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An Integrated Best-Worst and Interval Type-2 Fuzzy TOPSIS Methodology for Green Supplier Selection

Melih Yucesan [1], Suleyman Mete [2], Faruk Serin [3], Erkan Celik [2,*] and Muhammet Gul [2]

1 Munzur University, Faculty of Engineering, Department of Mechanical Engineering, 62000 Tunceli, Turkey; melihyucesan@munzur.edu.tr
2 Munzur University, Faculty of Engineering, Department of Industrial Engineering, 62000 Tunceli, Turkey; suleyman489@gmail.com (S.M.); muhammetgul@munzur.edu.tr (M.G.)
3 Munzur University, Faculty of Engineering, Department of Computer Engineering, 62000 Tunceli, Turkey; fserin@munzur.edu.tr
* Correspondence: erkancelik@munzur.edu.tr

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Abstract: Supplier selection is one of the most important multi-criteria decision-making (MCDM) problems for decision-makers in the competitive market. Today's organizations are seeking new ways to reduce the negative effects they have on the environment and to achieve a greener system. Currently, the concept of green supplier selection has gained great importance for its ability to incorporate environmental or green criteria into classical supplier selection practices. Therefore, in this study, a multi-phase MCDM model based on the best-worst method (BWM) and the interval type-2 fuzzy technique for order preference by similarity to ideal solution (IT2F TOPSIS) is proposed. A case study in a plastic injection molding facility in Turkey was carried out to show the applicability of the proposed integrated methodology. The paper offers insights into decision-making, methodology, and managerial implications. Results of the case study are examined and suggestions for future research are provided.

Keywords: MCDM; BWM; interval type-2 fuzzy sets; TOPSIS; green supplier selection; plastic injection molding

1. Introduction

Supply chain management (SCM) includes the creation of information and material flows, production scheduling, and the planning of distribution systems [1]. Adding value to supply chain management is crucial for today's businesses in order to improve organizational performance and provide a competitive advantage. This is necessary because competition no longer exists solely between institutions, but also in the area of SCM. SCM focuses not only on material resources but also on values such as knowledge. Information has become the most important source of SCM [2,3]. SCM builds an integrated approach by analyzing manufacturers, warehouses, production, and suppliers. Thus, enterprises produce and distribute products at the appropriate time and in appropriate quantities. SCM implements an entire system approach while managing materials and services. Decision-makers attach importance to the management of internal operations in order to increase the productivity of the enterprises. SCM requires the integration of internal and external activities in enterprises. With increasing global competition, the quality and price gaps between products are closing every day. Therefore, supplier selection is one of the most important multi-criteria decision-making (MCDM) problems for enterprises [4,5]. Choosing an appropriate supplier is one of the most important processes under the responsibility of the purchasing department. On the other hand, practices aimed at protecting the environment are gaining importance both in the private and public sectors. As environmental awareness increases, an environmentally-friendly approach also becomes an inevitable element in supply chain management applications. Currently, final consumers also consider environmentally sensitive products in their procurement processes.

The aim of green supply chain management (GSCM) is to minimize pollution and other factors affecting the environment. It helps suppliers recognize the significance of resolving environmental issues. In addition, GSCM helps enterprises achieve a balance between environmental and economic performance, thereby reducing the impact of their products and fostering an environmental image and environmentally friendly services. GSCM strives to increase the use of green products and encourage businesses to increase the market share of such products. In addition to traditional goals, GSCM also aims to establish and develop an environmentally friendly supply chain system. Therefore, environmental criteria should be used together with traditional criteria in selecting green suppliers. However, most of the green supplier selection studies in the literature are based on environmental criteria. The main criteria for the development of suppliers are green information transfer, investment and resource transfer, as well as management and organization practices. In the portfolio-based analysis, pollution prevention and avoidance of pollution are considered as major differences in the selection of green suppliers [6]. Some studies have also used criteria such as GSCM capabilities, strategic level of the procurement department, environmental commitment level, or degree of green supplier evaluation and cooperation. In the green purchasing process, regulation, customer pressure, social responsibility, and commercial benefits are among the most commonly used criteria [7].

This paper proposes an integrated best-worst and IT2F TOPSIS methodology for green supplier selection in the plastic injection molding industry. The methodology introduced for the selection of green suppliers was carried out under three phases. First, the selection criteria following the green concept were determined through a literature review and interviews with decision-makers. In the second phase, criteria weights were determined using best-worst method (BWM). Finally, to prioritize suppliers with respect to the weighted criteria, an IT2F TOPSIS method was utilized. This study is considered as the first attempt at integrating BWM and IT2F TOPSIS to obtain supplier selection knowledge. Since BWM is easier and more efficient than analytic hierarchy process (AHP) for pairwise comparisons, it was used in weighting the selection criteria. The use of the TOPSIS method extended with interval type-2 fuzzy sets (IT2FSs) allowed more uncertainty and ambiguity to be reflected in the decision-making process as well as including the concept of similarity to ideal solution.

The proposed approach was applied to the plastic injection molding industry to select a green supplier. The plastic injection products have been broadly used in high-tech commodities and different household necessities. In this regard, pipe and fitting production technology and raw material usage are intensive. In addition, the competition conditions of this production area are very fierce. Hence, choosing the right supplier plays a vital role in the success of the enterprises. There are few methods and studies covered in the literature for this area. Therefore, this paper proposes a multi-phase MCDM model to select which supplier is well-suited to the pipe manufacturing enterprise. The case design approach was carried out by incorporating data provided by a district -based small- and medium-sized enterprise. Specifically, the main contributions of this paper are summarized as follows: (i) An integrated approach based on best-worst and IT2F TOPSIS methodology was proposed. (ii) A case study was carried out for the plastic injection molding industry. This case study highlighted the implications of the methodology for the industry and the methodology followed can be easily adapted to another sector in this regard. (iii) IT2FSs were combined with BWM for the first time in the literature. As a result, uncertainty in the decision-making process can be clearly reflected as compared to type-1 fuzzy set theory [8–12].

The rest of the paper is presented as follows: A literature review regarding supply chain management and supplier selection is presented in the next section. The best-worst method is described and analyzed in Section 3. In Section 4, a case study is presented to help understand the proposed method, carried out for green supplier selection in an injection molding facility in Turkey. Finally, conclusions and directions for future research are presented in Section 5.

