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ORIGINAL ARTICLE

Green supplier selection by developing a new group decision-making method under type 2 fuzzy uncertainty

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Abstract One of the most important issues in green supply chain management is supplier selection. This issue has proven to be one of the most important decision-making processes for production, operations, and purchasing managers. This problem has to be dealt with in both industry and service environments and is essential to help the firms keep their competitive edge over their rivals. However, this vital process has imprecision and ambiguity. It enhances the difficulty of this important decision-making task. Dealing with uncertainty requires appropriate tools and techniques. In this paper, a new method of supplier selection is presented that uses interval type 2 fuzzy sets (IT2FSs) to deal with today's uncertain environment. To show the importance and the level of knowledge of each decision-maker in the process, the model applies a novel approach that gives the decision-makers a new weight based on their level of knowledge and the gathered judgments. Moreover, the concept of relative preference relation of IT2FSs is developed to address the weight of selection criteria. Eventually, the proposed uncertain supplier selection model develops the concept of multi-objective optimization by ratio analysis plus the full multiplicative form under type 2 fuzzy uncertainty to enhance the capability of the proposed model to function under real-world problems. Finally, to illustrate the capabilities of the introduced approach, first, two existing case studies at the manufacturing system level are taken from the literature and are solved. Then, to present the method in a step-by-step approach, a case study is adopted and solved by the proposed model and the results are presented.

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1 Introduction

Supply chain network management is mainly concerned with organizing the flow of raw materials from a number of suppliers to manufacturers in order to create products that are made to fulfill customers' value expectations. Obviously, in today's global marketplace which is identified by concepts such as globalization, expanding customers' expectations, increasing regulatory conformity, and extreme competitiveness, manufacturers have to choose and keep core suppliers in order to stay in the market and keep their competitive edge. Consequently, supplier evaluation and selection is characterized as one of the most important functions of supply management [1–3].

Supplier selection as a very common outsourcing problem involves the most critical aspects of any business firm. Since different suppliers have different lead times, capacities, and quality level, the process of supplier selection has a major role in reducing costs in cases when firms should select suppliers. This selection process is known to be the most important decision-making process among main decision-making processes of manufacturing organizations which include contract negotiations, producing or purchasing, collaboration design, choosing suppliers, sourcing assessment, and procurement [4]. Furthermore, buying is one of the main functions of any firm; therefore, choosing the best supplier is an essential part of the business relationship and is also a critical matter in the competitive environment [5].

The problem of supplier selection has only within the last decade initiated integrating various environmental aspects.

The importance of issues concerning green and environmental supply chain management is ever increasing. This practical issue contains assessing suppliers by considering their organizational environmental performance, in addition to finding out if their performance meets regulatory needs or the designs of advanced collaborative green product. Environmental awareness has led suppliers to adopt a number of green policies and practices [6–9].

It is obvious that in the green supply chain, the decision models would be more complex and comprehensive since they require considering many new dimensions. For instance, a tricky part is where the tradeoffs get more evident. Moreover, the decisions would also contain more intangible aspects like reputation, risk of supply chain, continuity of business, and social effects. The aforementioned novel criteria and aspects make it inevitable to rethink some of the more established methods. Furthermore, the decision-makers (DM) continue to increase under circumstances where environmental factors become active [10, 11].

An important phenomenon in any decision-making process is uncertain and imprecise data. If the vagueness (fuzziness) of the mankind process of decision-making is ignored, the outcomes could be misleading [12]. Fuzzy set theory has the merits of mathematically expressing ambiguity and vagueness in addition to providing formalized tools that deal with the imprecision of many problems [13]. Consequently, many scholars have applied fuzzy set theory to handle uncertainty in a green supplier selection problem. A number of recent studies on green supplier selection under fuzzy environment are reviewed in the following.

Lee et al. [12] developed a model of fuzzy analytic hierarchy process (AHP) that was integrated with the Delphi to assess a green supplier. The main idea of applying the Delphi method was to distinguish the criteria for assessing conventional and green suppliers. In their proposed model, fuzzy AHP was applied to deal with the process of green supplier selection. Hsu and Hu [14] used analytic network process (ANP) to further explore the green supplier selection problem. They also examined interdependencies of decision components. Grisi et al. [15] applied a method based on fuzzy AHP to a evaluate green supplier. In their approach, fuzzy logic was used to handle uncertainty of human qualitative judgment. Chen et al. [16] used fuzzy logic and gray relational analysis to select a green supplier. The introduced approach applied linguistic preference structures to express alternative priorities and employed gray numbers in all of the selection criteria and alternatives to overcome limitations related to the criteria. Bakeshlou et al. [17] proposed a hybrid method that integrated fuzzy ANP and fuzzy multi-objective linear programming to assess green suppliers. Büyüközkan and Çifçi [7, 8] developed a new hybrid multiple criteria decision-making (MCDM) model that integrated fuzzy DEMATEL, fuzzy ANP, and fuzzy technique for order preference by similarity to ideal solutions (TOPSIS) to assess green suppliers. Büyüközkan [13] developed a method that applied fuzzy AHP to determine the relative weights of the selection criteria and a decision-making process based on axiomatic design (AD) to evaluate the green suppliers. Kannan et al. [18] developed a multi-criteria decision-making method referred to as fuzzy axiomatic design (FAD) to find the best green supplier. They used their method to find the best green supplier in a plastic manufacturer in Singapore. Freeman and Chen [19] developed a framework for green supplier selection that was based on AHP-entropy-TOPSIS.

As it can be concluded from the above, different fuzzy-based techniques were used to assess and select green suppliers. However, classic fuzzy set theory has its own shortcomings. Conventional type-1 fuzzy sets have crisp membership functions in interval [0, 1]. This main characteristic of these sets stops them from fully supporting different types of uncertainties which take place in linguistic illustrations of numerical quantities or happen in subjectively denoted knowledge of experts [20, 21]. In supplier selection, issues like market changes, enhancing technology, variable customer demands, and many other aspects increase the level of uncertainty. As the uncertainty of this problem increases, classic fuzzy sets lose their effectiveness in dealing with decision-making problems. As it can be concluded from the mentioned related studies, a large number of them have applied classic fuzzy sets. However, the ever-increasing uncertainty of many aspects of these problems makes it inevitable to use more efficient uncertain modeling tools to handle this problem.

One of the tools that has recently been used by many scholars is type 2 fuzzy sets. It is known to be more effective to use membership in a set with “a grade of membership” instead of the conventional approach of “all or none membership” under real-world conditions. One of the most respected approaches in measuring grade of membership is the research of Zadeh [22] that introduced type 2 and higher-type FSs. Type 2 FSs are known as fuzzy sets that possess fuzzy membership functions (MFs) that are characterized as “membership of membership.” In type 2 FSs, dissimilar to type 1 FSs, each element possesses a membership value that is denoted by a fuzzy set in [0, 1], instead of a crisp number in [0, 1] [23, 24]. Despite all these positive points, unfortunately, T2FSs are still new to green supplier evaluation and selection problems.

In recent years, a number of studies on applying type 2 FS on supplier selection was carried out. Gong [25] used interval type 2 fuzzy sets (IT2FSs) to address supplier selection. This study showed that T2FSs give DMs more freedom in expressing the uncertainty and the fuzziness of the real word in comparison with type 1 sets. Heidarzade et al. [26] propose a hierarchical clustering-based model to address the supplier selection problem and find the proximity of the suppliers under uncertainty. This study through its case study and using the examples of the literature showed the advantages of applying T2FSs. Zhou et al. [27] developed a multi-objective data envelopment analysis (DEA) model to assess sustainable suppliers based on T2FSs. This study used a case study to display the additional abilities of the model in modeling uncertain environments. Ghorabaee et al. [28] applied T2FSs to handle the multi-criteria group decision-making problem of green supplier selection. By applying their study in a case study, they showed that T2FSs have more flexibility in modeling uncertainty in comparison with type 1 fuzzy sets.

It can be concluded that recently a number of studies have focused on using T2FSs in supplier selection problems. These studies through case study and numerical examples have shown the applicability and advantages of T2FSs. Despite the novelty of these studies in applying T2FSs, issues like processing decision-makers' weights, fuzzy preference relation of criteria weight, concept of multi-objective optimization by ratio analysis plus the full multiplicative were not applied. Moreover, the concept of green and sustainable supplier selection was only considered in a small number of those studies. In conclusion, the main motivations of this study are as follows:

- The ever-increasing uncertainty of this decision-making problem caused by various factors makes it inevitable to apply new uncertainty modeling tools. However, most of the studies in literature are based on classic fuzzy sets.
- As mentioned above, classic fuzzy sets have their own shortcomings in real-world applications. One way to overcome the shortcomings is to apply T2FSs. These sets were recently used in a number of studies, and the results have proven that these sets enhance the decision-making process. Despite using these sets in literature, this approach is still new and could be improved.
- In group decision-making, the expertise of each expert has its own importance which is based on the knowledge of that person in different aspects of the decision-making process and the gathered judgments. This importance has to be properly addressed in any decision-making process to improve the effectiveness of the decisions. However, this aspect was not properly addressed in green supplier selection.
- Developing T2FS-based methods of green and sustainable supplier selection despite its importance in the case of environmental issues has not yet been properly addressed.
- Applying concepts such as maximum deviation of each alternative from maximum reference, summarizing the index of each alternative, full multiplicative form, and the dominance theory under type 2 fuzzy uncertainty is new to this decision-making process.

To use the benefits of type 2 fuzzy sets in the green supplier selection problem, this paper offers a new approach that uses IT2FSs to express uncertainty. Moreover, the proposed method offers a new method of computing weights of decision-makers that due to being a last aggregation method, avoids information loss. Also, to further explore the weights given to the importance of criteria, the relative preference degrees of the fuzzy important levels over average are developed under IT2FSs and applied. The model also applies summarizing index of each alternative, the maximum deviation of each alternative from the maximum reference point, and full multiplicative form developed under IT2FSs to evaluate the alternatives. Finally, the dominance theory is used to finally rank the alternatives. Eventually, the main contributions of this paper that separate it from similar studies on this subject are as follows:

- Uncertainty is expressed by using IT2FSs that allows the model to be more effective under uncertain environments and gives it more flexibility in calculations.
- The importance of each criterion is computed by developing the relative preference degrees of the fuzzy important levels over average under IT2FSs.
- Summarizing the index of each alternative under IT2FS is applied in alternative ranking.
- The maximum deviation of each alternative from the maximum reference under the IT2FS point is used in ranking.
- The full multiplicative form under the IT2FS environment is applied in the ranking.
- The concept of the dominance theory is applied in the supplier selection process

The rest of this paper is presented as follows: In Section 2, the preliminary knowledge of IT2FSs is presented. Section 3 provides the presented method of green supplier selection, and Section 4 includes the application of the proposed method. Finally, Section 5 concludes the paper.

2 Preliminary

Type 2 fuzzy sets are identified by a measure of dispersion which shows the existing uncertainties. These sets are practical in situations in which expressing the exact membership function of a fuzzy set is not easily done [29]. Furthermore, type-2 FSs have more practicality in handling conditions that are more subjective and imprecise. One of the main features of these sets that has made them more common in real-world applications is their intensiveness [30]. In this section, a brief illustration of the basic concepts and operations of IT2FSs is presented.

Definition 1. A type 2 FS $\tilde{\tilde{A}}$ which is located in the universe of discourse X can be denoted by a type 2 membership function $\mu_{\tilde{\tilde{A}}}$, which is defined in the following [31]:

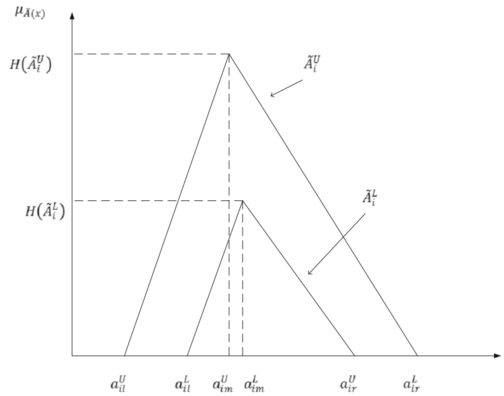

Fig. 1 A triangular interval type 2 fuzzy set

$$\tilde{\tilde{A}} = \left\{ \left((x,u), \mu_{\tilde{\tilde{A}}}(x,u) \right) | \forall x \in X, \forall u \in J_x \subseteq [0,1], 0 \leq \mu_{\tilde{\tilde{A}}}(x,u) \leq 1 \right\} \quad (1)$$

where J_x shows an interval in [0, 1].

