial criterion (C2) for which the maximum value is considered more important. We considered the left column of fuzzy number (0.8,0.8,0.3,0.5) then alternatives A1 and A2 have the same maximum value of 0.8 so we assign an average rank of 1.5 to both alternatives A1 and A2. The second maximum is 0.5 which corresponds to alternative A4 so we assign a rank of 3 to A4 and rank of 4 to A3. Similarly, we consider the middle column (0.9,0.9,0.5,0.5) then 0.9 is maximum value. Alternatives A1 and A2 both have a maximum value of 0.9 and hence an average of rank 1.5 is assigned to alternatives A1 and A2. Alternatives A3 and A4 have the value of 0.5 and an average rank of 3.5 is assigned to alternatives A3 and A4. Similarly, we obtain the rank for the right column (1,1,0.7,0.7) of the above fuzzy numbers. The ranking in terms of fuzzy numbers is given in Table 3.

Step 6: Assign the weights generated by the proposed method (using Equation (8)) to each rank shown in Table 3. The weights generated for different alternatives and criteria are shown in Table 4.

Table 4 shows the weights generated by Eq. (8) for 10 criteria or alternatives but Table 4 is not limited to only 10. The weights for any number of criteria or alternatives can be generated by Eq. (8) (Rao and Lakshmi, 2021 a, b). The same table can be used for assigning the weights to the criteria and the alternatives.

Table 4
Weights assigned to different criteria and alternatives.

Rank	Number of criteria or alternatives to be ranked								
	2	3	4	5	6	7	8	9	10
	Weights assigned								
1	0.600	0.452	0.371	0.319	0.283	0.255	0.233	0.215	0.201
2	0.400	0.301	0.248	0.213	0.188	0.170	0.155	0.144	0.134
3		0.247	0.203	0.174	0.154	0.139	0.127	0.117	0.109
4			0.178	0.153	0.136	0.122	0.112	0.103	0.096
5				0.140	0.124	0.112	0.102	0.094	0.088
6					0.115	0.104	0.095	0.088	0.082
7						0.098	0.090	0.083	0.077
8							0.086	0.079	0.074
9								0.076	0.071
10									0.068

Step 7: Multiply the criteria weights with the corresponding alternatives weights and compute a fuzzy composite score for each alternative.

Step 8: Convert fuzzy composite score into the crisp composite score by Eq. (7) and determine the overall rankings of the alternative.

3.3 Demonstration of working of the fuzzy R-method for supplier selection in group MCDM situation

To demonstrate the proposed fuzzy R-method, we generate a hypothetical problem of 4 suppliers (i.e., P, Q, R, and S). Four criteria C1, C2, C3, and C4 are considered of which C1and C4 are non-beneficial criteria and the remaining are beneficial criteria. Three decision-makers D1, D2, and D3 are considered in this problem.

As per Step 1, we define a 7- point fuzzy scale, linguistic terms, and corresponding TFNs. The fuzzy scale for this problem is shown in Table 5.

Table 5
7-point fuzzy scale.

Linguistic terms	Fuzzy numbers	Name assigned
None	0, 0, 0	TFN_1
Very poor	0, 0.1, 0.2	TFN_2
Poor	0.1, 0.3, 0.5	TFN_3
Medium	0.3, 0.5, 0.7	TFN_4
Good	0.5, 0.7, 0.9	TFN_5
Very good	0.8, 0.9, 1	TFN_6
Excellent	1, 1, 1	TFN_7

In Step 2, we obtain a fuzzy rating of each decision-maker as the positive TFN and evaluate the aggregated fuzzy number. The fuzzy aggregated rating is obtained by Eq. (6). For example, if we consider Criterion C1 and supplier P and if D1, D2, and D3 decision-makers give ratings of FN_5 (0.5, 0.7, 0.9), FN_4(0.3, 0.5, 0.7), and FN_5(0.5, 0.7, 0.9) respectively as shown in Table 5, then the fuzzy number A = min (0.5,0.3,0.5), B = ((0.7+0.5+0.7)/3), and C = max (0.9,0.7,0.9) and we obtain the aggregated rating as (A, B, C) = (0.3,0.63,0.9). Similarly, the fuzzy ratings for all the alternatives of each criterion are obtained and are shown in Table 6.

Table 6
Rating of each decision-maker and aggregated fuzzy rating.

Criteria	Alternative Supplier	D1	D2	D3	Aggregated fuzzy rating
C1	P	TFN_5	TFN_4	TFN_5	(0.3,0.63,0.9)
	Q	TFN_3	TFN_3	TFN_3	(0.1,0.3,0.5)
	R	TFN_2	TFN_2	TFN_3	(0,0.167,0.5)
	S	TFN_3	TFN_3	TFN_2	(0,0.233,0.5)
C2	P	TFN_3	TFN_4	TFN_4	(0.1,0.433,0.7)
	Q	TFN_3	TFN_3	TFN_4	(0.1,0.366,0.7)
	R	TFN_5	TFN_6	TFN_6	(0.5,0.833,1)
	S	TFN_7	TFN_6	TFN_7	(0.8,0.966,1)
C3	P	TFN_4	TFN_4	TFN_3	(0.1,0.433,0.7)
	Q	TFN_5	TFN_5	TFN_4	(0.3,0.633,0.9)
	R	TFN_7	TFN_7	TFN_7	(1,1,1)
	S	TFN_5	TFN_5	TFN_6	(0.5,0.767,1)
C4	P	TFN_6	TFN_5	TFN_5	(0.5,0.767,1)
	Q	TFN_4	TFN_3	TFN_3	(0.1,0.367,0.7)
	R	TFN_2	TFN_2	TFN_3	(0,0.161,0.5)
	S	TFN_3	TFN_4	TFN_4	(0.1,0.431,0.7)

As per step 3, we need to rank the criteria and assign the weights from Table 4. We assume that criteria ranking as decided by the decision-makers is C1>C2>C3>C4. So C1 obtains rank 1, C2 obtains rank 2, C3 obtains rank 3 and C4 obtains rank 4 and 0.371, 0.248, 0.203, and 0.178 are the weights assigned to C1, C2, C3, and C4 respectively. As per step 4, a decision table (Table 7) is prepared with the help of aggregated fuzzy ratings which are available in Table 6.