2. Literature Review

The literature review section is divided into two subsections. First, literature regarding green supplier selection is analyzed, then literature related to the best-worst method is addressed. Many studies related to green supplier selection and evaluation were found in the literature. Supplier selection can be defined as one of the most important phases in supply management function and purchasing [13]. A variety of MCDM methods have recently been used by researchers to deal with green supplier selection problems. In the literature, different supplier selection criteria were used such as quality, delivery, and cost for evaluating their suppliers [14]. A number of environmental factors were considered to select green suppliers [15]. Criteria such as pollution production [16,17], recycling utilization level of waste material [18], level of clean energy utilization [19], noise level [20], and level of environmental protection input [21] were considered by researchers. On the other hand, individual and hybrid methods were proposed for determining supplier selection in the literature [22]. A grey analytical network process (ANP)-based model to determine green supplier development programs to develop the performance of suppliers was introduced by [23]. The model was tested on real-world examples to show model effectiveness [24]. They proposed a preference ranking organization method for enrichment evaluation (PROMETHEE) method based on a hybrid multiple criteria decision-making approach to develop green supplier performance. A fuzzy axiomatic design approach was introduced to choose the best green supplier for a plastic manufacturing company in Singapore [16]. The requirements of the manufacturer and the supplier were evaluated using a proposed methodology with a multi-objective optimization model and fuzzy nature. Hashemi et al. [25] considered environmental and economic criteria and introduced a model based on improved grey relational analysis (GRA) and ANP for comprehensive green supplier selection. Uygun and Dede [26] proposed an integrated fuzzy MCDM method, which was based on fuzzy decision-making trial and evaluation laboratory (DEMATEL), fuzzy ANP, and fuzzy TOPSIS, to evaluate and select green suppliers by considering green purchasing, green design, green logistics, and reverse logistics. Yazdani et al. [19] designed a green supplier selection model. The proposed model focused on the interrelationships between the requirements of the customer with a DEMATEL method when constructing a relationship structure. Moreover, quality function deployment was used to determine the degree of relationship for the criteria of supplier selection pairs. Recently, three popular multi-criteria supplier selection applications, namely, TOPSIS, GRA, and Vise Kriterijumska Optimizacija I Kompromisno Resenje (VIKOR), were compared to each other by [13] under fuzzy environment. The method was applied to an actual company from the agri-food industry for green supplier evaluation and selection. Yu et al. [15] proposed a model based on the carbon footprint, including environmental and economic attributes to select a green supplier with a dynamic environment. Moreover, a literature review related to green supplier selection and estimation methods can be found in [27,28].

On the other hand, the best-worst method was first introduced by [29] to solve MCDM problems. In this method, many alternatives are considered according to different criteria in order to choose the best alternative. According to this method, two of the criteria, which are the best or most important criteria and the worst or least important criteria, are determined by the decision-maker. The method is a novel approach and has been applied to different research areas due to BWM's flexibility and simplicity for solving problems. Rezaei et al. [30] applied BWM to supplier segmentation to find the relative weight of the criteria. Then, the method was applied to different research areas, such as supplier selection [31,32], multi-criteria decision-making [17,33], evaluating freight bundling configurations [34], and assessment of other factors affecting sustainability in SCM [35]. Guo and Zhao [36] proposed the BWM technique with MCDM under fuzzy environment. Van de Kaa et al. [37] used the BWM technique and expert opinions for calculating the relative importance of factors to evaluate and rank technologies. The method was applied to the technology battle for biomass conversion in the Netherlands. Omrani et al. [38] proposed an integrated approach including Taguchi-neural network BWM and TOPSIS under fuzzy environment. The proposed integrated approach was applied to a case study to find the optimal combination of different power plants.

In light of the above, this paper aims to fill the gap in the literature for an integrated best-worst and IT2F TOPSIS methodology for green supplier selection in the plastic injection molding industry in Turkey.

3. Materials and Methods

3.1. The Evaluation Criteria for Green Supplier Selection

Within the context of green supplier selection, the recent review of [27] identified Environmental Management Systems (EMS) as the most popular environmental criteria due to its flexibility. Nielsen et al. [39] reviewed 57 related papers and, like Govindan et al. [27], found EMS the most important and comprehensive environmental criteria amongst over 90 identified measures. Using these reviews and the identified criteria, a combination of conventional and green supplier selection criteria is used in our study for the purpose of supplier assessment. The criteria used in relevant literatures are listed in Table 1.

Table 1. The used criteria in literature for supplier selection.

Study/Criteria	C1-Environmental.	C2-Social	C3-Quality	C4-Service	C5-Risk	C6-Cost/Price	C7-Capability	C8-Business structure
Kahraman et al. [40]			X	X		X		
Büyüközkan and Çiftçi [41]			X	X		X		
Chiou et al. [42]				X	X	X		
Demirtas and Ustun [43]			X	X		X	X	
Lee [44]			X	X	X	X	X	
Lin et al. [45]			X	X		X		
Liou and Chuang [46]			X	X		X		
Liu et al. [47]			X	X	X	X	X	
Liu et al. [48]			X	X	X	X		
Luthra et al. [49]			X	X		X	X	
Malmir et al. [50]			X	X	X	X	X	
Razmi et al. [51]			X	X	X	X	X	X
Da Silva et al. [52]			X	X		X	X	
Vinodh et al. [53]			X	X	X	X		
Wadhwa and Ravindran [54]			X		X	X		X
Wang et al. [55]			X			X		
Attari et al. [56]			X			X		X
Haq and Kannan [57]			X			X		X
Prahinsk and Benton [58]			X			X		
Chiou et al. [42]	X	X	X			X		
Freeman and chen [59]	X	X	X		X	X		
Hsu et al. [60]	X	X	X		X			
Kuo et al. [61]	X	X	X			X		X

3.2. Best-Worst Method

The best-worst method (BWM) was introduced for the choice phase [29]. The BWM is characterized by some salient features such as (i) it provides a very structured pairwise comparison, which results in highly consistent and reliable results; (ii) it uses only two vectors instead of a full pairwise comparison matrix. This implies less data collection effort, taking less time from the analyst and the decision-maker. Interestingly, as these two vectors are more structured than a full matrix, less data here leads to more reliability; (iii) the method uses only integer values, which makes it more practically understandable compared to methods utilizing fractions [31].

Step 1. Determine a set of decision criteria. In this step, we consider the criteria $(c_1, c_2, \ldots, c_n)$ that should be used to arrive at a decision.

Step 2. Determine the best (e.g., most desirable, most important) and the worst (e.g., least desirable, least important) criteria. In this step, the decision-maker identifies the best and the worst criteria in general. No comparison is made at this stage.

Step 3. Determine the preference of the best criterion over all the other criteria using a number between 1 and 9. The resulting Best-to-Others vector would be:

$$A_B = (a_{B1}, a_{B2}, \ldots, a_{Bn}),$$

where a_{Bj} indicates the preference of the best criterion B over criterion j. It is clear that $a_{BB} = 1$.

Step 4. Determine the preference of all the criteria over the worst criterion using a number between 1 and 9. The resulting Others-to-Worst vector would be

$$A_B = (a_{1W}, a_{2W}, \ldots, a_{nW})^T$$

where a_{jW} indicates the preference of the criterion j over the worst criterion W. It is clear that $a_{WW} = 1$.

Step 5. Find the optimal weights $(w_1^*,\ w_2^*,\ \ldots, w_n^*)$.