The type 2 fuzzy set $\tilde{\tilde{A}}$ can also be denoted as the following:

$$\tilde{\tilde{A}} = \int_{x \in X} \int_{u \in J_x} \frac{\mu_{A^{\approx}}(x,u)}{(x,u)} \quad (2)$$

where $J_x \subseteq [0, 1]$ and $\iint$. denote union over all admissible x and u.

Definition 2. If in $\tilde{\tilde{A}}$ all $\mu_{\tilde{\tilde{A}}}(x,u) = 1$, then $\tilde{\tilde{A}}$ is an IT2FS. This interval set is known as a special case of a type 2 fuzzy set and is presented as follows [31]:

$$\tilde{\tilde{A}} = \int_{x \in X} \int_{u \in J_x} \frac{1}{(x,u)} \quad (3)$$

where $J_x \subseteq [0, 1]$.

Definition 3. The uncertain bounded area for the primary membership function, which is the outcome of the union of all primary memberships, is known as the footprint of uncertainty (FOU). FOU is characterized by the upper membership function (UMF) and the lower membership function (LMF). However, UMF and LMF are type 1 fuzzy sets [31].

Definition 4. A fuzzy number is a triangular interval type 2 fuzzy number (TIT2FN) if and only if its UMF and the LMF are both triangular fuzzy numbers. A as a triangular interval type 2 fuzzy set can be displayed as follows:

$$\tilde{\tilde{A}}_i = \left(\tilde{A}_i^U, \tilde{A}_i^L \right) = \left(\left(a_{il}^U, a_{im}^U, a_{ir}^U; H\left(\tilde{A}_i^U \right) \right), \left(a_{il}^L, a_{im}^L, a_{ir}^L; H\left(\tilde{A}_i^U \right) \right) \right) \quad (4)$$

where $\tilde{A}_i^L$ and $\tilde{A}_i^U$ are both type 1 fuzzy sets. The reference points of the IT2FS $A_i^{\approx}$ are a_{il}^U, a_{im}^U, a_{ir}^U, and a_{ir}^L. The membership values of the elements a_i^U which belong to the upper triangular membership function of $\tilde{A}_i^U$ are determined by $H\left(\tilde{A}_i^U\right)$, and the membership values of the elements a_i^L which belong to the upper triangular membership function of $\tilde{A}_i^U$ are determined by $H\left(\tilde{A}_i^U\right)$. It should be considered that $H\left(\tilde{A}_i^U\right)$ and $H\left(\tilde{A}_i^L\right)$ belong to the interval of [0, 1] and $1 \leq i \leq 2$. This IT2FS is displayed in Fig. 1 [32].

Let $\tilde{\tilde{A}}_1$ and $\tilde{\tilde{A}}_2$ be two TIT2F numbers:

$$\tilde{\tilde{A}}_1 = \left(\tilde{A}_1^U, \tilde{A}_1^L \right) = \left(\left(a_{1l}^U, a_{1m}^U, a_{1r}^U; H\left(\tilde{A}_1^U \right), \right), \left(a_{1l}^L, a_{1m}^L, a_{1r}^L; H\left(\tilde{A}_1^L \right) \right) \right) \quad (5)$$

$$\tilde{\tilde{A}}_2 = \left(\tilde{A}_2^U, \tilde{A}_2^L \right) = \left(\left(a_{2l}^U, a_{2m}^U, a_{2r}^U; H\left(\tilde{A}_2^U \right), \right), \left(a_{2l}^L, a_{2m}^L, a_{2r}^L; H\left(\tilde{A}_2^L \right) \right) \right) \quad (6)$$

The basic algebraic of TIT2FSs is described as follows [32, 33]:

The addition operation between them is defined as follows:

$$\tilde{\tilde{A}}_1 \oplus \tilde{\tilde{A}}_2 = \left(\left(a_{1l}^U + a_{2l}^U, a_{1m}^U + a_{2m}^U, a_{1r}^U + a_{2r}^U; \min\left(H\left(\tilde{A}_i^U \right), H\left(\tilde{A}_2^U \right) \right), \right), \left(a_{1l}^L + a_{2l}^L, a_{1m}^L + a_{2m}^L, a_{1r}^L + a_{2r}^L; min\left(H\left(\tilde{A}_1^U \right), H\left(\tilde{A}_2^U \right) \right) \right) \right) \quad (7)$$

The subtraction operation is defined as follows:

$$\tilde{\tilde{A}}_1 \ominus \tilde{\tilde{A}}_2 = \left[\left(a_{1l}^U - a_{2r}^U, a_{1m}^U - a_{2m}^U, a_{1r}^U - a_{2l}^U; \min\left(H\left(\tilde{A}_1^U \right), H\left(\tilde{A}_2^U \right) \right) \right), \left(a_{1l}^L - a_{2r}^L, a_{1m}^L - a_{2m}^L, a_{1r}^L - a_{2l}^L; \min\left(H\left(\tilde{A}_1^U \right), H\left(\tilde{A}_2^U \right) \right) \right) \right] \quad (8)$$

The multiplication operation is defined as follows:

$$\tilde{\tilde{A}}_1 \otimes \tilde{\tilde{A}}_2 = \left(\left(a_{1l}^U \times a_{2l}^U, a_{1m}^U \times a_{2m}^U, a_{1r}^U \times a_{2r}^U; \min\left(H\left(\tilde{A}_1^U \right), H\left(\tilde{A}_2^U \right) \right), \right), \left(a_{1l}^L \times a_{2l}^L, a_{1m}^L \times a_{2m}^L, a_{1r}^L \times a_{2r}^L; \min\left(H\left(\tilde{A}_1^L \right), H\left(\tilde{A}_2^L \right) \right) \right) \right) \quad (9)$$

The multiplication operation between a crisp value (λ) and A_1 is defined as follows:

$$\lambda \tilde{\tilde{A}}_1 = \left(\left(\lambda \times a_{1l}^U, \lambda \times a_{1m}^U, \lambda \times a_{1r}^U; H\left(\tilde{A}_1^U\right) \right), \left(\left(\lambda \times a_{1l}^L, \lambda \times a_{1m}^L, \lambda \times a_{1r}^L; H\left(\tilde{A}_1^L\right) \right) \right) \right) \tag{10}$$

The division operation is defined as follows:

$$\tilde{\tilde{A}}_1 \oslash \tilde{\tilde{A}}_2 \cong \left[\left(a_{1l}^U/a_{2r}^U, a_{1m}^U/a_{2m}^U, a_{1r}^U/a_{2l}^U; \min\left(H\left(\tilde{A}_1^U\right), H\left(\tilde{A}_2^U\right) \right) \right), \left(a_{1l}^L/a_{2r}^L, a_{1m}^L/a_{2m}^L, a_{1r}^L/a_{2l}^L; \min\left(H\left(\tilde{A}_1^L\right), H\left(\tilde{A}_2^L\right) \right) \right) \right] \tag{11}$$

The inverse of a TIT2FS is denoted as follows:

$$\frac{1}{A_1^{\approx}} \cong \left[\left(1/a_{1r}^U, 1/a_{1m}^U, 1/a_{1l}^U; H\left(\tilde{A}_1^U\right) \right), \left(1/a_{1r}^L, 1/a_{1m}^L, 1/a_{1l}^L; H\left(\tilde{A}_1^L\right) \right) \right] \tag{12}$$

In order to rank IT2FSs, the concept of expected value defined by Hu et al. [34] was used. In this approach, the IT2FN with a higher $E(A)$ is determined as the bigger number. $E(A)$ is obtained as follows:

$$E(A) = \frac{1}{2} \left(\frac{1}{3} \sum_{i=1}^{3} a_i^L + a_i^U \right) \times \frac{1}{4} \left(\sum_{i=1}^{2} \left(H_i\left(A^L\right) + H_i\left(A^U\right) \right) \right) \tag{13}$$

3 Introduced supplier selection model

This section proposes a compromise ratio method that is based on the concepts of IT2FSs, relative preference relation, multi-objective optimization by ratio analysis plus the full multiplicative form, and decision-makers' weights. This systematic process gives the individual decisions a weight based on the gathered judgments of experts. Linguistic variables presented by Celik et al. [35] were adopted and used to present criteria weights and alternative ratings. The aforementioned values are presented in Table 1. Using IT2FSs provides the decision-maker (DM) with more power and flexibility in showing lack of knowledge and vague conditions in situations where denoting the membership degree by a crisp value is not efficient.

After gathering the judgments, first the normalization process is carried out. To calculate the weight of each decision-maker, first, a process is presented to give a weight to each decision-maker based on the gathered judgments. The calculated weights and weights given to each DM based on their field of expertise are aggregated. The weighted (on DM) decision matrix is then formed. After this step, fuzzy preference relation is extended under type 2 fuzzy sets to further process the weight of each criterion. To rank the alternatives, the computed decision matrix and criteria weights are first used to rank the alternatives based on summarizing index of each alternative. Secondly, they are used to rank the alternatives based on maximal deviance. Thirdly, they are used to rank the alternatives based on full multiplicative form. Finally, the three ranking results are aggregated by dominance theory to find the final ranking of alternatives. The step-by-step method is presented as follows:

The process begins with gathering the judgments of each DM. Consequently, the following are made:

$$\tilde{\tilde{D}}_k = \left(\tilde{\tilde{D}}_{ij} \right)_{m \times n} = \begin{bmatrix} \tilde{\tilde{D}}_{11}^K & \cdots & \tilde{\tilde{D}}_{1n}^K \\ \vdots & \ddots & \vdots \\ \tilde{\tilde{D}}_{m1}^K & \cdots & \tilde{\tilde{D}}_{mn}^K \end{bmatrix} \tag{14}$$

$$\tilde{\tilde{W}}_K = \left(\tilde{\tilde{W}}_{W1}^k, \tilde{\tilde{w}}_2^k, \ldots, \tilde{\tilde{w}}_n^k \right), K \in T \tag{15}$$

where $\tilde{\tilde{D}}_K$ denotes the decision matrix and $\tilde{\tilde{W}}_K$ denotes the weight of criteria, m shows the number of criteria, n shows

Table 1 Linguistic terms for ratings

Linguistic variable	IT2F number
Extremely high (EH)	((8,9,10; 1),(8.5,9,9.5;,0.9))
Very high (VH)	((6,7,8;1),(6.5,7,7.5;0.9))
High (H)	((4,5,6; 1),(4.5,5,5.5;0.9))
Medium high (MH)	((2,3,4; 1),(2.5,3,4.5;0.9))
M (medium)	((1,1,1; 1),(1,1,1;0.9))
Medium low (ML)	((0.25,0.33,0.5;1),(0.22,0.33,0.4;0.9))
Low (L)	((0.17,0.2,0.25; 1),(0.18,0.2,0.22;0.9))
Very low (VL)	((0.13,0.14,0.17;1),(0.13,0.14,0.15;0.9,))
Extremely low (EL)	((0.1,0.11,0.13;1),(0.11,0.11,0.12;0.9))

the number of compared alternatives, and T expresses the group of DMs. It should be noted that $\tilde{\tilde{D}}_K$ and $\tilde{\tilde{W}}_K$ are IT2FSs and are expressed as follows:

$$\tilde{\tilde{D}}_{ij}^{K} = \left(\left(d_{ij_l}^{U}, d_{ij_m}^{U}, d_{ij_r}^{U}; H\left(\tilde{D}_{ij}^{U}\right),\right), \left(d_{ij_l}^{L}, d_{ij_m}^{L}, d_{ij_r}^{L}; H\left(\tilde{D}_{ij}^{L}\right)\right)\right) \tag{16}$$

$$\tilde{\tilde{W}}_K = \left(\left(w_{j_l}^{U}, w_{j_m}^{U}, w_{j_r}^{U}; H\left(\tilde{w}_j^{U}\right),\right), \left(w_{j_l}^{L}, w_{j_m}^{L}, w_{j_r}^{L}; H\left(\tilde{w}_j^{L}\right)\right)\right) \tag{17}$$