Table 7
Aggregated fuzzy ratings.

Alternative Suppliers	C1	C2	C3	C4
P	(0.3,0.63,0.9)	(0.1,0.433,0.7)	(0.1,0.433,0.7)	(0.5,0.767,1)
Q	(0.1,0.3,0.5)	(0.1,0.366,0.7)	(0.3,0.633,0.9	(0.1,0.367,0.7)
R	(0.0.167,0.5)	(0.5,0.833,1)	(1,1,1)	(0,0.161,0.5)
S	(0,0.233,0.5	(0.8,0.966,1)	(0.5,0.767,1)	(0.1,0.431,0.7)

As explained in step 5, the rank of each number is based on the type of criterion (beneficial or non-beneficial) and the importance of each alternative.

Table 8
Ranked decision table.

Alternative Suppliers	C1	C2	C3	C4
P	(4,4,4)	(3.5,3,3.5)	(4,4,4)	(4,4,4)
Q	(3,3,2)	(3.5,4,3.5)	(3,3,3)	(2.5,2,2.5)
R	(1.5,1,2)	(2,2,1.5)	(1,1,1.5)	(1,1,1)
S	(1.5,2,2)	(1,1,1.5)	(2,2,1.5)	(2.5,3,2.5)

As per step 6, we assigned weights to the rank shown in Table 8. The weights are generated by the fuzzy R-method as shown in Table 4 for different ranks. Here, it may be noted that we have assigned rank of 1.5 for the left column of supplier R and S for criteria C1 but the weight corresponding to the rank of 1.5 is not given in Table 4. The rank of 1.5 is obtained by averaging the ranks 1 and 2 as explained in step 5 and hence we have to take the average weight of rank 1 and rank 2 (i.e. (0.371+0.248)/2 = 0.310). Similarly, the weights to all ranks are assigned and are shown in Table 9.

Table 9
Weighted decision table.

Alternative Suppliers	C1(0.371)	C2(0.248)	C3(0.203)	C4(0.178)
P	(0.178,0.178,0.178)	(0.190,0.203,0.190)	(0.178,0.178,0.178)	(0.178,0.178,0.178)
Q	(0.203,0.203,0.274)	(0.190,0.178,0.190)	(0.203,0.203,0.225)	(0.225,0.248,0.225)
R	(0.310,0.371,0.274)	(0.248,0.248,0.310)	(0.371,0.371,0.310)	(0.371,0.371,0.371)
S	(0.310,0.248,0.274)	(0.371,0.371,0.310)	(0.248,0.248,0.310)	(0.225,0.203,0.225)

Now, we need to multiply the criteria weights with the weights of the respective alternatives. Suppose we consider C1 criterion, then we obtain column for C1 in Table 10 by multiplying 0.371 with (0.178,0.178,0.178), (0.203,0.203,0.274), (0.310,0.371,0.274), and (0.310,0.248,0.274). Similarly, we obtain the fuzzy scores for all criteria as shown in Table 10.

Table 10
Fuzzy scores of the suppliers for different criteria.

Alternative	C1	C2	C3	C4
P	(0.066,0.066,0.066)	(0.047,0.050,0.047)	(0.050,0.047,0.036)	(0.036,0.036,0.032)
Q	(0.075,0.075,0.102)	(0.047,0.044,0.047)	(0.044,0.047,0.041)	(0.041,0.041,0.040)
R	(0.115,0.138,0.102)	(0.061,0.061,0.077)	(0.061,0.077,0.075)	(0.075,0.063,0.066)
S	(0.115,0.092,0.102)	(0.092,0.092,0.077)	(0.092,0.077,0.050)	(0.050,0.063,0.040)

As the last step, we need to convert the fuzzy score to a crisp score by using Eq. (7). For example (0.115,0.092,0.102) is the fuzzy score for supplier S and Criteria C1. We use Eq. (7) to generate a crisp score as (0.115+4*0.092+0.102)/6=0.097. Similarly, we can generate a crisp score for each fuzzy score shown in Table 10. The composite scores are computed and the overall rankings are given in Table 11.

Table 11
Crips score, composite score, and overall ranking of alternative suppliers.

Alternative Suppliers	C1	C2	C3	C4	Composite score	Overall ranking
P	0.066	0.049	0.036	0.032	0.183	4
Q	0.080	0.045	0.041	0.043	0.209	3
R	0.128	0.064	0.073	0.066	0.331	1
S	0.097	0.089	0.052	0.037	0.277	2

From the overall rankings, it can be understood that Supplier R is the first choice followed by Supplier S. Thus, the proposed fuzzy R-method can conveniently rank the suppliers and helps the management in selecting a suitable supplier. Now, two case studies taken from literature are presented. These case studies and the results obtained using different fuzzy methods like fuzzy PROMETHEE II and fuzzy TOPSIS were presented by the researchers recently. The same case studies are now attempted by the fuzzy R-method.

4. Case studies

To validate the proposed fuzzy R-method two case studies of supplier selection are considered. The proposed fuzzy R-method is applied to evaluate the performance of alternative green and sustainable suppliers.

4.1. Case study 1

This case study was attempted by Tong et al. (2020) using fuzzy PROMETHEE II and fuzzy TOPSIS. Four maintenance service providers (b1, b2, b3, and b4) were considered for a petrochemical company. The performance of each alternative service provider (b1, b2, b3, and b4) was required to be evaluated by the company. In this case study, five decision-makers and nine criteria were considered. The nine criteria were Supplier qualification (C1), Maintenance service performance (C2), Maintenance cost (C3), Quality management (C4), Schedule control (C5), Site management (C6), Sub-supplier management (C7), Environmental sustainability (C8), and Social sustainability (C9). All criteria, except C3, are beneficial criteria. A 7-point fuzzy scale is used for rating of the alternatives as shown in Table 5. The five decision-makers assigned their ratings to all the alternatives for each criterion as shown in Table 12.

Table 12
Rating given by each decision-maker and the aggregated fuzzy ratings corresponding to case study 1.