The optimal weight for the criteria is the one where, for each pair of w_B/w_j and w_j/w_w we have $w_B/w_j = a_{jw}$. To satisfy these for all j, we should find a solution where the maximum absolute differences $\left|\frac{w_B}{w_j} - a_{Bj}\right|$ and $\left|\frac{w_j}{w_W} - a_{jW}\right|$ for all j is minimized. Considering the non-negativity and sum condition for the weights, the following problem is resulted:

$$\min_j\max\left\{\left|\frac{w_B}{w_j} - a_{Bj}\right|, \left|\frac{w_j}{w_W} - a_{jW}\right|\right\}$$
s.t
$$\sum w_j = 1$$
$$w_j \geq 0 \text{ for all } j$$

Problem can be transferred to the following problem: ξ

$$\min \xi$$
$$\left|\frac{w_B}{w_j} - a_{Bj}\right| \leq \xi \text{ for all } j$$
$$\left|\frac{w_j}{w_W} - a_{jW}\right| \leq \xi \text{ for all } j$$
$$\sum w_j = 1$$
$$w_j \geq 0, \text{ for all } j$$

Solving problem, the optimal weights $(w_1^*,\ w_2^*,\ \ldots, w_n^*)$ and ξ^* are calculated. After that consistency ratio is calculated with consistency index (Table 2). It becomes clear that, the bigger the ξ^*, the higher the consistency ratio, and the less reliable the comparisons become.

Table 2. Consistency Index.

a_{BW}	1	2	3	4	5	6	7	8	9
consistency index	0.00	0.44	1.00	1.63	2.30	3.00	3.73	4.47	5.23

3.3. IT2F TOPSIS

TOPSIS approach aims to choose alternatives that simultaneously have the shortest distance from the positive ideal solution and the farthest distance from the negative-ideal solution [62–64]. IT2F TOPSIS, [65] Pythagorean fuzzy TOPSIS [66]. Ak and Gul [67] are developed as different versions of TOPSIS based on fuzzy sets. TOPSIS based on IT2FSs reflects uncertainty, vagueness, and ambiguity using advantages of IT2FSs [65,68–72] better than ordinary fuzzy TOPSIS. The proposed TOPSIS based on IT2FSs can be applied via a series of steps:

Step 1: Assume that there is a set S of alternatives, where $S = \{s_1, s_2, \ldots, s_n\}$, and assume that there is a set C of criteria, $C = \{c_1, c_2, \ldots, c_m\}$ and there are K decision-makers $D = \{D_1, D_2, \ldots, D_K\}$ Each decision-maker is a participant in our questionnaire and s/he has her/his own perception value regarding the performance of supplier with respect to each criterion. The aggregate performance value of supplier with respect to each criterion can be calculated using Equation (1):

$$E_c = (\tilde{\tilde{c}}_{ij}^{p})_{m\times n} = \begin{matrix} & s_1 & s_2 & \cdots & s_n \\ c_1 & \tilde{\tilde{c}}_{11}^{p} & \tilde{\tilde{c}}_{12}^{p} & \cdots & \tilde{\tilde{c}}_{1n}^{p} \\ c_2 & \tilde{\tilde{c}}_{21}^{p} & \tilde{\tilde{c}}_{22}^{p} & \cdots & \tilde{\tilde{c}}_{2n}^{p} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ c_m & \tilde{\tilde{c}}_{m1}^{p} & \tilde{\tilde{c}}_{m2}^{p} & \cdots & \tilde{\tilde{c}}_{mn}^{p} \end{matrix}, \quad (1)$$

where $\tilde{\tilde{c}}_{ij} = \left(\frac{\tilde{\tilde{c}}_{ij}^{1} \oplus \tilde{\tilde{c}}_{ij}^{2} \oplus \cdots \oplus \tilde{\tilde{c}}_{ij}^{k}}{k}\right)$, $\tilde{\tilde{s}}_{ij}$ is an IT2FS $1 \leq i \leq m, 1 \leq j \leq n, 1 \leq c \leq k$ and k denotes the number of expert,

$$\tilde{\tilde{c}}_{ij} = \left(\left(a_{i1}^{U}, a_{i2}^{U}, a_{i3}^{U}, a_{i4}^{U}; H_1\left(\tilde{A}_i^{U}\right), H_2\left(\tilde{A}_i^{U}\right)\right), \left(a_{i1}^{L}, a_{i2}^{L}, a_{i3}^{L}, a_{i4}^{L}; H_1\left(\tilde{A}_i^{L}\right), H_2\left(\tilde{A}_i^{L}\right)\right)\right)$$

Step 2: Obtain the weighting matrix W_s of the criteria using the best-worst method,

$$W_s = (w_i^s)_{1\times m} = \begin{matrix} c_1 & c_2 & \cdots & c_m \\ [w_1^s, & w_2^s, & \cdots, & w_m^s] \end{matrix} \quad (2)$$

Step 3: Calculate the weighted decision matrix by multiplying the importance weights of criteria and the values in the decision matrix. The weighted decision matrix $\tilde{\tilde{V}}$ for each criterion is defined as follows:

$$\tilde{\tilde{v}}_{ij} = \tilde{\tilde{c}}_{ij} \times w_i, \quad (3)$$

where $\tilde{\tilde{v}}_{ij}$ denotes the weighted trapezoidal interval type-2 fuzzy numbers.

Step 4: Calculate the ranking value $Rank\left(\tilde{\tilde{v}}_{ij}\right)$ of IT2FSs. The ranking weighted decision matrix E_w is constructed.

Step 5: Determine the positive ideal solution $x^* = \left(v_1^*, v_2^*, \ldots, v_m^*\right)$ and the negative-ideal solution $x^- = \left(v_1^-, v_2^-, \ldots, v_m^-\right)$ where

$$v_i^* = \begin{cases} \max\limits_{i\leq j\leq n}\left\{Rank\left(\tilde{\tilde{v}}_{ij}\right)\right\}, & if\ f_i \in B \\ \min\limits_{i\leq j\leq n}\left\{Rank\left(\tilde{\tilde{v}}_{ij}\right)\right\}, & if\ f_i \in C \end{cases}, \quad (4)$$

$$v_i^- = \begin{cases} \min\limits_{i\leq j\leq n}\left\{Rank\left(\tilde{\tilde{v}}_{ij}\right)\right\}, & if\ f_i \in B \\ \max\limits_{i\leq j\leq n}\left\{Rank\left(\tilde{\tilde{v}}_{ij}\right)\right\}, & if\ f_i \in C \end{cases}. \quad (5)$$

Then, positive $d^*(x_j)$ and negative $d^-(x_j)$ ideal solutions are determined for green supplier as follows:

$$d^*(x_j) = \sqrt{\sum_{i\in I}\left(Rank(\tilde{\tilde{v}}_{ij}) - v_i^*\right)^2} \quad (6)$$

$$d^-(x_j) = \sqrt{\sum_{i\in I}\left(Rank(\tilde{\tilde{v}}_{ij}) - v_i^-\right)^2} \quad (7)$$