The normalized decision matrix ($\widetilde{\widetilde{ND}}$) is computed by applying Eqs. (19) and (20). The normalization process is done to provide comparability for different criteria. In other words, dimensionless values of different criteria are the outcome of this process.

$$\tilde{\tilde{ND}} = \begin{bmatrix} \tilde{\tilde{ND}}_{11} & \cdots & \tilde{\tilde{ND}}_{1n} \\ \vdots & \ddots & \vdots \\ \tilde{\tilde{ND}}_{m1} & \cdots & \tilde{\tilde{ND}}_{mn} \end{bmatrix} \tag{18}$$

$$\tilde{\tilde{ND}}_{ij} = \left(\left(\frac{d_{ij_l}^{U}}{d^\star}, \frac{d_{ij_m}^{U}}{d^\star}, \frac{d_{ij_r}^{U}}{d^\star}; H\left(\tilde{D}_{ij}^{U}\right)\right), \left(\frac{d_{ij_l}^{L}}{d^\star}, \frac{d_{ij_m}^{L}}{d^\star}, \frac{d_{ij_r}^{L}}{d^\star}; H\left(\tilde{D}_{ij}^{L}\right)\right)\right) \quad i = 1, 2, \ldots, n, j \epsilon B \tag{19}$$

$$ND_{ij} = \left(\left(\frac{d^-}{d_{ij_r}^{L}}, \frac{d^-}{d_{ij_m}^{L}}, \frac{d^-}{d_{ij_l}^{L}}; H\left(\tilde{D}_{ij}^{U}\right)\right), \left(\frac{d^-}{d_{ij_r}^{U}}, \frac{d^-}{d_{ij_m}^{U}}, \frac{d^-}{d_{ij_l}^{U}}; H\left(\tilde{D}_{ij}^{L}\right)\right)\right) \quad i = 1, 2, \ldots, n, j \epsilon C \tag{20}$$

where B and C denote the set of benefit criteria and the set of cost criteria, respectively. $d^\star$ and d^- are also obtained as follows:

$$d_j^\star = \max_i d_{ij_r}^{U} \tag{21}$$

$$d_j^- = \min_i d_{ij_l}^{L} \tag{22}$$

To make the process more effective, it is better to address the impacts of each decision-maker's level of knowledge in the process. Therefore, a process to compute the weight of each DM is presented in Eqs. (23), (24), (25), (26), (27), (28), (29), (30), (31), and (32). According to the mean value, the average of all individual decisions yields the ideal decision of all individual ideas. The maximum distance from the positive ideal decision is called negative ideal decision. This approach gives two values of left negative ideal decision and right negative ideal decision [36]. The outcome of this issue can be referred to as the best decision (BD^*), the left negative best decision (BD_l^-), and the right negative best decision $\left(BD_r^-\right)$ which are obtained by the following:

$$\tilde{\tilde{BD}}^* = \begin{bmatrix} \tilde{\tilde{BD}}_{11}^* & \cdots & \tilde{\tilde{BD}}_{1n}^* \\ \vdots & \ddots & \vdots \\ \tilde{\tilde{BD}}_{m1}^* & \cdots & \tilde{\tilde{BD}}_{mn}^* \end{bmatrix}$$

$$\text{where } \tilde{\tilde{BD}}_{ij}^* = \left(\begin{array}{c} \left({}^1/_t \sum_{k=1}^{t} nd_{ij_l}^{U}, {}^1/_t \sum_{k=1}^{t} nd_{ij_m}^{U}, {}^1/_t \sum_{k=1}^{t} nd_{ij_r}^{U}; H\left(\tilde{D}_{ij}^{U}\right)\right), \\ \left({}^1/_t \sum_{k=1}^{t} nd_{ij_l}^{L}, {}^1/_t \sum_{k=1}^{t} nd_{ij_m}^{L}, {}^1/_t \sum_{k=1}^{t} nd_{ij_r}^{L}; H\left(\tilde{D}_{ij}^{L}\right)\right) \end{array}\right) \tag{23}$$

$$\tilde{\tilde{BD}}_L^- = \begin{bmatrix} \tilde{\tilde{BD}}_l^- & \cdots & \tilde{\tilde{BD}}_{l1n}^- \\ \vdots & \ddots & \vdots \\ \tilde{\tilde{BD}}_{lm1}^- & \cdots & \tilde{\tilde{BD}}_{mn}^- \end{bmatrix} \tag{24}$$

$$\text{where } \widetilde{\widetilde{BD}}_{l\,ij}^- = \min_{1 \le k \le t} \left\{ \widetilde{\widetilde{ND}}_{ij}^{k} \right\}$$

$$\tilde{\tilde{BD}}_R^- = \begin{bmatrix} \tilde{\tilde{BD}}_{r\,11}^- & \cdots & \tilde{\tilde{BD}}_{r\,1n}^- \\ \vdots & \ddots & \vdots \\ \tilde{\tilde{BD}}_{r\,m1}^- & \cdots & \tilde{\tilde{BD}}_{r\,mn}^- \end{bmatrix} \tag{25}$$

$$\text{where } \widetilde{\widetilde{BD}}_{r\,ij}^- = \max_{1 \le k \le t} \left\{ \widetilde{\widetilde{ND}}_{ij}^{k} \right\}$$

The distance of each individual opinion from the ideal decisions that include the positive, the left negative, and the right negative ideal decisions are respectively displayed by DBD_k^*, $DBD_{l\,k}^-$, and $DBD_{l\,r}^-$ which are computed by the following equations:

$$DBD_k^* = \sum_{j=1}^{n} \sqrt{\begin{array}{c} \left(nd_{ij_l}^{U\,k} - {}^1/_t \sum_{k=1}^{t} nd_{ij_l}^{U}\right)^2 + \left(nd_{ij_m}^{U\,k} - {}^1/_t \sum_{k=1}^{t} nd_{ij_m}^{U}\right)^2 + \\ \left(nd_{ij_r}^{U\,k} - {}^1/_t \sum_{k=1}^{t} nd_{ij_r}^{U}\right)^2 + \left(nd_{ij_l}^{L\,k} - {}^1/_t \sum_{k=1}^{t} nd_{ij_l}^{L}\right)^2 + \\ \left(nd_{ij_m}^{L\,k} - {}^1/_t \sum_{k=1}^{t} nd_{ij_m}^{L}\right)^2 + \left(nd_{ij_r}^{L\,k} - {}^1/_t \sum_{k=1}^{t} nd_{ij_r}^{L}\right)^2 + \\ \left(H\left(\tilde{ND}^{UK}\right) - H\left(\tilde{ND}^{U^*}\right)\right)^2 + \\ \left(H\left(\tilde{ND}^{LK}\right) - H\left(\tilde{ND}^{L^*}\right)\right)^2 \end{array}} \quad k \in T \tag{26}$$

$$DBD_l^- = \sum_{j=1}^{n} \sqrt{\begin{array}{c} \left(nd_{ij_l}^{U\,k} - \min nd_{ij_l}^{U}\right)^2 + \left(nd_{ij_m}^{U\,k} - \min nd_{ij_m}^{U}\right)^2 + \\ \left(nd_{ij_r}^{U\,k} - \min nd_{ij_r}^{U}\right)^2 + \left(nd_{ij_l}^{L\,k} - \min nd_{ij_l}^{L}\right)^2 + \\ \left(nd_{ij_m}^{L\,k} - \min nd_{ij_m}^{L}\right)^2 + \left(nd_{ij_r}^{L\,k} - \min nd_{ij_r}^{L}\right)^2 + \\ \left(H\left(\tilde{ND}^{UK}\right) - H\left(\tilde{ND}_{l}^{U^-}\right)\right)^2 + \\ \left(H\left(\tilde{ND}^{LK}\right) - H\left(\tilde{ND}_{l}^{L^-}\right)\right)^2 \end{array}} \quad k \in T \tag{27}$$

$$DBD_r^- = \sum_{j=1}^{n} \sqrt{\begin{array}{c} \left(nd_{ij_l}^{Uk} - \max nd_{ij_l}^{U}\right)^2 + \left(nd_{ij_m}^{Uk} - \max nd_{ij_m}^{U}\right)^2 + \\ \left(nd_{ij_r}^{Uk} - \max nd_{ij_r}^{U}\right)^2 + \left(nd_{ij_l}^{Lk} - \max nd_{ij_l}^{L}\right)^2 + \\ \left(nd_{ij_m}^{Lk} - \max nd_{ij_m}^{L}\right)^2 + \left(nd_{ij_r}^{Lk} - \max nd_{ij_r}^{L}\right)^2 + \\ \left(H\left(\tilde{ND}^{UK}\right) - H\left(\tilde{ND}^{U^-}_{r}\right)\right)^2 + \\ \left(H\left(\tilde{ND}^{LK}\right) - H\left(\tilde{ND}^{L^-}_{r}\right)\right)^2 \end{array}} \quad k \in t \tag{28}$$

After computing the distance, the closeness coefficient of the individual opinion considering ideal decisions should be computed. This value is presented by ($CCIO_k$) which is presented as follows:

$$\mathrm{CCIO}_k = \frac{DBD_r^- + DBD_l^-}{DBD_r^- + DBD_l^- + DBD_k^*}, K \in T \tag{29}$$

It is clear that bigger values of $CCIO_k$ express more emphasis on the kth DM's opinion, thus bigger values of weight for the kth DM [37]. As a matter of fact, the relative importance of each DM is not only measurable but also quantifiable. Consequently, the importance of a DM in his/her area of knowledge known as the individual importance is denoted by DMK_k. This value is given to each DM based on their level of knowledge and expertise in any field. Here, to enhance the process, DM weight addresses both of the aforementioned concepts. The following shows the aggregation form of two views:

$$\mathrm{ADMW}_k = \vartheta DMK_k + (1 - \vartheta)\mathrm{CCIO}_k, K \in T \tag{30}$$

where $\vartheta (0 \leq \vartheta \leq 1)$ denotes the optimistic coefficient which shows whose opinion can be preferred considering the group's ideas, $DMK_k (0 \leq DMK_k \leq 1)$ denotes the importance of the k th DM as a knowledgeable person in his/her own expertise.

Finally, weights of DMs are computed by employing the following:

$$EW_k = \frac{\mathrm{ADMW}_k}{\sum_{k=1}^{t} \mathrm{ADMW}_k}, K \in T \tag{31}$$

The weighted (on DMs) decision matrix ($\widetilde{\widetilde{WD}}_k$) for each DM is computed by using the following equation:

$$\tilde{\tilde{WD}}_k = \left(EW_k \times \tilde{\tilde{ND}}_{ij}\right)_{m \times n} = \begin{bmatrix} \tilde{\tilde{WD}}_{11}^k & \cdots & \tilde{\tilde{WD}}_{1n}^k \\ \vdots & \ddots & \vdots \\ \tilde{\tilde{WD}}_{m1}^k & \cdots & \tilde{\tilde{WD}}_{mn}^k \end{bmatrix} \tag{32}$$

where $\widetilde{\widetilde{WD}}_{ij} = \left(\left(EW_k \times nd_{ij_l}^{U}, EW_k \times nd_{ij_m}^{U}, EW_k \times nd_{ij_r}^{U}; H\left(\tilde{D}_{ij}^{U}\right)\right), \left(EW_k \times nd_{ij_l}^{L}, EW_k \times nd_{ij_m}^{L}, EW_k \times nd_{ij_r}^{L}; H\left(\tilde{D}_{ij}^{L}\right)\right)\right)$

After computing the weight of each decision-maker on each judgment, the weight vectors of attributes should also be processed so that the effectiveness of the model would be enhanced. In this part of the process, relative preference degrees of the fuzzy important levels over average are developed under IT2FSs. Therefore, first the average of the values for importance of criteria is computed. The following presents the process:

$$\tilde{\tilde{W}}_j = \left(\begin{array}{c} \left(1/t \sum_{k=1}^{t} w_{j_l}^{U}, 1/t \sum_{k=1}^{t} w_{j_m}^{U}, 1/t \sum_{k=1}^{t} w_{j_r}^{U}; H\left(\tilde{w}_j^U\right)\right), \\ \left(1/t \sum_{k=1}^{t} w_{j_l}^{L}, 1/t \sum_{k=1}^{t} w_{j_m}^{L}, 1/t \sum_{k=1}^{t} w_{j_r}^{L}; H\left(\tilde{w}_j^L\right)\right) \end{array}\right) \tag{33}$$