Criteria		D1	D2	D3	D4	D5	Aggregated fuzzy rating
C1	b1	TFN_7	TFN_6	TFN_5	TFN_5	TFN_6	(0.5,0.84,1)
	b2	TFN_5	TFN_5	TFN_5	TFN_4	TFN_5	(0.3,0.66,0.9)
	b3	TFN_5	TFN_4	TFN_4	TFN_6	TFN_4	(0.3,0.62,1)
	b4	TFN_6	TFN_6	TFN_6	TFN_5	TFN_7	(0.5,0.88,1)
C2	b1	TFN_5	TFN_6	TFN_5	TFN_6	TFN_5	(0.5,0.78,1)
	b2	TFN_4	TFN_6	TFN_6	TFN_7	TFN_6	(0.3,0.84,1)
	b3	TFN_4	TFN_3	TFN_3	TFN_4	TFN_4	(0.1,0.42,0.7)
	b4	TFN_6	TFN_6	TFN_7	TFN_5	TFN_6	(0.5,0.88,1)
C3	b1	TFN_5	TFN_6	TFN_5	TFN_3	TFN_4	(0.1,0.62,1)
	b2	TFN_6	TFN_4	TFN_6	TFN_4	TFN_5	(0.3,0.7,1)
	b3	TFN_4	TFN_5	TFN_4	TFN_5	TFN_6	(0.3,0.66,1)
	b4	TFN_4	TFN_6	TFN_7	TFN_6	TFN_5	(0.3,0.8,1)

Table 12
Rating given by each decision-maker and the aggregated fuzzy ratings corresponding to case study 1 (Continued)

Criteria		D1	D2	D3	D4	D5	Aggregated fuzzy rating
C4	b1	TFN_6	TFN_5	TFN_4	TFN_5	TFN_6	(0.3,0.74,1)
	b2	TFN_4	TFN_4	TFN_4	TFN_3	TFN_4	(0.1,0.46,0.7)
	b3	TFN_4	TFN_5	TFN_5	TFN_3	TFN_2	(0,0.46,0.9)
	b4	TFN_5	TFN_6	TFN_4	TFN_7	TFN_6	(0.3,0.8,1)
C5	b1	TFN_5	TFN_6	TFN_4	TFN_6	TFN_7	(0.3,0.8,1)
	b2	TFN_4	TFN_5	TFN_5	TFN_6	TFN_4	(0.3,0.66,1)
	b3	TFN_5	TFN_5	TFN_4	TFN_7	TFN_5	(0.3,0.72,1)
	b4	TFN_5	TFN_6	TFN_7	TFN_5	TFN_5	(0.5,0.8,1)
C6	b1	TFN_6	TFN_5	TFN_5	TFN_4	TFN_3	(0.1,0.62,1)
	b2	TFN_6	TFN_5	TFN_6	TFN_4	TFN_5	(0.3,0.74,1)
	b3	TFN_5	TFN_6	TFN_6	TFN_5	TFN_6	(0.5,0.82,1)
	b4	TFN_3	TFN_4	TFN_5	TFN_4	TFN_3	(0.1,0.46,0.9)
C7	b1	TFN_3	TFN_4	TFN_1	TFN_3	TFN_4	(0,0.32,0.7)
	b2	TFN_6	TFN_5	TFN_4	TFN_3	TFN_4	(0.1,0.58,1)
	b3	TFN_5	TFN_6	TFN_4	TFN_5	TFN_4	(0.3,0.66,1)
	b4	TFN_6	TFN_5	TFN_5	TFN_6	TFN_5	(0.5,0.78,1)
C8	b1	TFN_6	TFN_3	TFN_4	TFN_5	TFN_4	(0.1,0.58,1)
	b2	TFN_6	TFN_5	TFN_4	TFN_6	TFN_6	(0.3,0.78,1)
	b3	TFN_4	TFN_5	TFN_4	TFN_3	TFN_3	(0.1,0.46,0.9)
	b4	TFN_4	TFN_5	TFN_5	TFN_6	TFN_4	(0.3,0.66,1)
C9	b1	TFN_4	TFN_3	TFN_4	TFN_3	TFN_5	(0.1,0.46,0.9)
	b2	TFN_5	TFN_6	TFN_4	TFN_5	TFN_4	(0.3,0.66,1)
	b3	TFN_5	TFN_4	TFN_3	TFN_4	TFN_3	(0.1,0.46,0.9)
	b4	TFN_6	TFN_6	TFN_5	TFN_7	TFN_5	(0.5,0.84,1)

Now, the ranking of each criterion as per its importance is to be done. The criteria were ranked by Tong et al. (2020) as C1=C2>C9>C8>C6>C4>C3>C5>C7 and hence the same ranking is considered in this paper. As per the ranking of criteria, we need to assign the weights from column 9 of Table 4. The weights for C1, C2, C3, C4, C5, C6, C7, C8, and C9 are assigned as 0.179,0.179, 0.083, 0.088, 0.079, 0.094, 0.076, 0.103, and 0.117. Here C1 and C2 have the same rank of 1.5 and hence average weight of rank 1 and rank 2 ((0.215+0.444)/2) =0.179 is assigned to both C1 and C2. Table 13 shows the decision table.

Table 13
Decision table for case study 1

Alternatives	C1	C2	C3	C4	C5	C6	C7	C8	C9
b1	(0.5,0.84,1)	(0.5,0.78,1)	(0.1,0.2,1)	(0.3,0.74,1)	(0.3,0.8,1)	(0.1,0.62,1)	(0,0.32,0.7)	(0.1,0.58,1)	(0.1,0.46,0.9)
b2	(0.3,0.66,0.9)	(0.3,0.84,1)	(0.3,0.7,1)	(0.1,0.46,0.7)	(0.3,0.6,1)	(0.3,0.74,1)	(0.1,0.8,1)	(0.3,0.78,1)	(0.3,0.66,1)
b3	(0.3,0.62,1)	(0.1,0.42,0.7)	(0.3,0.66,1)	(0,0.46,0.9)	(0.3,0.2,1)	(0.5,0.82,1)	(0.3,0.6,1)	(0.1,0.46,0.9)	(0.1,0.46,0.9)
b4	(0.5,0.88,1)	(0.5,0.88,1)	(0.3,0.8,1)	(0.3,0.8, 1)	(0.5,0.8,1)	(0.1,0.46,0.9)	(0.5,0.8,1)	(0.3,0.66,1)	(0.5,0.84,1)

The ranking of alternatives as per importance for each criterion is given in Table 14. During ranking of alternatives for a particular criterion, we need to keep in mind the type of criterion (i.e., non-beneficial or beneficial) is to be kept in mind.