The ranking value $Rank(\tilde{\tilde{A}}_i)$ of the trapezoidal IT2FS $\tilde{\tilde{A}}_i$ is defined as follows:

$$\begin{aligned} Rank(\tilde{\tilde{v}}_i) &= M_1(\tilde{v}_i^U) + M_1(\tilde{v}_i^L) + M_2(\tilde{v}_i^U) + M_2(\tilde{v}_i^L) + M_3(\tilde{v}_i^U) + M_3(\tilde{v}_i^L) \\ &-\tfrac{1}{4}\left(S_1(\tilde{v}_i^U) + S_1(\tilde{v}_i^L) + S_2(\tilde{v}_i^U) + S_2(\tilde{v}_i^L) + S_3(\tilde{v}_i^U) + S_3(\tilde{v}_i^L) + S_4(\tilde{v}_i^U) + S_4(\tilde{v}_i^L)\right) \\ &+H_1(\tilde{v}_i^U) + H_1(\tilde{v}_i^L) + H_2(\tilde{v}_i^U) + H_2(\tilde{v}_i^L) \end{aligned}$$

where $M_p(\tilde{\tilde{v}}_i^j)$ denotes the average of the elements v_{ip}^j and $v_{i(p+1)}^j$, denotes the standard deviation of the elements v_{ip}^j and $v_{i(p+1)}^j$, $M_p(\tilde{\tilde{v}}_i^j) = \left(v_{ip}^j + v_{i(p+1)}^j\right)/2, 1 \le p \le 3$, denotes the standard deviation of the v_{iq}^j and $v_{i(q+1)}^j$, $S_q(\tilde{v}_i^j) = \sqrt{\frac{1}{2}\sum_{k=q}^{q+1}\left(v_{ik}^j - \frac{1}{2}\sum_{k=q}^{q+1} v_{ik}^j\right)^2}, 1 \le q \le 3$, $S_4(\tilde{v}_i^j)$ denotes the standard deviation of the elements $v_{i1}^j, v_{i2}^j, v_{i3}^j, v_{i4}^j$, $S_4(\tilde{v}_i^j) = \sqrt{\frac{1}{4}\sum_{k=1}^{4}\left(v_{ik}^j - \frac{1}{4}\sum_{k=1}^{4} v_{ik}^j\right)^2}$ $H_p(\tilde{v}_i^j)$ denotes the membership value of the element $v_{i(p+1)}^j$ in the trapezoidal membership function $\tilde{v}_i^j, 1 \le p \le 3, j \in \{U, L\}$, and $1 \le i \le n$.

Step 6: Then the closeness coefficient $CC(x_j)$ is calculated.

$$CC(x_j) = \frac{d^-(x_j)}{d^*(x_j) + d^-(x_j)} \tag{8}$$

Step 7: We can rank alternatives in decreasing order. The larger the value of $CC(x_j)$, the higher the preference of the green supplier.

4. Case Study

Injection molding is one of the most common methods in plastic parts production. With this method, complex geometric products can be produced easily. Molding machine, raw plastic material and mold of the product to be produced are required for the production by injection molding. The raw material used in this production method is directly related to the quality of the product. In this respect, supplier choice plays an important role in the success of the operator. The injection molding method consists of four main stages as demonstrated in Figure 1. These stages are drying, blending and dosing, injection molding and regrinding, respectively. In the drying stage, the material (plastic beads and the reusable scrap) is fed into the dryer, to remove or reduce moisture to an acceptable level. In the second stage, material is further mixed with the additives. In the third stage, the injection molding process takes place, wherein the plastic mixture is melted and converted into a solid part. In the final stage, runner, gates, and any other unwanted plastic which is attached to the part, is removed and ground into appropriate granules [73]. In this study, we carried out the case study in an injection molding facility in Turkey.

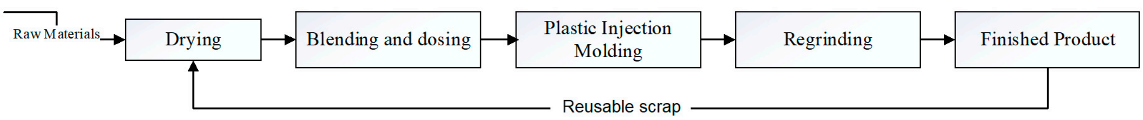

Figure 1. Stages of an injection molding process.

4.1. The Calculation Process of the Proposed Model

In this paper, we applied the BWM to obtain importance weights of the green criteria for supplier selection in injection molding. This method is based on comparison matrices as in AHP [29]. It requires less pairwise comparison data compared to AHP. In applying the proposed model, five experts evaluated the predefined green criteria. Expert 1 works as the manager of the facility and has 10 years of experience. Expert 2 is a five year experienced chemical engineer. He is also responsible for quality control of the facility. Expert 3 serves as a machine technician. The responsibility of the Expert 3 is to determine the raw material ratios and connect the molds to the machines. Expert 4 is a machine technician, too and has the same duties as Expert 3. Expert 5 works as a purchasing manager in the facility. He works in coordination with the company manager for the determination of appropriate suppliers. The first process in the proposed model is application of BWM to obtain weights of green supplier selection criteria. As an example, to the calculation of the main criteria with respect to Expert 1, the following formulae is presented:

$$\begin{aligned}
&\min \xi \\
&st. \\
&\left|\frac{w_6}{w_1}-4\right| \leq \xi,\ \left|\frac{w_6}{w_2}-7\right| \leq \xi,\ \left|\frac{w_6}{w_3}-1\right| \leq \xi,\ \left|\frac{w_6}{w_4}-2\right| \leq \xi, \\
&\left|\frac{w_6}{w_5}-3\right| \leq \xi,\ \left|\frac{w_6}{w_7}-7\right| \leq \xi,\ \left|\frac{w_6}{w_8}-7\right| \leq \xi, \\
&\left|\frac{w_1}{w_8}-4\right| \leq \xi,\ \left|\frac{w_2}{w_8}-1\right| \leq \xi,\ \left|\frac{w_3}{w_8}-7\right| \leq \xi,\ \left|\frac{w_4}{w_8}-6\right| \leq \xi, \\
&\left|\frac{w_5}{w_8}-5\right| \leq \xi,\ \xi, \left|\frac{w_7}{w_8}-1\right| \leq \xi, \\
&w_1+w_2+w_3+w_4+w_5+w_6+w_7+w_8=1 \\
&w_1, w_2, w_3, w_4, w_5, w_6, w_7, w_8 \geq 0
\end{aligned}$$

Then, the BWM procedure is applied for each sub-criterion according to the five experts. Results of all calculations are presented in Table 3. The importance weights of green criteria are then used in evaluating suppliers by IT2F TOPSIS procedure. On the other hand, the calculated consistency ratios with respect to the experts are presented in Table 4. w1, w2, w3, w4, w5, w6, w7 and w8 are found as 0.100, 0.035, 0.205, 0.170, 0.135, 0.285, 0.035 and 0.035, respectively. We calculated the consistency ratios using ξ and the corresponding consistency index in Table 2 by Equation (9).

$$Consistency\ ratio = \frac{\xi}{Consistency\ index} \tag{9}$$

Table 3. The local and global weights.