The relative preference relation (RPR) which is best known by its membership function $\mu_{\mathrm{RPMF}}\left(W_{kj}, \overline{W}_j\right)$ indicates the relative preference degree of W_{kj} over $\overline{W}_j$. The following presents how it is computed:

$$\mu_{\mathrm{RPMF}}\left(\tilde{\tilde{W}}_{kj}, \tilde{\tilde{W}}_j\right) = \frac{1}{2}\left(\frac{\left(w_{tjl}^{U} - \frac{\sum_{j=1}^{T} w_{jl}^{U\sim}}{T}\right) + 2\left(w_{tj\,m}^{U} - \frac{\sum_{j=1}^{T} w_{j\,m}^{U}}{T}\right) + \left(w_{tjr}^{U} - \frac{\sum_{j=1}^{T} w_{jr}^{\sim}}{T}\right)}{2\|Q_W\|} + 1\right) \tag{34}$$

where $\|Q_W\|$:

$$\begin{cases} \dfrac{\left(q_{w\,l}^{+U} - q_{wr}^{-U}\right) + 2\left(q_{w\,m}^{+U} - q_{wm}^{-U}\right) + \left(q_{w\,r}^{+U} - q_{wl}^{-U}\right)}{2}, & if q_{w\,l}^{+U} \geq q_{wr}^{-U} \\ \dfrac{\left(q_{w\,l}^{+U} - q_{wr}^{-U}\right) + 2\left(q_{w\,m}^{+U} - q_{wm}^{-U}\right) + \left(q_{w\,r}^{+U} - q_{wl}^{-U}\right)}{2} + 2\left(\overline{q}_{wr}^{\,U} - q_{w\,l}^{+U}\right), & if q_{w\,l}^{+U} \leq q_{wr}^{-U} \end{cases} \tag{35}$$

$q_{w\,l}^{+U} = \max_K w_{kj\,l}^{U}, q_{w\,m}^{+} = \max_K w_{kj\,m}^{U}, q_{w\,r}^{+U} = \max_K w_{kj\,r}^{U}, q_{wl}^{-U} = \min_K w_{kj\,l}^{U}, q_{wm}^{-} = \min_K w_{kj\,m}^{U}, q_{wr}^{-U} = \min_K w_{kj\,r}^{U}$

Eventually, the obtained weights of criteria receive a value that denotes their importance which is based on the RPR. The modified weights (MW) of criteria are computed as follows:

$$\tilde{\tilde{MW}}_j = \mu_{\text{RPMF}}\left(\tilde{\tilde{MW}}_{kj}, \tilde{\tilde{MW}}_j\right) \times \tilde{\tilde{W}}_j \tag{36}$$

The normalized weighted decision matrix is calculated by employing Eq. (38).

$$\tilde{\tilde{B}} = \begin{bmatrix} \tilde{\tilde{B}}_{11} & \cdots & \tilde{\tilde{B}}_{1n} \\ \vdots & \ddots & \vdots \\ \tilde{\tilde{B}}_{m1} & \cdots & \tilde{\tilde{B}}_{mn} \end{bmatrix} \tag{37}$$

$$\tilde{\tilde{B}}_{ij} = \tilde{\tilde{WD}}_{ij} \times \tilde{\tilde{MW}}_j = \left(\left(mw_{j_l}^U \times wd_{ij_l}^U, mw_{j_m}^U \times wd_{ij_m}^U, mw_{j_r}^U \times wd_{ij_r}^U; \min\left(H\left(\tilde{WD}_j^U\right), H\left(\tilde{MW}_{ij}^U\right)\right)\right)\left(mw_{j_l}^L \times wd_{ij_l}^L, mw_{j_m}^L \times wd_{ij_m}^L, mw_{j_r}^L \times wd_{ij_r}^L; \min\left(H\left(\tilde{WD}_j^L\right), H\left(\tilde{MW}_{ij}^L\right)\right)\right)\right) \tag{38}$$

In the next step, the summarizing index of each alternative is computed by using the following:

$$SI_i = \left(\left(\sum_{j\in B} b_{ij_l}^U, \sum_{j\in B} b_{ij_m}^U, \sum_{j\in B} b_{ij_r}^U; \min\left(H\left(\tilde{B}_{ij}^U\right)\right)\right), \left(\sum_{j\in B} b_{ij_l}^L, \sum_{j\in B} b_{ij_m}^L, \sum_{j\in B} b_{ij_r}^L; \min\left(H\left(\tilde{B}_{ij}^U\right)\right)\right)\right) - \left(\left(\sum_{j\in C} b_{ij_l}^U, \sum_{j\in C} b_{ij_m}^U, \sum_{j\in C} b_{ij_r}^U; \min\left(H\left(\tilde{B}_{ij}^U\right)\right)\right), \left(\sum_{j\in C} b_{ij_l}^L, \sum_{j\in C} b_{ij_m}^L, \sum_{j\in C} b_{ij_r}^L; \min\left(H\left(\tilde{B}_{ij}^U\right)\right)\right)\right) \tag{39}$$

Then, alternatives are ranked based on the obtained values of SI_i.

The maximum reference point (max RP) should be decided. In this approach, the maximum reference points are denoted as follows:

$$\max RP = ((1,1,1;1),(1,1,1;1)), j\in B \tag{40}$$

$$\max RP = ((0,0,0;1,),(0,0,0;1)), j\in C \tag{41}$$

The maximum deviation of each alternative from max RP is obtained by the following equation:

$$\max RP \text{ distance} = \sqrt{\begin{matrix}\left(b_{ij_l}^U-1\right)^2 + \left(b_{ij_m}^U-1\right)^2 + \\ \left(b_{ij_r}^U-1\right)^2 + \left(b_{ij_l}^L-1\right)^2 + \\ \left(b_{ij_m}^L-1\right)^2 + \left(b_{ij_r}^L-1\right)^2 + \\ \left(H\left(\tilde{B}^U\right)\right)^2 + \\ \left(H\left(\tilde{B}^L\right)\right)^2\end{matrix}} \tag{42}$$

$$\max RP \text{ distance} = \sqrt{\begin{matrix}\left(b_{ij_l}^U-0\right)^2 + \left(b_{ij_m}^U-0\right)^2 + \\ \left(b_{ij_r}^U-0\right)^2 + \left(b_{ij_l}^L-0\right)^2 + \\ \left(b_{ij_m}^L-0\right)^2 + \left(b_{ij_r}^L-0\right)^2 + \\ \left(H\left(\tilde{B}^U\right)\right)^2 + \\ \left(H\left(\tilde{B}^L\right)\right)^2\end{matrix}} \tag{43}$$

In order to rank the alternatives, the maximal deviance (MD) is computed as presented below; then, the alternatives are ranked based on minimizing order of MD.

$$MD_j = \max_j \text{distance}\left(\tilde{\tilde{B}}_{ij}, \max RP\right) \tag{44}$$

The third ranking of alternatives is carried out by applying full multiplicative form. The IT2F utility of the ith alternative is computed by using the following equation:

$$\text{IT2FU}_i = \frac{\left(\left(\prod_{j\in B} b_{ij_l}^U, \prod_{j\in B} b_{ij_m}^U, \prod_{j\in B} b_{ij_r}^U; \min\left(H\left(\tilde{B}_{ij}^U\right)\right)\right), \left(\prod_{j\in B} b_{ij_l}^L, \prod_{j\in B} b_{ij_m}^L, \prod_{j\in B} b_{ij_r}^L; \min\left(H\left(\tilde{B}_{ij}^U\right)\right)\right)\right)}{\left(\left(\prod_{j\in C} b_{ij_l}^U, \prod_{j\in C} b_{ij_m}^U, \prod_{j\in C} b_{ij_r}^U; \min\left(H\left(\tilde{B}_{ij}^U\right)\right)\right), \left(\prod_{j\in C} b_{ij_l}^L, \prod_{j\in C} b_{ij_m}^L, \prod_{j\in C} b_{ij_r}^L; \min\left(H\left(\tilde{B}_{ij}^U\right)\right)\right)\right)} \tag{45}$$

Finally, the third ranking is made by ordering the crisp values of IT2FU in decreasing order.

As it can be observed, the alternatives were ranked by ratio system, reference point, and full multiplicative form. To aggregate these three parts into a final ranking, the dominance theory developed by Brauers and Zavadskas [38] is used. Therefore, the final ranking of alternatives is yielded.

4 Application of the proposed approach

In this section, two existing case studies at the manufacturing system level are presented and solved with the presented approach. Then, in order to display the step-by-step process of the green supplier selection approach, the method is applied in the case study of an Iranian firm to assess and find the best green supplier.

Table 2 The importance of criteria [39]

Criteria	DM1	DM2	DM3
Quality	VH	H	VH
Technological capabilities	M	L	H
Total cost	H	H	VH
Buyer-supplier partnership	M	M	M
Geographical location	VL	L	M
Flexibility	M	H	H
Production performance	L	M	M
Just-in-time delivery	H	M	M

4.1 Application in literature case studies

The first investigated case study [39] belongs to a medium-sized manufacturer that produces plaster and cement-based productions. There are eight suppliers to select from. A team of three experts is made and they are asked to express their opinions. The decision-making criteria are quality, technological capabilities, total cost, buyer-supplier partnership, geographic location, flexibility, production performance, and just-in-time delivery. The linguistic variables provided in Tables 2 and 3 are used to assess the suppliers. However, it should be noted that the case was applied with classic fuzzy sets. In order to use IT2FSs, the equivalent value of the linguistic variables of Tables 2 and 3 was taken from Table 1 to be used in the process.

The final rankings of suppliers are presented in Table 4. As it can be seen, the results verify the presented method.

In order to investigate further the application of the introduced approach, an existing case study of green supplier selection at the manufacturing system level [40] is presented and solved in this part. In this case study, a food-processing company is trying to find the

Table 3 Rating of suppliers [39]

	Quality	Total cost	Technological capabilities	Buyer-supplier partnership	Geographical location	Flexibility	Production performance	Just-in-time delivery
DM1								
Supplier 1	G	G	G	G	F	F	G	P
Supplier 2	F	F	F	G	G	F	F	W
Supplier 3	F	F	G	P	W	B	G	F
Supplier 4	B	G	G	F	F	G	F	P
Supplier 5	G	F	F	P	W	F	F	P
Supplier 6	P	G	F	G	F	F	P	W
Supplier 7	F	P	W	F	B	P	F	P
Supplier 8	F	F	G	W	F	P	G	P
DM2								
Supplier 1	G	F	F	F	P	F	P	F
Supplier 2	F	G	F	P	F	P	F	W
Supplier 3	G	F	P	G	P	G	F	P
Supplier 4	G	F	F	B	F	F	W	P
Supplier 5	G	P	P	F	P	F	P	W
Supplier 6	F	F	F	G	P	P	F	P
Supplier 7	P	F	P	P	G	F	W	F
Supplier 8	F	G	F	F	G	G	F	P
DM3								
Supplier 1	G	F	F	F	F	G	F	F
Supplier 2	G	F	G	P	F	F	F	P
Supplier 3	F	G	F	F	P	F	G	W
Supplier 4	F	F	G	F	F	G	F	P
Supplier 5	F	F	F	B	P	F	P	F
Supplier 6	F	F	F	G	P	F	F	P
Supplier 7	G	F	F	P	B	P	F	W
Supplier 8	W	F	F	G	G	F	G	W

Table 4 Final rankings of suppliers

Supplier	Ranking [39]	Ranking of presented method
Supplier 1	2	2
Supplier 2	3	3
Supplier 3	4	4
Supplier 4	1	1
Supplier 5	7	7
Supplier 6	6	6
Supplier 7	8	8
Supplier 8	5	5

best raw oil supplier by considering the green assessment criteria. A three-member team of experts was formed to evaluate the suppliers. Tables 5 and 6 present the judgment of experts.

It should be noted that like the previous example, in order to apply the presented method, equivalents of the linguistic values were taken from Table 1. The final results of the literature and the presented method are depicted in Table 7.