Table 14
Ranked decision table for case study 1

Alternatives	C1	C2	C3	C4	C5	C6	C7	C8	C9
b1	(1.5,2 ,2)	(1.5,3,2)	(1,1,2.5)	(1.5,2,1.5)	(3,1.5,2.5)	(3.5,3,2)	(4,4,4)	(3.5,3,2)	(3.5,3.5,3.5)
b2	(3.5,3,4)	(3,2,2)	(3,3,2.5)	(3,3.5,4)	(3,4,2.5)	(2,2,2)	(3,3,2)	(1.5,1,2)	(2,2,1.5)
b3	(3.5,4,2)	(4,4,4)	(3,2,2.5)	(4,3.5,3)	(3,3,2.5)	(1,1,2)	(2,2,2)	(3.5,4,4)	(3.5,3.5,3.5)
b4	(1.5,1,2)	(1.5,1,2)	(3,4,2.5)	(1.5,1,1.5)	(1,1.5,2.5)	(3.5,4,4)	(1,1,2)	(1.5,2,2)	(1,1,1.5)

Now, the weights from column 4 of Table 4 are assigned to all the ranks obtained in Table 14. After assigning the weights, the weighted decision table for case study 1 is obtained and is shown in Table 15.

Table 15
Weighted decision table for case study 1

Alternatives	C1 (0.179)	C2 (0.179)	C3 (0.083)	C4 (0.087)	C5 (0.079)	C6 (0.094)	C7 (0.076)	C8 (0.103)	C9 (0.117)
b1	(0.310, 0.248, 0.274)	(0.310, 0.203, 0.274)	(0.371, 0.371, 0.250)	(0.310, 0.248, 0.310)	(0.210, 0.310, 0.250)	(0.190, 0.203, 0.274)	(0.178, 0.178, 0.178)	(0.190, 0.203, 0.274)	(0.190, 0.190, 0.190)
b2	(0.190, 0.203, 0.178)	(0.203, 0.248, 0.274)	(0.210, 0.203, 0.250)	(0.203, 0.190, 0.178)	(0.210, 0.178, 0.250)	(0.248, 0.248, 0.274)	(0.203, 0.203, 0.274)	(0.310, 0.371, 0.274)	(0.248, 0.248, 0.310)
b3	(0.190, 0.178, 0.274)	(0.178, 0.178, 0.178)	(0.210, 0.248, 0.250)	(0.178, 0.190, 0.203)	(0.210, 0.203, 0.250)	(0.371, 0.371, 0.274)	(0.248, 0.248, 0.274)	(0.190, 0.178, 0.178)	(0.190, 0.190, 0.190)
b4	(0.310, 0.371, 0.274)	(0.310, 0.371, 0.274)	(0.210, 0.178, 0.250)	(0.310, 0.371, 0.310)	(0.371, 0.310, 0.250)	(0.190, 0.178, 0.178)	(0.371, 0.371, 0.274)	(0.310, 0.248, 0.274)	(0.371, 0.371, 0.310)

Now, the criteria weights are multiplied with the respective weights of the alternatives as explained in the demonstration example. The fuzzy scores for each alternative are obtained and are shown for all criteria in Table 16. With the help of Eq. (7), the crisp scores and composite scores are obtained and are shown in Table 17.

Table 16
Fuzzy scores for case study 1

Alternatives	C1	C2	C3	C4	C5	C6	C7	C8	C9
b1	(0.056, 0.044, 0.049)	(0.056, 0.036, 0.049)	(0.031, 0.031, 0.021)	(0.027, 0.022, 0.027)	(0.017, 0.025, 0.020)	(0.018, 0.019, 0.026)	(0.014, 0.014, 0.014)	(0.020, 0.021, 0.028)	(0.022, 0.022, 0.022)
b2	(0.034, 0.036, 0.032)	(0.036, 0.044, 0.049)	(0.017, 0.017, 0.021)	(0.018, 0.017, 0.016)	(0.017, 0.014, 0.020)	(0.023, 0.023, 0.026)	(0.015, 0.015, 0.021)	(0.032, 0.038, 0.028)	(0.029, 0.029, 0.036)
b3	(0.034, 0.032, 0.049)	(0.032, 0.032, 0.032)	(0.017, 0.021, 0.021)	(0.016, 0.017, 0.018)	(0.017, 0.016, 0.020)	(0.035, 0.035, 0.026)	(0.019, 0.019, 0.021)	(0.020, 0.018, 0.018)	(0.022, 0.022, 0.022)
b4	(0.056, 0.067, 0.049)	(0.056, 0.067, 0.049)	(0.017, 0.015, 0.021)	(0.027, 0.033, 0.027)	(0.029, 0.025, 0.020)	(0.018, 0.017, 0.017)	(0.028, 0.028, 0.021)	(0.032, 0.026, 0.028)	(0.044, 0.044, 0.036)

Table 17
Crips score, composite score, and rankings for case study 1.

Alternatives	C1	C2	C3	C4	C5	C6	C7	C8	C9	C.Score	Ranking
b1	0.047	0.042	0.029	0.024	0.022	0.020	0.014	0.022	0.022	0.242	2
b2	0.035	0.044	0.018	0.017	0.015	0.024	0.016	0.036	0.030	0.235	3
b3	0.035	0.032	0.020	0.017	0.017	0.033	0.019	0.019	0.022	0.214	4
b4	0.062	0.062	0.016	0.031	0.025	0.017	0.027	0.027	0.042	0.309	1