Criteria	Expert 1	Expert 2	Expert 3	Expert 4	Expert 5	Local Weights	Global Weights	Ranking Order
C1: Environmental	0.1	0.159	0.086	0.197	0.2204		0.152	
C11: Environment management systems	0.073	0.091	0.09	0.107	0.0683	0.086	0.013	21
C12: Green design and purchasing	0.05	0.024	0.025	0.078	0.0249	0.041	0.006	35
C13: Green manufacturing	0.327	0.249	0.233	0.293	0.2306	0.267	0.041	12
C14: Green management	0.129	0.067	0.145	0.029	0.1467	0.103	0.016	18
C15: Green packing and labeling	0.123	0.225	0.209	0.136	0.1808	0.175	0.027	15
C16: Waste management and pollution prevention	0.224	0.201	0.233	0.164	0.0932	0.183	0.028	14
C17: Environmental competencies	0.073	0.143	0.065	0.193	0.2555	0.146	0.022	16
C2: Social	0.035	0.102	0.05	0.043	0.049		0.056	
C21: Occupational Health and Safety Systems	0.376	0.29	0.346	0.243	0.3302	0.317	0.018	17
C22: The interests and rights of employees	0.084	0.226	0.231	0.277	0.1967	0.203	0.011	25
C23: The rights of stakeholders	0.142	0.097	0.077	0.097	0.1157	0.106	0.006	36
C24: Information Disclosure	0.084	0.097	0.115	0.141	0.0796	0.103	0.006	37
C25: Labor relation records	0.057	0.032	0.038	0.034	0.0405	0.041	0.002	40
C26: training aids	0.257	0.258	0.192	0.209	0.2373	0.231	0.013	23
C3: Quality	0.205	0.196	0.191	0.14	0.1959		0.186	
C31: Low defect rate	0.455	0.388	0.419	0.383	0.5367	0.436	0.081	2
C32: Inspections methods and plans	0.35	0.184	0.15	0.213	0.2317	0.226	0.042	9
C33: Adherence to quality tools	0.123	0.326	0.349	0.319	0.1618	0.256	0.047	6
C34: Quality systems	0.072	0.102	0.083	0.085	0.0698	0.082	0.015	19
C4: Service	0.17	0.085	0.136	0.091	0.1224		0.121	
C41: Quick Responsiveness	0.1	0.1	0.1	0.125	0.1111	0.107	0.013	22
C42: Flexibility and Agility	0.416	0.3	0.254	0.399	0.3143	0.337	0.041	11
C43: After sales service	0.484	0.6	0.646	0.476	0.5746	0.556	0.067	3
C5: Risk	0.135	0.177	0.214	0.221	0.0816		0.166	
C51: Supply Constraint	0.225	0.247	0.281	0.269	0.1722	0.239	0.04	13
C52: Buyer Supplier Constraint	0.035	0.035	0.03	0.03	0.0353	0.033	0.005	38
C53: Bad Performance History and Reputation of supplier	0.051	0.07	0.047	0.047	0.0662	0.056	0.009	29
C54: Variation in price	0.333	0.351	0.311	0.311	0.3226	0.326	0.054	5
C55: Supplier's production limitations	0.045	0.044	0.043	0.043	0.0397	0.043	0.007	31
C56: amount of past business	0.051	0.039	0.037	0.037	0.0413	0.041	0.007	32
C57: Uncompleted orders	0.26	0.212	0.251	0.253	0.3226	0.26	0.043	7

Table 3. *Cont.*

Criteria	Expert 1	Expert 2	Expert 3	Expert 4	Expert 5	Local Weights	Global Weights	Ranking Order
C6: Cost/Price	0.285	0.215	0.237	0.244	0.2449		0.245	
C61: Transportation Cost	0.196	0.176	0.123	0.178	0.1958	0.174	0.043	8
C62: Purchase Cost	0.251	0.242	0.205	0.232	0.2511	0.236	0.058	4
C63: Quantity discount	0.055	0.053	0.036	0.054	0.0553	0.051	0.012	24
C64: Payment terms	0.141	0.123	0.086	0.124	0.3572	0.166	0.041	10
C65: Profit on Product	0.357	0.407	0.55	0.412	0.1405	0.373	0.092	1
C7: Capability of supplier	0.035	0.047	0.063	0.024	0.0612		0.046	
C71: Financial capability	0.128	0.203	0.141	0.125	0.0912	0.138	0.006	33
C72: Change order capability	0.182	0.17	0.287	0.178	0.1985	0.203	0.009	28
C73: Technical capability	0.278	0.286	0.12	0.27	0.2192	0.234	0.011	26
C74: Understanding of technology	0.128	0.107	0.141	0.151	0.156	0.137	0.006	34
C75: Engineering/technical support resources	0.027	0.028	0.031	0.099	0.0207	0.041	0.002	42
C76: Technical know how	0.101	0.078	0.11	0.026	0.1365	0.09	0.004	39
C77: Distribution capability	0.155	0.129	0.171	0.151	0.1779	0.157	0.007	30
C8: Business structure of supplier	0.035	0.019	0.028	0.043	0.0245		0.03	
C81: Knowledge of market	0.047	0.05124	0.0558	0.0387	0.0465	0.048	0.001	44
C82: Information systems	0.052	0.05855	0.0632	0.0453	0.041	0.052	0.002	43
C83: Communication system	0.041	0.04005	0.0632	0.0292	0.0525	0.045	0.001	45
C84: Desire for business	0.369	0.36957	0.3664	0.2661	0.3686	0.348	0.01	27
C85: Management and organizations	0.41	0.40962	0.4104	0.5661	0.4095	0.441	0.013	20
C86: Market share	0.082	0.07097	0.0409	0.0546	0.0819	0.066	0.002	41

Table 4. The consistency for all experts.

Criteria	Expert 1	Expert 2	Expert 3	Expert 4	Expert 5
Main criteria	0.3070	0.4721	0.2406	0.2406	0.1912
Sub criteria of C1	0.1786	0.2275	0.3120	0.2406	0.2406
Sub criteria of C2	0.1786	0.2237	0.2237	0.3072	0.3072
Sub criteria of C3	0.0995	0.1181	0.0870	0.2174	0.1832
Sub criteria of C4	0.0706	0.0000	0.1529	0.1181	0.1716
Sub criteria of C5	0.1030	0.1912	0.2710	0.1912	0.2521
Sub criteria of C6	0.1529	0.1832	0.2092	0.1832	0.1529
Sub criteria of C7	0.2406	0.2528	0.2666	0.2406	0.3049
Sub criteria of C8	0.1912	0.2348	0.1009	0.2155	0.1912

For example, the consistency ratio for main criteria with respect to Expert 1 is calculated as $\xi/3.73 = 0.307$ which implies a very good consistency.