Applying the introduced method of supplier selection in the existing case studies of the literature shows that the method is reliable and provides acceptable results. However, the presented method in comparison with the existing methods has several novelties. First of all, it uses IT2FSs to address uncertainty. Second, the presented method addresses the weight of each decision-maker in the process. This means that an expert with more expertise is given a more important role in the process. Third, the concept of fuzzy relative preference is used to address the importance of each decision-making criterion. It should also be noted that the method benefits from the advantages of the ratio system, reference point, and full multiplicative form.

4.2 Case study of green supplier selection

The proposed model is applied to select suppliers in an Iranian construction complex while considering green

Table 5 Importance of criteria [40]

Decision-maker	C1	C2	C3	C4
DM1	H	H	MH	ML
DM2	VH	MH	H	M
DM3	H	VH	MH	MH

Table 6 Supplier rankings against decision criteria [40]

Olive oil supplier	Decision-maker	Supplier	C1	C2	C3	C4
	DM1	O1	F	MP	MP	VG
		O2	G	F	F	MG
		O3	MP	VG	MG	G
		O4	P	VP	P	MP
	DM2	O1	P	G	MP	F
		O2	F	G	MG	F
		O3	VG	MP	VG	VG
		O4	MP	MG	F	MG
	DM3	O1	MP	F	G	MG
		O2	VG	P	G	G
		O3	P	G	G	G
		O4	F	P	G	G

aspects. The studied company manages a number of firms that operate in different construction industry segments and also operates in the full scope of work, differing from raw material extraction and producing building materials to constructing residential and commercial properties. The firm's engineering and technical teams are highly experienced and qualified in engineering and construction spheres; therefore, in the process of applying the developed model in the case study of the firm, a three-membered team of experts with at least 15 years of experience was formed. The mission of the construction firm is to have competitive edge over rivals in the construction market, construct more affordable housing with better quality, and eventually enhance the living conditions of people. The strategic goal of the firm is to develop its local and national situation in the market through considering sustainable aspects of development.

The firm is trying to enhance its environmental friendliness through implementing green criteria in its processes. The purchasing department of the firm intends to perform a comprehensive assessment of four alternative suppliers and apply the results to select the

Table 7 Final ranking of suppliers

Supplier	Ranking [40]	Ranking of presented method
O1	3	3
O2	2	2
O3	1	1
O4	4	4

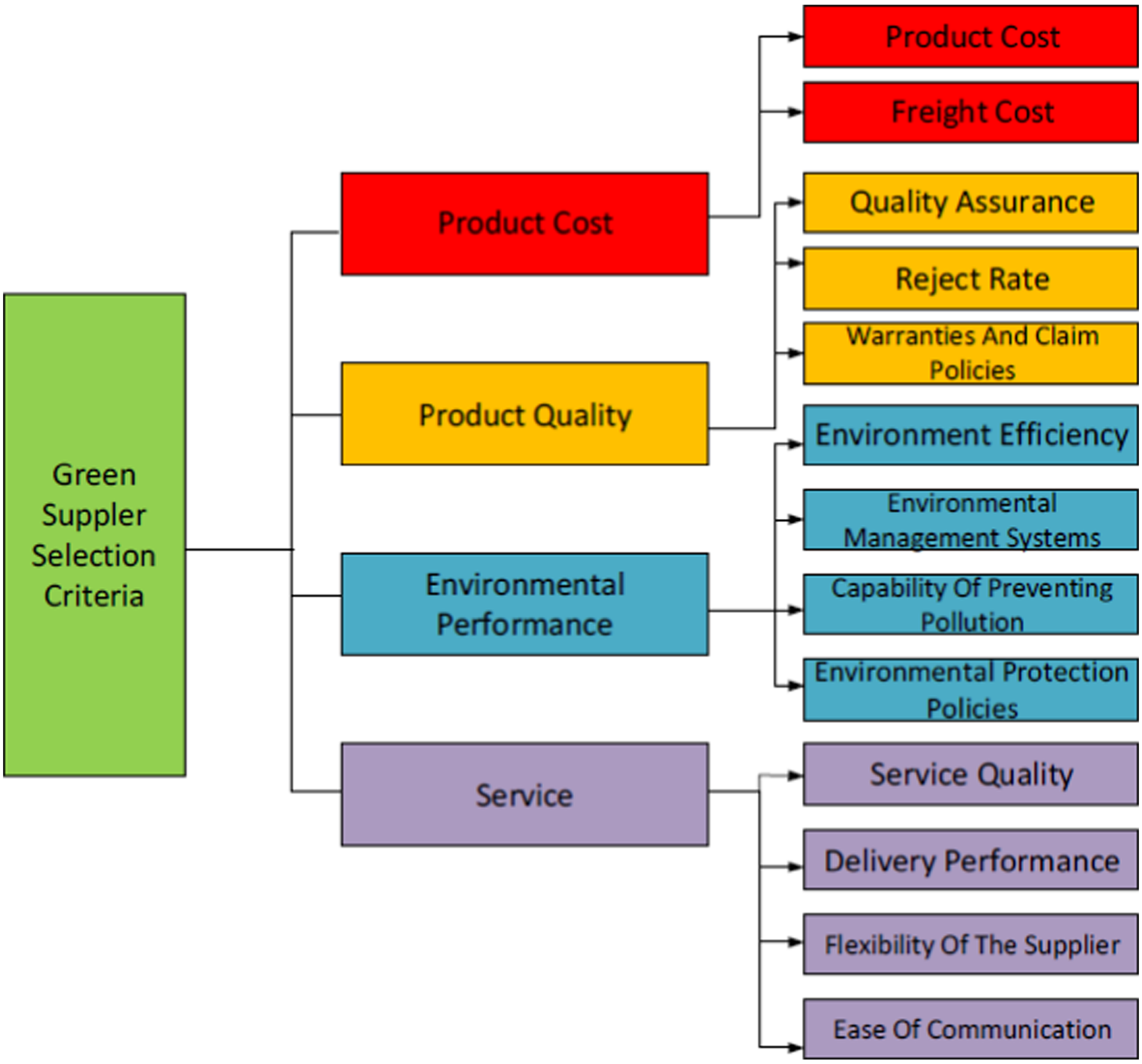

Fig. 2 Visual presentation of the selection criteria

best supplier. It should be considered that due to the competitive environment of the firm, the company has reserved the information of candidate suppliers as confidential. Due to confidentiality of the information, limited details of the suppliers are presented. The knowledge and experiences of experts were used to distinguish the relative importance of proposed criteria of green supplier selection. After careful review of the existing researches (i.e., [9, 17, 18, 41]) and considering the company's specific circumstance and requirements, the evaluation criteria were defined and applied. The evaluation criteria are set as follows:

The selection criteria are divided into four main groups of product cost, product quality, environmental performance, and service. The product cost consists two criteria of product cost (C_1) and freight cost (C_2). These two criteria are considered as cost criteria while the rest are benefit criteria. Product quality has these criteria: quality assurance (C_3), reject rate (C_4), and warranties and claim policies (C_5). To evaluate environmental performance, these criteria are evaluated: environment efficiency (C_6), environmental management systems (C_7), capability of preventing pollution (C_8), and environmental protection policies (C_9). Eventually, service includes the following criteria: service quality (C_{10}), delivery performance (C_{11}), flexibility of the supplier (C_{12}), and ease of communication (C_{13}). To present the different aspects of the criteria in a better way, a visual description of the green supplier selection criteria is presented in Fig. 2.

Questionnaires were used to gather data from professional experts of the aforementioned company. The data is gathered and presented in Tables 8 and 9. Table 8 displays the ratings of the alternatives for each criteria, and Table 9 displays the importance of each criteria.

In order to find the best supplier, the following steps are carried out:

Table 8 Ratings of each alternative

Criterion	Expert	A_1	A_2	A_3	A_4
C_1	E_1	M	MH	ML	MH
	E_2	ML	MH	ML	M
	E_3	MH	M	M	M
C_2	E_1	M	MH	ML	MH
	E_2	M	ML	M	ML
	E_3	ML	M	ML	ML
C_3	E_1	MH	H	VH	L
	E_2	M	VH	H	ML
	E_3	MH	H	EH	M
C_4	E_1	M	MH	MH	M
	E_2	ML	M	M	ML
	E_3	ML	H	MH	MH
C_5	E_1	L	H	M	ML
	E_2	ML	M	MH	L
	E_3	VL	H	MH	ML
C_6	E_1	VL	ML	H	EL
	E_2	VL	H	H	VL
	E_3	L	MH	VH	VL
C_7	E_1	EL	H	MH	VL
	E_2	VL	H	VH	EL
	E_3	VL	VH	MH	L
C_8	E_1	VL	M	M	VL
	E_2	L	ML	H	L
	E_3	L	ML	H	VL
C_9	E_1	ML	M	H	EL
	E_2	VL	MH	H	VL
	E_3	ML	M	MH	EL
C_{10}	E_1	VL	ML	MH	ML
	E_2	MH	M	MH	M
	E_3	ML	ML	M	ML
C_{11}	E_1	MH	H	MH	ML
	E_2	MH	MH	MH	ML
	E_3	ML	MH	H	MH
C_{12}	E_1	EL	M	H	L
	E_2	VL	ML	H	L
	E_3	EL	M	MH	EL
C_{13}	E_1	VH	VH	E	MH
	E_2	H	EH	H	H
	E_3	H	EH	MH	MH

Table 9 The weight vector of attributes

Criterion	Expert		
	E_1	E_2	E_3
C_1	H	VH	VH
C_2	VH	EH	EH
C_3	H	H	MH
C_4	H	H	EH
C_5	M	VH	MH
C_6	ML	ML	M
C_7	ML	M	M
C_8	H	MH	VH
C_9	H	VH	MH
C_{10}	VH	VH	H
C_{11}	EH	VH	VH
C_{12}	M	EH	VH
C_{13}	ML	H	VH

1. First of all, the gathered judgments are normalized by applying Eqs. 19 and 20.
2. The weight of each decision-maker should be obtained. Therefore, the following substeps are carried out:

    2.1. Equations 23, 24, and 25 are applied to compute the best decision (BD^*), the left negative best decision (BD_l^-), and the right negative best decision $\left(BD_r^-\right)$, respectively. Table 10 displays the results.

    2.2. The distance of each individual opinion from the ideal decisions that include the positive, the left negative, and the right negative ideal decisions is respectively calculated by applying Eqs. 26, 27, and 28. Table 11 displays the results.

    2.3. The closeness coefficient of the individual opinion considering ideal decisions is computed by Eq. 29, and the results are displayed in Table 12. It should be noted that after discussing the model with the decision-makers, ϑ was considered as 0.5 and DMK_k was considered as 0.3 for each DM. Equations 30 and 31 are applied to compute the weights of DMs.