C.Score: Composite score

In this case study, the Fuzzy R-method suggested that maintenance service providers b4 is the best choice and b1 is the second choice. The overall order of maintenance service providers is b4>b1>b2>b3. Now, we compare the proposed fuzzy R-method with fuzzy PROMETHEE II, and fuzzy TOPSIS methods applied by previous researchers (Tong et al., 2020). The ranking obtained by all these methods is given in Table 18. All methods shown in Table 18 suggested that alternative service provider b4 is the best choice. From the ranking shown in Table 18, the proposed method suggests alternative b1 as the second choice while Fuzzy PROMETHEE II suggested alternative b2 as the second choice and Fuzzy TOPSIS suggested alternative b3 as the second choice. In this case study, there are five decision-makers and nine criteria, so a total of 45 decisions per each alternative service providers (i.e. 9*5=45). If Table 12 is analyzed, it can be observed that out of 45 decisions, 17 decisions show that b1 is good compared to b2 and 16 decisions show that b2 is good compared to b1 and 12 decisions are neutral (i.e., b1 and b2 equally good). From the above discussion, it is proved that b1 is slightly better than b2. If b1 is compared with b3 then it can be observed that out of 45 decisions, 22 decisions show that b1 is good compared to b3 and 18 decisions show that b3 is good compared to b1 and 5 decisions are neutral (i.e., b1 and b3 equally good). From these comparisons it is proved that b1 is better than b2 and b3. Thus, proposing b1 as the second choice is genuine. Similar comparisons prove that the proposed fuzzy R-method gives a more reliable and logical ranking to the alternatives.

Table 18
Results comparison for case study 1

Maintenance service providers	Fuzzy R-method	Fuzzy PROMETHEE II	Fuzzy TOPSIS
	Ranking	Ranking	Ranking
b1	2	4	4
b2	3	2	3
b3	4	3	2
b4	1	1	1

This method also gives a score under each criterion for a particular supplier. As per Table 17, the maintenance service provider (b4) is excellent in maintenance service performance and supplier qualification criteria but poor in maintenance cost criteria. The fuzzy R-method helps management choose sustainable maintenance service providers. Management can also understand that whether a particular maintenance service provider is excellent or poor w.r.t. a specific criterion. Management may suggest the maintenance service provider to improve work under the particular criterion, which will help to strengthen sustainability in the company.

4.1.1. Sensitivity analysis of case study 1

To study the stability of the fuzzy R-method, the fuzzy weights of the criteria are changed in 16 experiments. The proposed method is applied to rank the alternatives for each experiment. Table 19 shows the rankings. The details of the 16 experiments are given in Table 19. In this case study, fuzzy weights for C1, C2, C3, C4, C5, C6, C7, C8, and C9 are assigned as (0.5,0.88,1), (0.5,0.88,1), (0.3,0.66,1), (0.3,0.8,1), (0,0.42,0.9), (0.5,0.78,1), (0.1,0.58,1), (0.5,0.84,1), and (0.5,0.86,1).

Table 19
Sensitivity analysis experiment for case study 1

Exp.	Criteria	Fuzzy weight	Alternatives				Ranking
			b1	b2	b3	b4	
E1	C1 to C9	0, 0, 0	0.224	0.221	0.202	0.285	**b4 > b1 > b2 > b3**
E2	C1 to C9	0, 0.1, 0.2	0.228	0.219	0.208	0.281	**b4 > b1 > b2 > b3**
E3	C1 to C9	0.1, 0.3, 0.5	0.245	0.235	0.223	0.302	**b4 > b1 > b2 > b3**
E4	C1 to C9	0.3, 0.5, 0.7	0.268	0.258	0.244	0.331	**b4 > b1 > b2 >b3**
E5	C1 to C9	0.5, 0.7, 0.9	0.305	0.293	0.278	0.376	**b4 > b1 > b2 > b3**
E6	C1 to C9	0.8, 0.9, 1	0.372	0.358	0.339	0.460	**b4 > b1 > b2 > b3**
E7	C1 to C9	1, 1, 1	0.558	0.537	0.509	0.689	**b4 > b1 > b2 > b3**
E8	C1= (1,1,1)	Other remaining same	0.243	0.233	0.215	0.309	**b4 > b1 > b2> b3**
E9	C2= (1,1,1)	Other remaining same	0.241	0.237	0.214	0.309	**b4 > b1 > b2 > b3**
E10	C3= (1,1,1))	Other remaining same	0.257	0.232	0.221	0.291	**b4 > b1 > b2 > b3**
E11	C4= (1,1,1)	Other remaining same	0.257	0.232	0.221	0.291	**b4 > b1 > b2 > b3**
E12	C5= (1,1,1)	Other remaining same	0.247	0.230	0.216	0.306	**b4 > b1 > b2 > b3**
E13	C6= (1,1,1)	Other remaining same	0.239	0.237	0.235	0.289	**b4 > b1 > b2 > b3**
E14	C7= (1,1,1)	Other remaining same	0.233	0.232	0.222	0.313	**b4 > b1 > b2 > b3**
E15	C8= (1,1,1)	Other remaining same	0.239	0.248	0.214	0.299	b4 > b2 > b1 > b3
E16	C9= (1,1,1)	Other remaining same	0.236	0.239	0.215	0.310	b4 > b2 > b1 > b3

Fig. 2 shows the result of sensitivity analysis.

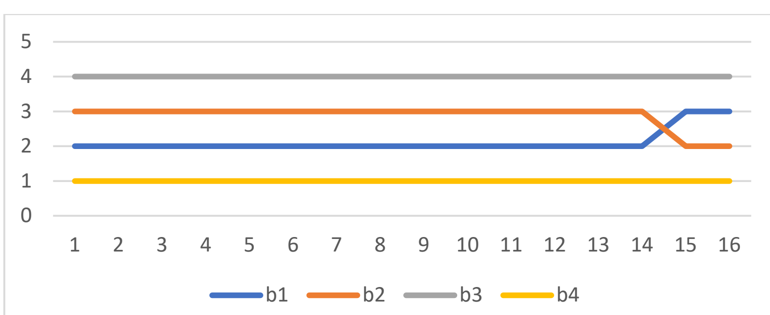

Fig. 2. Result of sensitivity analysis for case study 1.