The second process is concerned with IT2F TOPSIS application for suppliers. The suppliers are named as Supplier 1, Supplier 2 and Supplier 3. Supplier 1 is a local company. Compared to the other two companies, its production volume and transportation network is limited. Supplier 2 has a strong sales figure and its transportation network throughout the country is wide. This company makes production according to national and international quality standards. Supplier 3 is a global company. Technological levels are higher than the two other companies. Its number of defective products is relatively low, and its production volume is high. On the other hand, raw material prices are higher than the other two firms.

In this second process, the aggregated IT2F evaluation matrix for green supplier evaluation is obtained and it is shown in Table 5. Then, the weighted evaluation matrix is calculated multiplying the importance weights of green criteria and the aggregated IT2F evaluation matrix. The weighted evaluation matrix is presented in Table 6. Here, the importance weights of green criteria which are obtained from BWM are used as inputs of IT2F TOPSIS. Then, the ranking values for each green criterion with respect to three suppliers are calculated. The results are presented in Table 7.

Table 5. The aggregated evaluation matrix.

Criteria	Supplier 1	Supplier 2	Supplier 3
C1			
C11	((0.05;0.2;0.2;0.4;1;1),(0.13;0.2;0.2;0.3;0.9;0.9))	((0.3;0.5;0.5;0.7;1;1),(0.4;0.5;0.5;0.6;0.9;0.9))	((0.5;0.7;0.7;0.85;1;1),(0.6;0.7;0.7;0.78;0.9;0.9))
C12	((0;0.1;0.1;0.3;1;1),(0.05;0.1;0.1;0.2;0.9;0.9))	((0.3;0.5;0.5;0.7;1;1),(0.4;0.5;0.5;0.6;0.9;0.9))	((0.3;0.5;0.5;0.7;1;1),(0.4;0.5;0.5;0.6;0.9;0.9))
C13	((0.05;0.2;0.2;0.4;1;1),(0.13;0.2;0.2;0.3;0.9;0.9))	((0.3;0.5;0.5;0.7;1;1),(0.4;0.5;0.5;0.6;0.9;0.9))	((0.4;0.6;0.6;0.75;1;1),(0.5;0.6;0.6;0.68;0.9;0.9))
C14	((0;0.1;0.1;0.3;1;1),(0.05;0.1;0.1;0.2;0.9;0.9))	((0.1;0.3;0.3;0.5;1;1),(0.2;0.3;0.3;0.4;0.9;0.9))	((0.1;0.3;0.3;0.5;1;1),(0.2;0.3;0.3;0.4;0.9;0.9))
C15	((0.05;0.2;0.2;0.4;1;1),(0.13;0.2;0.2;0.3;0.9;0.9))	((0.15;0.3;0.3;0.5;1;1),(0.23;0.3;0.3;0.4;0.9;0.9))	((0.15;0.3;0.3;0.5;1;1),(0.23;0.3;0.3;0.4;0.9;0.9))
C16	((0.2;0.4;0.4;0.6;1;1),(0.3;0.4;0.4;0.5;0.9;0.9))	((0.5;0.7;0.7;0.9;1;1),(0.6;0.7;0.7;0.8;0.9;0.9))	((0.6;0.8;0.8;0.95;1;1),(0.7;0.8;0.8;0.88;0.9;0.9))
C17	((0.1;0.3;0.3;0.5;1;1),(0.2;0.3;0.3;0.4;0.9;0.9))	((0.2;0.4;0.4;0.6;1;1),(0.3;0.4;0.4;0.5;0.9;0.9))	((0.3;0.5;0.5;0.7;1;1),(0.4;0.5;0.5;0.6;0.9;0.9))
C2	((0;0;0;0;0;0),(0;0;0;0;0;0))	((0;0;0;0;0;0),(0;0;0;0;0;0))	((0;0;0;0;0;0),(0;0;0;0;0;0))
C21	((0.3;0.5;0.5;0.7;1;1),(0.4;0.5;0.5;0.6;0.9;0.9))	((0.5;0.7;0.7;0.9;1;1),(0.6;0.7;0.7;0.8;0.9;0.9))	((0.9;1;1;1;1;1),(0.95;1;1;1;0.9;0.9))
C22	((0.05;0.2;0.2;0.4;1;1),(0.13;0.2;0.2;0.3;0.9;0.9))	((0.1;0.3;0.3;0.5;1;1),(0.2;0.3;0.3;0.4;0.9;0.9))	((0.2;0.4;0.4;0.6;1;1),(0.3;0.4;0.4;0.5;0.9;0.9))
C23	((0.7;0.85;0.85;0.95;1;1),(0.78;0.85;0.85;0.9;0.9;0.9))	((0.5;0.7;0.7;0.85;1;1),(0.6;0.7;0.7;0.78;0.9;0.9))	((0.5;0.7;0.7;0.9;1;1),(0.6;0.7;0.7;0.8;0.9;0.9))
C24	((0.05;0.2;0.2;0.4;1;1),(0.13;0.2;0.2;0.3;0.9;0.9))	((0;0.05;0.05;0.2;1;1),(0.03;0.05;0.05;0.13;0.9;0.9))	((0;0.05;0.05;0.2;1;1),(0.03;0.05;0.05;0.13;0.9;0.9))