    2.4. The weighted (on DMs) decision matrix ($\widetilde{\widetilde{WD}}_k$) for each DM is computed by using Eq. 32.

3. After computing the weights of DMs, relative preference degrees of the fuzzy importance levels over average are computed by the following:

Table 10 The best decision, the left negative best decision, and the right negative best decision

Criteria	Alternative	BD^*	$BD_{\bar{l}}$	$BD_{\bar{r}}$
C_1	A_1	((0.27,0.32,0.43;1),(0.23,0.32,0.4,0.9))	((0.55,0.66,1;1),(0.4,0.62,0.8,0.9))	((0.06,0.07,0.08;1),(0.05,0.07,0.1,0.9))
	A_2	((0.11,0.12,0.13;1),(0.11,0.12,0.13,0.9))	((0.2,0.2,0.2;1),(0.2,0.2,0.2,0.9))	((0.06,0.07,0.08;1),(0.05,0.07,0.1,0.9))
	A_3	((0.44,0.51,0.74;1),(0.36,0.5,0.6,0.9))	((0.55,0.66,1;1),(0.4,0.62,0.8,0.9))	((0.2,0.2,0.2;1),(0.2,0.2,0.2,0.9))
	A_4	((0.16,0.17,0.17;1),(0.16,0.17,0.17,0.9))	((0.2,0.2,0.2;1),(0.2,0.2,0.2,0.9))	((0.06,0.07,0.08;1),(0.05,0.07,0.1,0.9))
C_2	A_1	((0.3,0.36,0.48;1),(0.4,0.36,0.4,0.9))	((0.55,0.66,1;1),(0.4,0.62,0.8,0.9))	((0.2,0.2,0.2;1),(0.2,0.2,0.2,0.9))
	A_2	((0.27,0.32,0.43;1),(0.3,0.32,0.4,0.9))	((0.5,0.6,1;1),(0.44,0.6,0.8,0.9))	((0.06,0.07,0.08;1),(0.05,0.07,0.1,0.9))
	A_3	((0.44,0.51,0.74;1),(0.36,0.5,0.6,0.9))	((0.5,0.6,1;1),(0.44,0.6,0.8,0.9))	((0.2,0.2,0.2;1),(0.2,0.2,0.2,0.9))
	A_4	((0.38,0.46,0.7;1),(0.3,0.46,0.6,0.9))	((0.5,0.6,1;1),(0.44,0.6,0.8,0.9))	((0.06,0.07,0.08;1),(0.05,0.07,0.1,0.9))
C_3	A_1	((0.16,0.2,0.3;1),(0.2,0.23,0.26,0.9))	((0.1,0.1,0.1;1),(0.1,0.1,0.1,0.9))	((0.2,0.3,0.4;1),(0.25,0.3,0.35,0.9))
	A_2	((0.46,0.56,0.66;1),(0.51,0.56,0.6,0.9))	((0.4,0.5,0.6;1),(0.45,0.5,0.55,0.9))	((0.6,0.7,0.8;1),(0.65,0.7,0.75,0.9))
	A_3	((0.6,0.7,0.8;1),(0.65,0.7,0.75,0.9))	((0.4,0.5,0.6;1),(0.45,0.5,0.55,0.9))	((0.8,0.9,1;1),(0.85,0.9,0.95,0.9))
	A_4	((0.04,0.05,0.05;1),(0.04,0.05,0.05,0.9))	((0.01,0.02,0.025;1),(0.01,0.02,0.02,0.9))	((0.1,0.1,0.1;1),(0.1,0.1,0.1,0.9))
C_4	A_1	((0.8,0.9,1;1),(0.85,0.9,0.95,0.9))	((0.04,0.05,0.08;1),(0.035,0.05,0.06,0.9))	((0.16,0.16,0.16;1),(0.16,0.16,0.16,0.9))
	A_2	((0.38,0.5,0.6;1),(0.4,0.5,0.55,0.9))	((0.16,0.16,0.16;1),(0.16,0.16,0.16,0.9))	((0.6,0.8,1;1),(0.75,0.8,0.9,0.9))
	A_3	((0.2,0.3,0.5;1),(0.3,0.3,0.4,0.9))	((0.16,0.16,0.16;1),(0.16,0.16,0.16,0.9))	((0.3,0.5,0.6;1),(0.4,0.5,0.58,0.9))
	A_4	((0.18,0.24,0.3;1),(0.2,0.24,0.27,0.9))	((0.04,0.05,0.08;1),(0.035,0.05,0.06,0.9))	((0.3,0.5,0.6;1),(0.4,0.5,0.58,0.9))
C_5	A_1	((0.03,0.03,0.05;1),(0.02,0.03,0.04,0.9))	((0.02,0.02,0.02;1),(0.02,0.02,0.02,0.9))	((0.04,0.05,0.08;1),(0.03,0.05,0.06,0.9))
	A_2	((0.5,0.6,0.7;1),(0.5,0.6,0.6,0.9))	((0.16,0.16,0.16;1),(0.16,0.16,0.16,0.9))	((0.6,0.8,1;1),(0.75,0.8,0.9,0.9))
	A_3	((0.2,0.3,0.5;1),(0.3,0.3,0.4,0.9))	((0.3,0.5,0.6;1),(0.4,0.5,0.58,0.9))	((0.3,0.5,0.6;1),(0.4,0.5,0.58,0.9))
	A_4	((0.03,0.04,0.06;1),(0.03,0.04,0.05,0.9))	((0.02,0.03,0.04;1),(0.03,0.03,0.03,0.9))	((0.04,0.05,0.08;1),(0.03,0.05,0.06,0.9))
C_6	A_I	((0.01,0.02,0.02;1),(0.01,0.02,0.02,0.9))	((0.01,0.01,0.02;1),(0.01,0.01,0.01,0.9))	((0.02,0.02,0.03;1),(0.02,0.02,0.02,0.9))
	A_2	((0.26,0.34,0.43;1),(0.3,0.3,0.4,0.9))	((0.03,0.04,0.06;1),(0.02,0.04,0.05,0.9))	((0.5,0.6,0.7;1),(0.5,0.6,0.6,0.9))
	A_3	((0.5,0.7,0.8;1),(0.6,0.7,0.7,0.9))	((0.5,0.6,0.7;1),(0.5,0.6,0.6,0.9))	((0.7,0.8,1;1),(0.8,0.8,0.9,0.9))
	A_4	((0.01,0.01,0.02;1),(0.01,0.01,0.01,0.9))	((0.01,0.01,0.02;1),(0.01,0.01,0.01,0.9))	((0.01,0.01,0.02;1),(0.01,0.01,0.01,0.9))
C_7	A_1	((0.01,0.01,0.02;1),(0.01,0.01,0.01,0.9))	((0.01,0.01,0.01;1),(0.01,0.01,0.01,0.9))	((0.01,0.01,0.02;1),(0.01,0.01,0.01,0.9))
	A_2	((0.5,0.7,0.8;1),(0.6,0.7,0.7,0.9))	((0.5,0.6,0.7;1),(0.5,0.6,0.6,0.9))	((0.7,0.8,1;1),(0.8,0.8,0.9,0.9))
	A_3	((0.4,0.5,0.6;1),(0.4,0.5,0.6,0.9))	((0.25,0.37,0.5;1),(0.3,0.3,0.4,0.9))	((0.7,0.8,1;1),(0.8,0.8,0.9,0.9))
	A_4	((0.01,0.01,0.02;1),(0.01,0.01,0.01,0.9))	((0.01,0.01,0.01;1),(0.01,0.01,0.01,0.9))	((0.02,0.02,0.03;1),(0.02,0.02,0.02,0.9))
C_8	A_1	((0.02,0.03,0.03;1),(0.02,0.03,0.03,0.9))	((0.02,0.02,0.02;1),(0.02,0.02,0.02,0.9))	((0.02,0.03,0.04;1),(0.03,0.03,0.03,0.9))
	A_2	((0.08,0.09,0.1;1),(0.08,0.09,0.1,0.9))	((0.04,0.05,0.08;1),(0.03,0.05,0.06,0.9))	((0.16, 0.16, 0.16;1),(0.16, 0.16, 0.16,0.9))
	A_3	((0.5,0.6,0.7;1),(0.5,0.6,0.6,0.9))	((0.16, 0.16, 0.16;1),(0.16, 0.16, 0.16,0.9))	((0.6,0.8,1;1),(0.7,0.8,0.9,0.9))
	A_4	((0.02,0.02,0.03;1),(0.03,0.04,0.05,0.9))	((0.02,0.02,0.02;1),(0.02,0.02,0.02,0.9))	((0.02,0.03,0.04;1),(0.03,0.03,0.03,0.9))
C_9	A_1	((0.03,0.04,0.06;1),(0.03,0.03,0.03,0.9))	((0.02,0.02,0.02;1),(0.02,0.02,0.02,0.9))	((0.04,0.05,0.08;1),(0.03,0.05,0.06,0.9))
	A_2	((0.02,0.03,0.03;1),(0.02,0.03,0.03,0.9))	((0.16, 0.16, 0.16;1),(0.16, 0.16, 0.16,0.9))	((0.3,0.5,0.6;1),(0.4,0.5,0.58,0.9))
	A_3	((0.5,0.7,0.8;1),(0.6,0.7,0.8,0.9))	((0.3,0.5,0.6;1),(0.4,0.5,0.58,0.9))	((0.6,0.8,1;1),(0.7,0.8,0.9,0.9))
	A_4	((0.01,0.02,0.02;1),(0.01,0.01,0.02,0.9))	((0.016,0.018,0.02;1),(0.018,0.018,0.02,0.9))	((0.02,0.02,0.02;1),(0.02,0.02,0.02,0.9))
C_{10}	A_1	((0.19, 0.28, 0.38;1),(0.23, 0.28, 0.33,0.9))	((0.03,0.03,0.04;1),(0.03,0.03,0.03,0.9))	((0.5,0.75,1;1),(0.62,0.75,0.87,0.9))

Table 10 (continued)

Criteria	Alternative	BD*	$BD_{\bar{i}}$	$BD_{\bar{r}}$
	A_2	((0.12, 0.13, 0.16;1),(0.12, 0.13, 0.15,0.9))	((0.06,0.08,0.1;1),(0.05,0.08,0.1,0.9))	((0.25,0.25,0.25;1),(0.25,0.25,0.25,0.9))
	A_3	((0.4,0.58,0.75;1),(0.5,0.58,0.66,0.9))	((0.5,0.75,1;1),(0.62,0.75,0.87,0.9))	((0.5,0.75,1;1),(0.62,0.75,0.87,0.9))
	A_4	((0.12, 0.13, 0.16;1),(0.12, 0.13, 0.15,0.9))	((0.06,0.08,0.1;1),(0.05,0.08,0.1,0.9))	((0.25,0.25,0.25;1),(0.25,0.25,0.25,0.9))
C_{11}	A_1	((0.2,0.35,0.47;1),(0.2,0.3,0.4,0.9))	((0.04,0.05,0.08;1),(0.03,0.05,0.06,0.9))	((0.3,0.5,0.6;1),(0.4,0.5,0.58,0.9))
	A_2	((0.4,0.6,0.7;1),(0.5,0.6,0.69,0.9))	((0.3,0.5,0.6;1),(0.4,0.5,0.58,0.9))	((0.06,0.08,0.1;1),(0.05,0.08,0.1,0.9))
	A_3	((0.4,0.6,0.7;1),(0.5,0.6,0.69,0.9))	((0.06,0.08,0.1;1),(0.05,0.08,0.1,0.9))	((0.3,0.5,0.6;1),(0.4,0.5,0.58,0.9))
	A_4	((0.13, 0.2, 0.27;1),(0.16, 0.2, 0.23,0.9))	((0.04,0.05,0.08;1),(0.03,0.05,0.06,0.9))	((0.3,0.5,0.6;1),(0.4,0.5,0.58,0.9))
C_{12}	A_1	((0.01,0.02,0.02;1),(0.02,0.02,0.02,0.9))	((0.01,0.01,0.02;1),(0.01,0.01,0.02,0.9))	((0.02,0.02,0.02;1),(0.02,0.02,0.02,0.9))
	A_2	((0.12, 0.12, 0.13;1),(0.12, 0.12, 0.13,0.9))	((0.04,0.05,0.08;1),(0.03,0.05,0.06,0.9))	((0.16, 0.16, 0.16;1),(0.16, 0.16, 0.16,0.9))
	A_3	((0.5,0.7,0.8;1),(0.6,0.7,0.8,0.9))	((0.3,0.5,0.6;1),(0.4,0.5,0.58,0.9))	((0.6,0.8,1;1),(0.7,0.8,0.9,0.9))
	A_4	((0.02,0.02,0.03;1),(0.02,0.02,0.03,0.9))	((0.01,0.01,0.02;1),(0.01,0.01,0.02,0.9))	((0.02,0.03,0.04;1),(0.03,0.03,0.03,0.9))
C_{13}	A_1	((0.4,0.5,0.6;1),(0.5,0.5,0.6,0.9))	((0.4,0.5,0.6;1),(0.4,0.5,0.5,0.9))	((0.6,0.7,0.8;1),(0.6,0.7,0.7,0.9))
	A_2	((0.7,0.8,0.9;1),(0.7,0.8,0.8,0.9))	((0.6,0.7,0.8;1),(0.6,0.7,0.7,0.9))	((0.8,0.9,1;1),(0.85,0.9,0.9,0.9))
	A_3	((0.2,0.3,0.3;1),(0.2,0.3,0.3,0.9))	((0.4,0.5,0.6;1),(0.4,0.5,0.5,0.9))	((0.1, 0.1, 0.1;1),(0.1, 0.1, 0.1,0.9))
	A_4	((0.26,0.36,0.46;1),(0.3,0.3,0.4,0.9))	((0.2,0.3,0.4;1),(0.25,0.3,0.35,0.9))	((0.4,0.5,0.6;1),(0.4,0.5,0.5,0.9))