From Table 19 and Fig. 2, it can be observed that the ranking is changed only in two experiments (i.e., experiment 15 and experiment 16) out of 16 experiments. Hence, the proposed method is stable at about 87.5 %. When the sensitivity analysis result of the fuzzy R-method is compared with the sensitivity analysis result of the other two methods i.e. fuzzy PROMETHEE II and fuzzy TOPSIS, it can be observed that fuzzy PROMETHEE II had given a consistent ranking in 14 experiments out of 16 experiments and fuzzy TOPSIS had given a consistent ranking in 12 experiments out of 16 experiments. The stability of fuzzy PROMETHEE II and fuzzy TOPSIS is at about 87.5% and around 75% respectively. The stability of the proposed method is equal to fuzzy PROMETHEE II method and more than the fuzzy TOPSIS method in this case study. Hence, it is proved that the fuzzy R-method is robust and stable to changes in weights of the criteria.

4.2. Case study 2

This case study was attempted by Santos et al., (2018) using fuzzy TOPSIS. In this case study, three green suppliers (S1, S2, and S3) were considered for the Brazilian industry. The industry wanted to evaluate the performance of each green supplier. Three decision-makers and seven criteria were considered. The seven criteria were: Pollution Production (C1), Resource consumption (C2), Eco-design (C3), Green image (C4), Environmental management system (C5), Commitment of managers from Green Supply chain Management (C6), and Use of environmentally friendly material (C7). Pollution Production (C1) and Resource consumption (C2) are the non-beneficial criteria, and others are the beneficial criteria. The five-point fuzzy scale, linguistic terms, and corresponding TFNs are generated and are shown in Table 20.

Table 20
Fuzzy scale for case study 2.

Linguistic terms	Fuzzy numbers	Name assigned
Very poor	0,0.2,0.4	TFN_1
Poor	0.1,0.3,0.5	TFN_2
Medium	0.3,0.5,0.7	TFN_3
Good	0.5,0.7,0.9	TFN_4
Very good	0.6,0.8,1	TFN_5

The three decision-makers assigned their ratings to all the alternatives for each criterion as shown in Table 21.

Table 21
Rating given by each decision-maker and the aggregated fuzzy ratings corresponding to case study 2

Criteria		DM1	DM2	DM3	Aggregated fuzzy rating
C1	S1	TFN_3	TFN_2	TFN_3	(0.1,0.433,0.7)
	S2	TFN_3	TFN_4	TFN_2	(0.1,0.500,0.9)
	S3	TFN_3	TFN_3	TFN_2	(0.1,0.433,0.7)
C2	S1	TFN_3	TFN_1	TFN_3	(0,0.400,0.7)
	S2	TFN_4	TFN_4	TFN_3	(0.3,0.633,0.9)
	S3	TFN_3	TFN_2	TFN_3	(0.1,0.433,0.7)
C3	S1	TFN_2	TFN_1	TFN_4	(0,0.400,0.9)
	S2	TFN_2	TFN_4	TFN_3	(0.1,0.500,0.9)
	S3	TFN_1	TFN_3	TFN_2	(0,0.333,0.7)
C4	S1	TFN_2	TFN_3	TFN_4	(0.1,0.500,0.9)
	S2	TFN_4	TFN_3	TFN_2	(0.1,0.500,0.9)
	S3	TFN_2	TFN_1	TFN_3	(0,0.333,0.7)
C5	S1	TFN_4	TFN_4	TFN_3	(0.3,0.633,0.9)
	S2	TFN_3	TFN_3	TFN_2	(0.1,0.433,0.7)
	S3	TFN_2	TFN_2	TFN_3	(0.1,0.367,0.7)
C6	S1	TFN_3	TFN_3	TFN_4	(0.3,0.567,0.9)
	S2	TFN_2	TFN_3	TFN_3	(0.1,0.433,0.7)
	S3	TFN_4	TFN_3	TFN_3	(0.3,0.567,0.9)
C7	S1	TFN_3	TFN_4	TFN_3	(0.3,0.567,0.9)
	S2	TFN_3	TFN_4	TFN_2	(0.1,0.500,0.9)
	S3	TFN_3	TFN_3	TFN_2	(0.1,0.433,0.7)

Now, the ranking of each criterion as per its importance is to be done. The criteria were ranked by Santos et al. (2018) as C6>C3>C5>C1>C2>C4>C7 and hence the same ranking is considered in this paper. As per the ranking of criteria, we need to assign the weights from column 7 of Table 4 (i.e., seven criteria). The weights for C1, C2, C3, C4, C5, C6, and C7 are assigned as 0.122, 0.112, 0.170, 0.104, 0.139, 0.255, and 0.098.

Table 22
Decision matrix for case study 2

Alternatives	C1	C2	C3	C4	C5	C6	C7
S1	(0.1, 0.433, 0.7)	(0,0.400, 0.7)	(0,0.400, 0.9)	(0.1,0.500, 0.9)	(0.3,0.633, 0.9)	(0.3,0.567, 0.9)	(0.3,0.567, 0.9)
S2	(0.1,0.500, 0.9)	(0.3,0.633, 0.9)	(0.1,0.500, 0.9)	(0.1,0.500, 0.9)	(0.1,0.433, 0.7)	(0.1,0.433, 0.7)	(0.1,0.500, 0.9)
S3	(0.1,0.433, 0.7)	(0.1,0.433, 0.7)	(0,0.333, 0.7)	(0,0.333, 0.7)	(0.1,0.367, 0.7)	(0.3,0.567, 0.9)	(0.1,0.433, 0.7)

The ranking of alternatives as per importance of each criterion is given in Table 23. During the ranking of alternatives for a particular criterion, the type of criterion (i.e., non-beneficial or beneficial) is to be kept in mind.

Table 23
Ranked decision matrix for case study 2

Alternatives	C1	C2	C3	C4	C5	C6	C7
S1	(2,1.5,1.5)	(1,1,1.5)	(2.5,2,1.5)	(1.5,1.5,1.5)	(1,1,1)	(1.5,1.5,1.5)	(1,1,1.5)
S2	(2,3,3)	(3,3,3)	(1,1,1.5)	(1.5,1.5,1.5)	(2.5,2,2.5)	(3,3,3)	(2.5,2,1.5)
S3	(2,1.5,1.5)	(2,2,1.5)	(2.5,3,3)	(3,3,3)	(2.5,3,2.5)	(1.5,1.5,1.5)	(2.5,3,3)

Now, the weights from column 3 (i.e., three alternatives) of Table 4 are assigned to all the ranks obtained in Table 23. After assigning the weights, the weighted decision matrix for case study 2 is obtained and is shown in Table 24.