C25	((0.15;0.3;0.3;0.5;1;1),(0.23;0.3;0.3;0.4;0.9;0.9))	((0.05;0.2;0.2;0.4;1;1),(0.13;0.2;0.2;0.3;0.9;0.9))	((0.05;0.2;0.2;0.4;1;1),(0.13;0.2;0.2;0.3;0.9;0.9))
C26	((0.15;0.3;0.3;0.5;1;1),(0.23;0.3;0.3;0.4;0.9;0.9))	((0.9;1;1;1;1;1),(0.95;1;1;1;0.9;0.9))	((0.8;0.95;0.95;1;1;1),(0.88;0.95;0.95;0.98;0.9;0.9))
C3	((0;0;0;0;0;0),(0;0;0;0;0;0))	((0;0;0;0;0;0),(0;0;0;0;0;0))	((0;0;0;0;0;0),(0;0;0;0;0;0))
C31	((0.2;0.4;0.4;0.6;1;1),(0.3;0.4;0.4;0.5;0.9;0.9))	((0.4;0.6;0.6;0.8;1;1),(0.5;0.6;0.6;0.7;0.9;0.9))	((0.7;0.85;0.85;0.95;1;1),(0.78;0.85;0.85;0.9;0.9;0.9))
C33	((0.1;0.3;0.3;0.5;1;1),(0.2;0.3;0.3;0.4;0.9;0.9))	((0.4;0.6;0.6;0.8;1;1),(0.5;0.6;0.6;0.7;0.9;0.9))	((0.7;0.85;0.85;0.95;1;1),(0.78;0.85;0.85;0.9;0.9;0.9))
C34	((0.3;0.5;0.5;0.7;1;1),(0.4;0.5;0.5;0.6;0.9;0.9))	((0.5;0.7;0.7;0.9;1;1),(0.6;0.7;0.7;0.8;0.9;0.9))	((0.6;0.8;0.8;0.95;1;1),(0.7;0.8;0.8;0.88;0.9;0.9))
C35	((0.2;0.4;0.4;0.6;1;1),(0.3;0.4;0.4;0.5;0.9;0.9))	((0.7;0.85;0.85;0.95;1;1),(0.78;0.85;0.85;0.9;0.9;0.9))	((0.7;0.85;0.85;0.95;1;1),(0.78;0.85;0.85;0.9;0.9;0.9))
C4	((0;0;0;0;0;0),(0;0;0;0;0;0))	((0;0;0;0;0;0),(0;0;0;0;0;0))	((0;0;0;0;0;0),(0;0;0;0;0;0))
C41	((0.4;0.6;0.6;0.8;1;1),(0.5;0.6;0.6;0.7;0.9;0.9))	((0.8;0.95;0.95;1;1;1),(0.88;0.95;0.95;0.98;0.9;0.9))	((0.7;0.9;0.9;1;1;1),(0.8;0.9;0.9;0.95;0.9;0.9))
C42	((0.3;0.5;0.5;0.7;1;1),(0.4;0.5;0.5;0.6;0.9;0.9))	((0.5;0.7;0.7;0.9;1;1),(0.6;0.7;0.7;0.8;0.9;0.9))	((0.6;0.8;0.8;0.95;1;1),(0.7;0.8;0.8;0.88;0.9;0.9))
C44	((0.3;0.5;0.5;0.7;1;1),(0.4;0.5;0.5;0.6;0.9;0.9))	((0.2;0.4;0.4;0.6;1;1),(0.3;0.4;0.4;0.5;0.9;0.9))	((0.5;0.7;0.7;0.9;1;1),(0.6;0.7;0.7;0.8;0.9;0.9))
C5	((0;0;0;0;0;0),(0;0;0;0;0;0))	((0;0;0;0;0;0),(0;0;0;0;0;0))	((0;0;0;0;0;0),(0;0;0;0;0;0))
C51	((0.4;0.6;0.6;0.8;1;1),(0.5;0.6;0.6;0.7;0.9;0.9))	((0.6;0.8;0.8;0.95;1;1),(0.7;0.8;0.8;0.88;0.9;0.9))	((0.25;0.4;0.4;0.6;1;1),(0.33;0.4;0.4;0.5;0.9;0.9))
C52	((0.2;0.4;0.4;0.6;1;1),(0.3;0.4;0.4;0.5;0.9;0.9))	((0;0.05;0.05;0.2;1;1),(0.03;0.05;0.05;0.13;0.9;0.9))	((0.15;0.3;0.3;0.5;1;1),(0.23;0.3;0.3;0.4;0.9;0.9))
C54	((0.3;0.5;0.5;0.7;1;1),(0.4;0.5;0.5;0.6;0.9;0.9))	((0.05;0.2;0.2;0.4;1;1),(0.13;0.2;0.2;0.3;0.9;0.9))	((0;0.05;0.05;0.2;1;1),(0.03;0.05;0.05;0.13;0.9;0.9))
C56	((0.3;0.5;0.5;0.7;1;1),(0.4;0.5;0.5;0.6;0.9;0.9))	((0.15;0.3;0.3;0.5;1;1),(0.23;0.3;0.3;0.4;0.9;0.9))	((0.05;0.2;0.2;0.4;1;1),(0.13;0.2;0.2;0.3;0.9;0.9))
C57	((0.2;0.4;0.4;0.6;1;1),(0.3;0.4;0.4;0.5;0.9;0.9))	((0.05;0.15;0.15;0.3;1;1),(0.1;0.15;0.15;0.23;0.9;0.9))	((0.15;0.3;0.3;0.5;1;1),(0.23;0.3;0.3;0.4;0.9;0.9))
C58	((0.4;0.6;0.6;0.8;1;1),(0.5;0.6;0.6;0.7;0.9;0.9))	((0.8;0.95;0.95;1;1;1),(0.88;0.95;0.95;0.98;0.9;0.9))	((0.8;0.95;0.95;1;1;1),(0.88;0.95;0.95;0.98;0.9;0.9))
C59	((0.2;0.4;0.4;0.6;1;1),(0.3;0.4;0.4;0.5;0.9;0.9))	((0;0.05;0.05;0.2;1;1),(0.03;0.05;0.05;0.13;0.9;0.9))	((0;0.05;0.05;0.2;1;1),(0.03;0.05;0.05;0.13;0.9;0.9))
C6	((0;0;0;0;0;0),(0;0;0;0;0;0))	((0;0;0;0;0;0),(0;0;0;0;0;0))	((0;0;0;0;0;0),(0;0;0;0;0;0))
C61	((0.05;0.2;0.2;0.4;1;1),(0.13;0.2;0.2;0.3;0.9;0.9))	((0.15;0.3;0.3;0.5;1;1),(0.23;0.3;0.3;0.4;0.9;0.9))	((0.2;0.4;0.4;0.6;1;1),(0.3;0.4;0.4;0.5;0.9;0.9))