Table 11 The distance of each individual opinion from the ideal decisions

Criteria	Alternative		DBD_k^*	DBD_k^-	DBD_r^-
C_1	A_1	E_1	0.3	1.2	0.35
		E_2	0.094	0	1.6
		E_3	0.63	1.5	0
	A_2	E_1	0.11	0.3	0
		E_2	0.11	0.3	0
		E_3	0.23	0	0.35
	A_3	E_1	0.42	0	1.2
		E_2	0.42	0	1.2
		E_3	0.84	1.2	0
	A_4	E_1	0.23	0.35	0
		E_2	0.11	0	0.35
		E_3	0.11	0	0.35
C_2	A_1	E_1	0.42	1.2	0
		E_2	0.42	1.2	0
		E_3	0.84	0	1.2
	A_2	E_1	0.63	1.5	0
		E_2	0.94	0	1.5
		E_3	0.32	1.2	0.35
	A_3	E_1	0.42	0	0
		E_2	0.84	1.2	1.2
		E_3	0.42	0	0
	A_4	E_1	1.5	1.5	0
		E_2	0.5	0	1.5
		E_3	0.5	0	1.5
C_3	A_1	E_1	0.17	0.51	0
		E_2	0.34	0	0.51
		E_3	0.17	0.51	0
	A_2	E_1	0.16	0	0.48
		E_2	0.32	0.48	0
		E_3	0.16	0	0.48
	A_3	E_1	1.9	0.48	0.48
		E_2	0.48	0	0.97
		E_3	0.48	0.97	0
	A_4	E_1	0.07	0	0.19
		E_2	0.04	0.03	0.16
		E_3	0.11	0.19	0
C_4	A_1	E_1	0.18	0.27	0
		E_2	0.09	0	0.27
		E_3	0.09	0	0.27
	A_2	E_1	0.08	0.8	0.8
		E_2	0.8	0	1.6
		E_3	0.8	1.6	0
	A_3	E_1	0.28	0.85	0
		E_2	0.5	0	0.85
		E_3	0.28	0.85	0
	A_4	E_1	0.2	0.2	0.85
		E_2	0.45	0	1.1
		E_3	0.65	1.1	0
C_5	A_1	E_1	0.01	0.02	0.06
		E_2	0.04	0.08	0
		E_3	0.03	0	0.08
	A_2	E_1	0.5	1.6	0

Table 11 (continued)

Criteria	Alternative		DBD_k^*	DBD_k^-	DBD_r^-
		E_2	1.1	0	1.6
		E_3	0.55	1.6	0
	A_3	E_1	0.57	0.85	0.85
		E_2	0.28	0	0
		E_3	0.28	0	0
	A_4	E_1	0.02	0.06	0
		E_2	0.04	0	0.06
		E_3	0.02	0.06	0
C_6	A_1	E_1	0.006	0	0.01
		E_2	0.006	0	0.01
		E_3	0.01	0.01	0
	A_2	E_1	0.75	0	1.4
		E_2	0.68	1.4	0
		E_3	0.08	0.8	0.61
	A_3	E_1	0.2	0	0.61
		E_2	0.2	0	0.61
		E_3	0.4	0.6	0
	A_4	E_1	0.006	0	0.009
		E_2	0.003	0.009	0
		E_3	0.003	0.009	0
C_7	A_1	E_1	0.006	0	0.009
		E_2	0.003	0.009	0
		E_3	0.003	0.009	0
	A_2	E_1	0.2	0	0.6
		E_2	0.2	0	0.6
		E_3	0.4	0.6	0
	A_3	E_1	0.4	0	1.2
		E_2	0.8	1.2	0
		E_3	0.4	0	1.2
	A_4	E_1	0.003	0.009	0.01
		E_2	0.01	0	0.02
		E_3	0.01	0.02	0
C_8	A_1	E_1	0.01	0	0.02
		E_2	0.008	0.02	0
		E_3	0.008	0.02	0
	A_2	E_1	0.18	0.27	0
		E_2	0.09	0	0.2
		E_3	0.09	0	0.2
	A_3	E_1	1.1	0	1.6
		E_2	0.5	1.6	0
		E_3	0.5	1.6	0
	A_4	E_1	0.008	0	0.02
		E_2	0.01	0.02	0
		E_3	0.008	0	0.02
C_9	A_1	E_1	0.02	0.08	0
		E_2	0.05	0	0.08
		E_3	0.02	0.08	0
	A_2	E_1	0.2	0	0.8
		E_2	0.57	0.87	0
		E_3	0.28	0	0.85
	A_3	E_1	0.27	0.81	0
		E_2	0.27	0.81	0

Table 11 (continued)

Criteria	Alternative		DBD_k^*	DBD_k^-	DBD_r^-
		E_3	0.54	0	0.8
	A_4	E_1	0.02	0.01	0.07
		E_2	0.008	0.01	0
		E_3	0.004	0	0.01
C_{10}	A_1	E_1	0.6	0	1.8
		E_2	1.1	1.8	0
		E_3	0.5	0.12	1.6
	A_2	E_1	0.13	0	0.4
		E_2	0.2	0.4	0
		E_3	0.13	0	0.4
	A_3	E_1	0.42	0	0
		E_2	0.42	0	0
		E_3	0.85	1.2	1.2
	A_4	E_1	0.12	0	0.4
		E_2	0.2	0.4	0
		E_3	0.13	0	0.4
C_{11}	A_1	E_1	0.37	1.1	0
		E_2	0.37	1.1	0
		E_3	0.7	0	1.1
	A_2	E_1	0.5	0.8	0
		E_2	0.2	0	0.8
		E_3	0.2	0	0.8
	A_3	E_1	0.2	0.8	0
		E_2	0.2	0.8	0
		E_3	0.5	0	0.8
	A_4	E_1	0.3	0	1.1
		E_2	0.3	0	1.1
		E_3	0.7	1.1	0
C_{12}	A_1	E_1	0.004	0	0.01
		E_2	0.008	0.012	0
		E_3	0.004	0	0.01
	A_2	E_1	0.09	0.27	0
		E_2	0.18	0	0.2
		E_3	0.09	0.27	0
	A_3	E_1	0.27	0.81	0
		E_2	0.27	0.81	0
		E_3	0.54	0	0.81
	A_4	E_1	0.01	0.03	0
		E_2	0.01	0.03	0
		E_3	0.02	0	0.03
C_{13}	A_1	E_1	0.32	0.48	0
		E_2	0.16	0	0.48
		E_3	0.16	0	0.48
	A_2	E_1	0.32	0	0.48
		E_2	0.16	0.48	0
		E_3	0.16	0.48	0
	A_3	E_1	0.5	0.99	0
		E_2	0.49	0	0.99
		E_3	0.05	0.48	0.51
	A_4	E_1	0.16	0	0.48
		E_2	0.32	0.48	0
		E_3	0.16	0	0.48

Table 12 The results of $CCIO_k$, $ADMW_k$, and EW_k

Criteria	Alternative		$CCIO_k$	$ADMW_k$	EW_k
C_1	A_1	E_1	0.83	0.56	0.36
		E_2	0.62	0.46	0.3
		E_3	0.7	0.5	0.32
	A_2	E_1	0.75	0.52	0.35
		E_2	0.75	0.52	0.35
		E_3	0.6	0.45	0.3
	A_3	E_1	0.75	0.52	0.35
		E_2	0.75	0.52	0.35
		E_3	0.6	0.45	0.3
	A_4	E_1	0.6	0.45	0.3
		E_2	0.75	0.52	0.35
		E_3	0.75	0.52	0.35
C_2	A_1	E_1	0.75	0.52	0.3
		E_2	0.75	0.52	0.3
		E_3	0.6	0.45	0.3
	A_2	E_1	0.71	0.5	0.32
		E_2	0.62	0.46	0.3
		E_3	0.83	0.56	0.36
	A_3	E_1	0	0.15	0.18
		E_2	0.75	0.52	0.63
		E_3	0	0.15	0.18
	A_4	E_1	0.6	0.45	0.3
		E_2	0.75	0.52	0.35
		E_3	0.75	0.52	0.35
C_3	A_1	E_1	0.75	0.52	0.35
		E_2	0.6	0.45	0.3
		E_3	0.75	0.52	0.35
	A_2	E_1	0.75	0.52	0.35
		E_2	0.6	0.45	0.3
		E_3	0.75	0.52	0.35
	A_3	E_1	1	0.65	0.4
		E_2	0.6	0.48	0.29
		E_3	0.6	0.48	0.29
	A_4	E_1	0.71	0.5	0.33
		E_2	0.81	0.55	0.36
		E_3	0.62	0.46	0.3
C_4	A_1	E_1	0.6	0.45	0.3
		E_2	0.75	0.52	0.35
		E_3	0.75	0.52	0.35
	A_2	E_1	0.95	0.62	0.39
		E_2	0.66	0.48	0.3
		E_3	0.66	0.48	0.3
	A_2	E_1	0.75	0.52	0.35
		E_2	0.6	0.45	0.3
		E_3	0.75	0.52	0.35
	A_3	E_1	0.84	0.57	0.37
		E_2	0.7	0.5	0.32
		E_3	0.62	0.46	0.3
C_5	A_1	E_1	0.87	0.58	0.37

Table 12 (continued)

Criteria	Alternative		$CCIO_k$	$ADMW_k$	EW_k
		E_2	0.63	0.46	0.3
		E_3	0.69	0.49	0.32
	A_2	E_1	0.75	0.52	0.35
		E_2	0.6	0.45	0.3
		E_3	0.75	0.52	0.35
	A_3	E_1	0.75	0.52	0.63
		E_2	0	0.15	0.18
		E_3	0	0.15	0.18
	A_4	E_1	0.75	0.52	0.35
		E_2	0.6	0.45	0.3
		E_3	0.75	0.52	0.35
C_6	A_1	E_1	0.75	0.52	0.35
		E_2	0.75	0.52	0.35
		E_3	0.6	0.45	0.3
	A_2	E_1	0.65	0.47	0.3
		E_2	0.67	0.48	0.3
		E_3	0.94	0.62	0.39
	A_3	E_1	0.75	0.52	0.35
		E_2	0.75	0.52	0.35
		E_3	0.6	0.45	0.3
	A_2	E_1	0.6	0.45	0.3
		E_2	0.75	0.52	0.35
		E_3	0.75	0.52	0.35
C_7	A_1	E_1	0.6	0.45	0.3
		E_2	0.75	0.52	0.35
		E_3	0.75	0.52	0.35
	A_2	E_1	0.75	0.52	0.35
		E_2	0.75	0.52	0.35
		E_3	0.6	0.45	0.3
	A_3	E_1	0.75	0.52	0.35
		E_2	0.6	0.45	0.3
		E_3	0.75	0.52	0.35
	A_4	E_1	0.89	0.59	0.38
		E_2	0.69	0.49	0.31
		E_3	0.64	0.47	0.3
C_8	A_1	E_1	0.6	0.45	0.3
		E_2	0.75	0.52	0.35
		E_3	0.75	0.52	0.35
	A_2	E_1	0.6	0.45	0.3
		E_2	0.75	0.52	0.35
		E_3	0.75	0.52	0.35
	A_3	E_1	0.6	0.45	0.3
		E_2	0.75	0.52	0.35
		E_3	0.75	0.52	0.35
	A_4	E_1	0.75	0.52	0.35
		E_2	0.6	0.45	0.3
		E_3	0.75	0.52	0.35
C_9	A_1	E_1	0.75	0.52	0.35
		E_2	0.6	0.45	0.3

Table 12 (continued)