Table 24
Weighted decision matrix for case study 2

Alternatives	C1(0.122)	C2(0.112)	C3(0.170)	C4(0.104)	C5(0.139)	C6(0.255)	C7(0.098)
S1	(0.333, 0.37, 0.277)	(0.452, 0.452, 0.377)	(0.274, 0.301, 0.377)	(0.377, 0.377, 0.377)	(0.452, 0.452, 0.452)	(0.377, 0.377, 0.377)	(0.452, 0.452, 0.377)
S2	(0.333, 0.24, 0.247)	(0.247, 0.247, 0.247)	(0.452, 0.452, 0.377)	(0.377, 0.377, 0.377)	(0.274, 0.301, 0.274)	(0.247, 0.247, 0.247)	(0.274, 0.301, 0.377)
S3	(0.333, 0.37, 0.377)	(0.301, 0.301, 0.377)	(0.274, 0.247, 0.247)	(0.247, 0.247, 0.247)	(0.274, 0.247, 0.274)	(0.377, 0.377, 0.377)	(0.274, 0.247, 0.247)

After obtaining the weighted decision matrix, the criteria weights are multiplied with the respective weights of alternatives as explained in the demonstration example. After this exercise, the fuzzy scores for each alternative are obtained and are shown in Table 25. With the help of Eq. (7), the crips scores and the composite scores are obtained and are shown in Table 26.

Table 25
Fuzzy scores for case study 2

Alternatives	C1	C2	C3	C4	C5	C6	C7
S1	(0.041,0.04,0.046)	(0.050, 0.050, 0.042)	(0.047, 0.051, 0.064)	(0.039, 0.039, 0.039)	(0.063, 0.063, 0.063)	(0.096, 0.096, 0.096)	(0.044, 0.044, 0.037)
S2	(0.041,0.03,0.030)	(0.028, 0.028, 0.028)	(0.077, 0.077, 0.064)	(0.039, 0.039, 0.039)	(0.038, 0.042, 0.038)	(0.063, 0.063, 0.063)	(0.027, 0.030, 0.037)
S3	(0.041,0.04, 0.046)	(0.034, 0.034, 0.042)	(0.047, 0.042, 0.042)	(0.026, 0.026, 0.026)	(0.038, 0.034, 0.038)	(0.096, 0.096, 0.096)	(0.027, 0.024, 0.024)

Table 26
Crips score, composite score, and rankings for case study 2

Alternatives	C1	C2	C3	C4	C5	C6	C7	Composite score	Ranking
S1	0.045	0.049	0.053	0.039	0.063	0.096	0.043	0.388	1
S2	0.032	0.028	0.075	0.039	0.041	0.063	0.030	0.307	2
S3	0.045	0.035	0.043	0.026	0.036	0.096	0.025	0.305	3

In this case, the fuzzy R-method suggested green suppliers S1 as the best choice and S2 as the second choice. The overall order of green suppliers is given as S1>S2>S3. Now, we compare the fuzzy R-method with the fuzzy TOPSIS applied by previous researchers (Santos et al., 2018). The rankings obtained by the fuzzy-R method and fuzzy TOPSIS method are given in Table 27.

Table 27
Comparison of the fuzzy R-method with fuzzy TOPSIS method for case study 2.

Green suppliers	Fuzzy R-method	Fuzzy TOPSIS (Santos et al., 2018)
	Ranking	Ranking
S1	1	1
S2	2	3
S3	3	2

Both methods shown in Table 27 suggested that alternative S1 is the best choice. From the rankings shown in Table 27, the proposed method suggests alternative S2 as the second choice while Fuzzy TOPSIS suggested alternative S3 as the second choice. In this case study, there are three decision-makers and seven criteria so a total of 21 decisions per alternative (i.e. 3*7=21). If Table 21 is analyzed, then it can be observed that out of 21 decisions, 8 decisions show S2 is good compared to S3 and 6 decisions show that S3 is good compared to S2 and 7 decisions are neutral (i.e., S2 and S3 equally good). Hence, it is proved that S2 is better than S3 and the proposed method gives a better rank to S2 as compared to S3. The proposed fuzzy R-method gives a more reliable and logical ranking to the alternatives. As per Table 26, the green supplier (S1) is excellent in managers' commitment from green supply chain management criteria but poor in green image criteria. Management may suggest the green supplier to improve work under the particular criterion, which will help to strengthen sustainability in the company. The fuzzy R-method helps management choose a sustainable green supplier.

4.2.1. Sensitivity analysis of case study 2

To study the stability of the fuzzy R-method, the fuzzy weights of the criteria are changed in 12 experiments. The proposed method is applied to rank the alternatives for each experiment. The rankings obtained are shown in Table 28. The details of the 12 experiments are given in Table 28.

Table 28
Sensitivity analysis experiment for case study 2.

Exp.	Definition	A1	A2	A3	Ranking
E1	C1 to C7 = 0.6,0.8,1	0.882827403	0.693911	0.659628	**S1>S2>S3**
E2	C1 to C7 = 0.5,0.7,0.9	0.588551601	0.462607	0.439752	**S1>S2>S3**
E3	C1 to C7 = 0.3,0.5,0.7	0.48154222	0.378497	0.359797	**S1>S2>S3**
E4	C1 to C7 = 0.1,0.3,0.5	0.423757153	0.333077	0.316622	**S1>S2>S3**
E5	C1 to C7 = 0,0.2,0.4	0.386639737	0.303902	0.288888	**S1>S2>S3**
E6	C1 = 0.6,0.8,1, C2 to C7 = 0,0.2,0.4	0.452984851	0.350774	0.355233	S1>S3>S2
E7	C2 = 0.6,0.8,1, C1,C3 to C7 = 0.1,0.3,0.5	0.496770942	0.374041	0.368774	**S1>S2>S3**
E8	C3 = 0.6,0.8,1, C1 to C2,C4 to C7 = 0.3,0.5,0.7	0.526467152	0.44232	0.396268	**S1>S2>S3**
E9	C4 = 0.6,0.8,1, C1 to C3,C5 to C7 = 0.5,0.7,0.9	0.628669068	0.502725	0.466011	**S1>S2>S3**
E10	C5 = 0,0.2,0.4, C1 to C4,C6 to C7 = 0.6,0.8,1	0.801655419	0.641436	0.613713	**S1>S2>S3**
E11	C6 = 0.1,0.3,0.5,C1 to C5, C7=0.3,0.5,0.7	0.473664608	0.37334	0.35192	**S1>S2>S3**
E12	C7 = 0.3,0.5,0.7, C1 to C6= 0.6,0.8,1	0.81900416	0.648986	0.623158	**S1>S2>S3**

Fig. 3 shows the result of sensitivity analysis for case study 2.