Criteria	Alternative		$CCIO_k$	$ADMW_k$	EW_k
		E_3	0.75	0.52	0.35
	A_2	E_1	0.75	0.52	0.35
		E_2	0.6	0.45	0.3
		E_3	0.75	0.52	0.35
	A_3	E_1	0.75	0.52	0.35
		E_2	0.75	0.52	0.35
		E_3	0.6	0.45	0.3
	A_4	E_1	0.75	0.52	0.35
		E_2	0.6	0.45	0.3
		E_3	0.75	0.52	0.35
C_{10}	A_1	E_1	0.73	0.51	0.34
		E_2	0.6	0.45	0.3
		E_3	0.77	0.53	0.35
	A_2	E_1	0.75	0.52	0.35
		E_2	0.6	0.45	0.3
		E_3	0.75	0.52	0.35
	A_3	E_1	0	0.15	0.18
		E_2	0	0.15	0.18
		E_3	0.75	0.52	0.63
	A_4	E_1	0.75	0.52	0.35
		E_2	0.6	0.45	0.3
		E_3	0.75	0.52	0.35
C_{11}	A_1	E_1	0.75	0.52	0.35
		E_2	0.75	0.52	0.35
		E_3	0.6	0.45	0.3
	A_2	E_1	0.6	0.45	0.3
		E_2	0.75	0.52	0.35
		E_3	0.75	0.52	0.35
	A_3	E_1	0.75	0.52	0.35
		E_2	0.75	0.52	0.35
		E_3	0.6	0.45	0.3
	A_4	E_1	0.75	0.52	0.35
		E_2	0.75	0.52	0.35
		E_3	0.6	0.45	0.3
C_{12}	A_1	E_1	0.75	0.52	0.35
		E_2	0.6	0.45	0.3
		E_3	0.75	0.52	0.35
	A_2	E_1	0.75	0.52	0.35
		E_2	0.6	0.45	0.3
		E_3	0.75	0.52	0.35
	A_3	E_1	0.75	0.52	0.35
		E_2	0.75	0.52	0.35
		E_3	0.6	0.45	0.3
	A_4	E_1	0.75	0.52	0.35
		E_2	0.75	0.52	0.35
		E_3	0.6	0.45	0.3
C_{13}	A_1	E_1	0.6	0.45	0.3
		E_2	0.75	0.52	0.35
		E_3	0.75	0.52	0.35

Table 12 (continued)

Criteria	Alternative		$CCIO_k$	$ADMW_k$	EW_k
	A_2	E_1	0.6	0.45	0.3
		E_2	0.75	0.52	0.35
		E_3	0.75	0.52	0.35
	A_3	E_1	0.66	0.48	0.3
		E_2	0.66	0.48	0.3
		E_3	0.95	0.62	0.39
	A_4	E_1	0.75	0.52	0.35
		E_2	0.6	0.45	0.3
		E_3	0.75	0.52	0.35

3.1. First, the average of the values for importance of criteria is computed. Therefore, first of all, the average weight of the criteria is computed by using Eq. 33. The results are displayed in Table 13.

3.2. Equations 34 and 35 are used to compute the relative preference of each value, and the new weights are obtained. The new weights of criteria are displayed in Table 14.

4. Finally, the normalized weighted decision matrix is calculated by employing Eq. 38.
5. After computing the final decision matrix, Eq. 39 is used to compute the summarizing index of each alternative. The results are displayed in Table 15.
6. Equations 42 and 43 are used to calculate the maximum deviation of each alternative from the max reference point. The results are displayed in Table 16.

Table 13 The average of criteria weights

Criterion	Average of the values
C_1	((5.3,6.3,7.3;1),(5.8,6.3,6.8,0.9))
C_2	((7.3,8.3,9.3;1),(7.8,8.3,8.3,0.9))
C_3	((3.3,4.3,5.3;1),(3.8,4.3,4.8,0.9))
C_4	((5.3,6.3,7.3;1),(5.8,6.3,6.8,0.9))
C_5	((3,3.6,4.3;1),(3.3,3.6,4,0.9))
C_6	((0.5,0.55,0.66;1),(0.48,0.55,0.6,0.9))
C_7	((0.75,0.77,0.83;1),(0.74,0.77,0.8,0.9))
C_8	((4,5,6;1),(4.5,5,5.5,0.9))
C_9	((4,5,6;1),(4.5,5,5.5,0.9))
C_{10}	((5.3,6.3,7.3;1),(5.8,6.3,6.8,0.9))
C_{11}	((6.6,7.6,8.6;1),(7.1,7.6,8.1,0.9))
C_{12}	((5,5.6,6.3;1),(5.3,5.6,6,0.9))
C_{13}	((3.4,4.1,4.8;1),(3.7,4.1,4.46,0.9))

Table 14 The new weights of criteria

Criterion	Expert		
	E_1	E_2	E_3
C_1	((0.6,0.8,1;1),(0.75,0.83,0.91,0.9))	((4,4.6,5.3;1),(4.3,4.6,5,0.9))	((4,4.6,5.3;1),(4.3,4.6,5,0.9))
C_2	((1,1.1,1.3;1),(1,1.1,1.2,0.9))	((5.3,6,6.6;1),(5.6,6,6.3,0.9))	((5.3,6,6.6;1),(5.6,6,6.3,0.9))
C_3	((2.6,3.3,4;1),(3,3.3,3.6,0.9))	((2.6,3.3,4;1),(3,3.3,3.6,0.9))	((0.3,0.5,0.6;1),(0.4,0.5,0.58,0.9))
C_4	((1.3,1.6,2;1),(1.5,1.6,1.8,0.9))	((1.3,1.6,2;1),(1.5,1.6,1.8,0.9))	(6.6,7.5,8.3;1),(7,7.5,7.9,0.9))
C_5	((0.27,0.27,0.27;1),(0.27,0.27,0.27,0.9))	((4.6,5.4,6.2;1),(5,5.4,5.8,0.9))	((0.8,1.3,1.7;1),(1,1.3,1.5,0.9))
C_6	((0.08,0.1,0.16;1),(0.07,0.1,0.13,0.9))	((0.08,0.1,0.16;1),(0.07,0.1,0.13,0.9))	((0.8,0.8,0.8;1),(0.8,0.8,0.8,0.9))
C_7	((0.04,0.05,0.08;1),(0.03,0.05,0.06,0.9))	((0.6,0.6,0.6;1),(0.6,0.6,0.6,0.9))	((0.6,0.6,0.6;1),(0.6,0.6,0.6,0.9))
C_8	((2,2.5,3;1),(2.25,2.5,2.75,0.9))	((0.5,0.75,1;1),(0.62,0.75,0.87,0.9))	((4.5,5.2,6;1),(4.8,5.2,5.6,0.9))
C_9	((2,2.5,3;1),(2.25,2.5,2.75,0.9))	((4.5,5.2,6;1),(4.8,5.2,5.6,0.9))	((0.5,0.75,1;1),(0.62,0.75,0.87,0.9))
C_{10}	((4,4.6,5.3;1),(4.3,4.6,5,0.9))	((4,4.6,5.3;1),(4.3,4.6,5,0.9))	((0.6,0.8,1;1),(0.75,0.83,0.9,0.9))
C_{11}	(6.6,7.5,8.3;1),(7,7.5,7.9,0.9))	((2,2.3,2.6;1),(2.1,2.3,2.5,0.9))	((2,2.3,2.6;1),(2.1,2.3,2.5,0.9))
C_{12}	((0.2,0.2,0.2;1),(0.2,0.2,0.2,0.9))	((5.6,6.3,7;1),(6,6.3,6.7,0.9))	((3.5,4,4.6;1),(3.8,4,4.3,0.9))
C_{13}	((0.04,0.05,0.08;1),(0.03,0.05,0.06,0.9))	((2.3,2.9,3.4;1),(2.6,2.9,3.2,0.9))	((4.5,5.2,6;1),(4.9,5.2,5.66,0.9))

7. Full multiplicative form is applied by using Eqs. 44 and 45. The results are displayed in Table 17.
8. Obviously, the alternatives were ranked by three different methods of ratio system, reference point, and full multiplicative form. The dominance theory developed by Brauers and Zavadskas [38] is applied to aggregate these three methods into a final ranking, and the final ranking is presented in Table 18.

Discussion: This method, in addition to its ability in modeling type 2 fuzzy uncertainty, provides the decision-maker with a comprehensive understanding of the problem as different methods are applied to rank the alternatives and the results are finally aggregated. Tables 16, 17, and 18 present the results from different perspectives whereas Table 19 presents the final results. In the studied case, A_3 was selected as the best alternative and A_4 was determined as the most unsuitable alternative. Moreover, in order to validate the results, the method of Ghorabaee [42] is used to solve the case study. The results verify the method. Moreover, the proposed method has advantages like addressing decision-makers' weights and applying the concept of relative preference relation and the dominance theory in the decision-making process. To better illustrate the advantages of the introduced method, a comparative analysis of the proposed model and the existing similar methods [39–41, 43] was carried out and the results are given in Table 19.

Table 15 The results of summarizing index of each alternative

Alternative	SI	Ranking
A_1	((−0.35,0.8,1.9;1),(0.15,0.86,1.5,0.9))	3
A_2	((1.8,3.36,5;1),(2.4,3.3,4.2,0.9))	2
A_3	((1.7,4.2,6.7;1),(2.9,4.2,5.6,0.9))	1
A_4	((−1.05,0.05,0.9;1),(−0.6,0.04,0.7,0.9))	4

5 Conclusion

Evaluating and selecting the right suppliers is a critical issue in supply chain management. Over the years, many scholars have approached this decision-making problem from different perspectives. However, the importance of this decision-making process has increased over the years as the necessity for concepts such as green supply chain management arose. Therefore, it is necessary to address green criteria in this process. On the other hand, uncertainty is another aspect of this process that requires careful consideration. In this paper, a new decision-making process for selecting the green supplier was introduced. The proposed model used type 2 fuzzy sets to model uncertainty. This approach gave

Table 16 The results of maximum deviation from the max reference point

Alternative	Max distance	Ranking
A_1	24.52	3
A_2	24.41	2
A_3	24.3	1
A_4	24.53	4

Table 17 The results of the full multiplicative form

Alternative	Maximum deviation	Ranking
A_1	((2.9,4,5.1;1),(3,4.6,5,0.9))	2
A_2	((2.7,3.1,3.8;1),(2.9,3.2,3.6,0.9))	3
A_3	((3.7,4.2,6;1),(4,4.5,5.6,0.9))	1
A_4	((1,1.3,1.4;1),(1.1,1.2,1.35,0.9))	4

Table 18 Final ranking

Alternative	*SI*	Maximum deviation	Full multiplicative form	Final ranking	Existing type 2 MCDM method [42]
A_1	3	3	2	3	3
A_2	2	2	3	2	2
A_3	1	1	1	1	1
A_4	4	4	4	4	4

Table 19 Comparative analysis of the proposed model and the existing similar methods

Comparison parameter	Results and explanations
Expressing uncertainty	Applying IT2FSs in this method provides more flexibility in expressing and calculating the existing uncertainty of this problem. Therefore, this method, unlike most of the existing methods, uses a better tool to address uncertainty.
Addressing decision-maker importance	In a group decision-making process, since each DM comes from a different background or department, each DM has better opinions in one field. Moreover, the gathered judgments could be used to assess the weight of each DM. This method, unlike most of the existing studies, offered an approach that addressed both perspectives in the decision-making process.
Addressing the importance of criteria	In order to address the importance of criteria, the presented method used the fuzziness of given data to investigate the importance of each decision-making criterion. Given the advantages of fuzzy relative preference, it was used to compute the weight of each criterion.
Ranking and evaluation approach	The developed method used the advantages of the ratio system, reference point approach, and full multiplicative form under IT2F uncertainty in addition to the dominance theory to achieve a final ranking of alternatives. Therefore, it can be concluded that the results are more convincing than most of the existing methods in the literature.

the model more flexibility in modeling uncertainty. Moreover, to model the importance of each decision-maker, a process is developed under type 2 fuzzy uncertainty to compute the weight of each decision-maker based on the expertise and the gathered judgments. The weight of each criterion is also evaluated and given a membership degree based on the concept of relative preference relation. Eventually, this last aggregation decision-making model applies the concepts of multi-objective optimization by ratio analysis plus the full multiplicative form under type 2 fuzzy uncertainty. To display the applicability of the model, the first two case studies at the manufacturing system level are taken from the literature and are solved. Then, in order to display the step-by-step application of the developed method, a case study from a construction complex is adopted and solved. An existing type 2 fuzzy MCDM is used to verify the method. The case study shows how the model provides the process with more flexibility and more power in expressing uncertainty and gives the decision-maker a better understanding of the problem. For further research, an interesting issue could be applying other fuzzy sets such as intuitionistic fuzzy set, hesitant fuzzy set, neutrosophic set, etc. in green supplier selection and comparing the results to find out which set performs better under different circumstances.

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