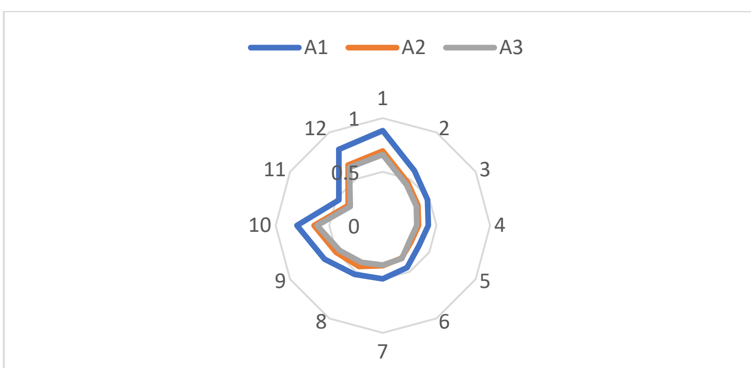

Fig. 3. Result of sensitivity analysis for case study 2

From Table 28 and Fig. 3, it can be observed that only in one experiment (i.e. experiment 6) out of 12 experiments the ranking is changed. Hence, the proposed method is stable at about 91.67 %. When the sensitivity analysis result of the fuzzy R-method is compared with the sensitivity analysis result of the fuzzy TOPSIS, it can be observed that fuzzy TOPSIS had given a consistent ranking in 10 experiments out of 12 experiments so that the stability of fuzzy TOPSIS is around 83.33% for this case study. The stability of the proposed method is more compared to the fuzzy TOPSIS method. Hence, it is proved that the fuzzy R-method is robust and stable to changes in weights of the criteria.

4.3. Managerial, theoretical, and societal implications of the present study

The proposed fuzzy R-method helps practitioners and managers to choose a most proper green and sustainable supplier in fuzzy decision-making situations. This method helps practitioners and managers to choose the right suppliers. This method can deal with any number of qualitative and quantitative criteria and the alternative suppliers and obtains the composite scores to evaluate and rank the suppliers to find the best supplier. This method also gives a score under each criterion for each supplier. Suppose, a supplier is excellent in maintenance service performance criterion and supplier qualification criterion but poor in maintenance cost criterion. In that case, the management may suggest the supplier to improve under the particular maintenance cost criterion, which will help to strengthen sustainability in the company. The use of the proposed R-method provides a simple yet strong theoretical foundation to analyze the criteria in the performance evaluation and selecting the right suppliers in different organizations. The proposed method provides an easy means of computing the criteria weights and for computing the weights of different alternative suppliers based on their ranks under each criterion. The methodology proposed in this paper encourages the researchers to apply the methodology to different selection problems of the industries. The methodology can be computerized in the form of a software so that the risk of incorrect decision-making due to lack of knowledge is avoided.

Choosing the sustainable and green suppliers for the sustainability of industries is not only useful for the economic benefit of the industries and for the development of nation, but also helps in getting societal and environmental benefits.

5. Conclusions

One of the important tasks of the industries is to select appropriate suppliers from various alternative suppliers to realize the goals of sustainability and greening the supply chain. Hence, a fuzzy R- method is proposed in this paper to select suppliers based on green and sustainable innovation ability. The fuzzy R-method deals with uncertainty in the information. The main issue of the existing fuzzy MCDM methods is that the researchers need to apply another method like AHP, BWM, SWARA, or other methods to generate weights for the criteria. The criteria weights and alternative suppliers are generated using a simple equation in the proposed fuzzy R-method, and there is no need to apply different methods for weights generation and ranking. The novelty of the proposed method is that it is simple, can deal with qualitative and quantitative criteria of supplier selection, and requires less computational effort to evaluate and rank the green and sustainable suppliers in fuzzy group decision-making situations. The purpose of introducing fuzzy numbers in the R-method is to make the method simple for ranking the alternative suppliers on each criterion by different decision-makers in a group decision-making situation. Another benefit of using the fuzzy number is that the partialness and ambiguity in the available information can be dealt with. The proposed method is validated on two realistic group decision-making problems of sustainable and green supplier selection. The method is a simple, logical, effective, and convenient MCDM method. From sensitivity analysis, we can say that the fuzzy R-method is consistent for the ranking of alternative suppliers. The fuzzy R-method is applied to three real case studies of selecting sustainable suppliers and green suppliers. From the case studies, we can say that the proposed method can rank the alternative suppliers more logically. The fuzzy R-method is compared with the fuzzy PROMETHEE II and fuzzy TOPSIS in these case studies to demonstrate and validate the results obtained. The method has given precise and reliable results and is believed to have the potential to solve the MCDM problems. The proposed fuzzy R-method is an influential tool for sustainable supplier selection considering social, economic, and environmental criteria. The proposed method makes it possible to assess alternatives where uncertainty and lack of quantitative data are available in the selection process. The proposed method is useful in all general situations, and particularly in the situations of imprecise data, limited time availability, presence of qualitative criteria, and decision maker's limited capability to process the information. Also, the decision maker can assign weights of importance of his/her choice to the attributes, instead of using the weights suggested by the proposed methodology. Then, the remaining methodology can be applied to get the composite ranks of the alternatives. The methodology simultaneously considers any number of qualitative and quantitative criteria and obtains the composite scores to evaluate and rank the alternative suppliers for a given green and sustainable supplier selection problem. We will take up future studies on the use of Z- number, Pythagorean fuzzy number, interval type -2 fuzzy number to address the uncertainty and lack of information in the decision-making process. The proposed method will be validated further on more realistic fuzzy MCDM situations of the industries.

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