Table 5. *Cont.*

Criteria	Supplier 1	Supplier 2	Supplier 3
C62	((0.3;0.5;0.5;0.7;1;1),(0.4;0.5;0.5;0.6;0.9;0.9))	((0.5;0.7;0.7;0.85;1;1),(0.6;0.7;0.7;0.78;0.9;0.9))	((0.6;0.8;0.8;0.95;1;1),(0.7;0.8;0.8;0.88;0.9;0.9))
C63	((0.15;0.3;0.3;0.5;1;1),(0.23;0.3;0.3;0.4;0.9;0.9))	((0.2;0.4;0.4;0.6;1;1),(0.3;0.4;0.4;0.5;0.9;0.9))	((0.3;0.5;0.5;0.7;1;1),(0.4;0.5;0.5;0.6;0.9;0.9))
C64	((0.6;0.8;0.8;0.95;1;1),(0.7;0.8;0.8;0.88;0.9;0.9))	((0.4;0.6;0.6;0.8;1;1),(0.5;0.6;0.6;0.7;0.9;0.9))	((0.2;0.4;0.4;0.6;1;1),(0.3;0.4;0.4;0.5;0.9;0.9))
C65	((0.4;0.6;0.6;0.8;1;1),(0.5;0.6;0.6;0.7;0.9;0.9))	((0.1;0.3;0.3;0.5;1;1),(0.2;0.3;0.3;0.4;0.9;0.9))	((0.2;0.4;0.4;0.6;1;1),(0.3;0.4;0.4;0.5;0.9;0.9))
C7	((0;0;0;0;0;0),(0;0;0;0;0;0))	((0;0;0;0;0;0),(0;0;0;0;0;0))	((0;0;0;0;0;0),(0;0;0;0;0;0))
C71	((0.2;0.4;0.4;0.6;1;1),(0.3;0.4;0.4;0.5;0.9;0.9))	((0.4;0.6;0.6;0.8;1;1),(0.5;0.6;0.6;0.7;0.9;0.9))	((0.5;0.7;0.7;0.9;1;1),(0.6;0.7;0.7;0.8;0.9;0.9))
C72	((0.5;0.7;0.7;0.9;1;1),(0.6;0.7;0.7;0.8;0.9;0.9))	((0.4;0.6;0.6;0.8;1;1),(0.5;0.6;0.6;0.7;0.9;0.9))	((0.3;0.5;0.5;0.7;1;1),(0.4;0.5;0.5;0.6;0.9;0.9))
C73	((0.1;0.3;0.3;0.5;1;1),(0.2;0.3;0.3;0.4;0.9;0.9))	((0.4;0.6;0.6;0.8;1;1),(0.5;0.6;0.6;0.7;0.9;0.9))	((0.7;0.85;0.85;0.95;1;1),(0.78;0.85;0.85;0.9;0.9;0.9))
C74	((0.2;0.4;0.4;0.6;1;1),(0.3;0.4;0.4;0.5;0.9;0.9))	((0.5;0.7;0.7;0.9;1;1),(0.6;0.7;0.7;0.8;0.9;0.9))	((0.6;0.8;0.8;0.95;1;1),(0.7;0.8;0.8;0.88;0.9;0.9))
C75	((0.2;0.4;0.4;0.6;1;1),(0.3;0.4;0.4;0.5;0.9;0.9))	((0.7;0.85;0.85;0.95;1;1),(0.78;0.85;0.85;0.9;0.9;0.9))	((0.7;0.9;0.9;1;1;1),(0.8;0.9;0.9;0.95;0.9;0.9))
C76	((0.2;0.4;0.4;0.6;1;1),(0.3;0.4;0.4;0.5;0.9;0.9))	((0.9;1;1;1;1;1),(0.95;1;1;1;0.9;0.9))	((0.8;0.95;0.95;1;1;1),(0.88;0.95;0.95;0.98;0.9;0.9))
C77	((0.2;0.4;0.4;0.6;1;1),(0.3;0.4;0.4;0.5;0.9;0.9))	((0.5;0.7;0.7;0.9;1;1),(0.6;0.7;0.7;0.8;0.9;0.9))	((0.4;0.6;0.6;0.8;1;1),(0.5;0.6;0.6;0.7;0.9;0.9))
C8	((0;0;0;0;0;0),(0;0;0;0;0;0))	((0;0;0;0;0;0),(0;0;0;0;0;0))	((0;0;0;0;0;0),(0;0;0;0;0;0))
C81	((0.6;0.75;0.75;0.85;1;1),(0.68;0.75;0.75;0.8;0.9;0.9))	((0.6;0.8;0.8;0.95;1;1),(0.7;0.8;0.8;0.88;0.9;0.9))	((0.6;0.8;0.8;0.95;1;1),(0.7;0.8;0.8;0.88;0.9;0.9))
C82	((0;0.05;0.05;0.2;1;1),(0.03;0.05;0.05;0.13;0.9;0.9))	((0;0.1;0.1;0.3;1;1),(0.05;0.1;0.1;0.2;0.9;0.9))	((0.05;0.2;0.2;0.4;1;1),(0.13;0.2;0.2;0.3;0.9;0.9))
C83	((0.2;0.4;0.4;0.6;1;1),(0.3;0.4;0.4;0.5;0.9;0.9))	((0.1;0.3;0.3;0.5;1;1),(0.2;0.3;0.3;0.4;0.9;0.9))	((0.2;0.4;0.4;0.6;1;1),(0.3;0.4;0.4;0.5;0.9;0.9))
C84	((0.7;0.85;0.85;0.95;1;1),(0.78;0.85;0.85;0.9;0.9;0.9))	((0.4;0.6;0.6;0.8;1;1),(0.5;0.6;0.6;0.7;0.9;0.9))	((0.2;0.4;0.4;0.6;1;1),(0.3;0.4;0.4;0.5;0.9;0.9))
C85	((0.05;0.2;0.2;0.4;1;1),(0.13;0.2;0.2;0.3;0.9;0.9))	((0.2;0.4;0.4;0.6;1;1),(0.3;0.4;0.4;0.5;0.9;0.9))	((0.3;0.5;0.5;0.7;1;1),(0.4;0.5;0.5;0.6;0.9;0.9))
C86	((0.4;0.6;0.6;0.8;1;1),(0.5;0.6;0.6;0.7;0.9;0.9))	((0.2;0.4;0.4;0.6;1;1),(0.3;0.4;0.4;0.5;0.9;0.9))	((0.2;0.4;0.4;0.6;1;1),(0.3;0.4;0.4;0.5;0.9;0.9))

Table 6. The weighted evaluation matrix.

Criteria	Supplier 1	Supplier 2	Supplier 3
C1			
C11	((0;0;0;0.01;1;1),(0;0;0;0;0.9;0.9))	((0;0.01;0.01;0.01;1;1),(0.01;0.01;0.01;0.01;0.9;0.9))	((0.01;0.01;0.01;0.01;1;1),(0.01;0.01;0.01;0.01;0.9;0.9))
C12	((0;0;0;0;1;1),(0;0;0;0;0.9;0.9))	((0;0;0;0;1;1),(0;0;0;0;0.9;0.9))	((0;0;0;0;1;1),(0;0;0;0;0.9;0.9))
C13	((0;0.01;0.01;0.02;1;1),(0.01;0.01;0.01;0.01;0.9;0.9))	((0.01;0.02;0.02;0.03;1;1),(0.02;0.02;0.02;0.02;0.9;0.9))	((0.02;0.02;0.02;0.03;1;1),(0.02;0.02;0.02;0.03;0.9;0.9))
C14	((0;0;0;0;1;1),(0;0;0;0;0.9;0.9))	((0;0;0;0.01;1;1),(0;0;0;0.01;0.9;0.9))	((0;0;0;0.01;1;1),(0;0;0;0.01;0.9;0.9))
C15	((0;0.01;0.01;0.01;1;1),(0;0.01;0.01;0.01;0.9;0.9))	((0;0.01;0.01;0.01;1;1),(0.01;0.01;0.01;0.01;0.9;0.9))	((0;0.01;0.01;0.01;1;1),(0.01;0.01;0.01;0.01;0.9;0.9))
C16	((0.01;0.01;0.01;0.02;1;1),(0.01;0.01;0.01;0.01;0.9;0.9))	((0.01;0.02;0.02;0.03;1;1),(0.02;0.02;0.02;0.02;0.9;0.9))	((0.02;0.02;0.02;0.03;1;1),(0.02;0.02;0.02;0.02;0.9;0.9))
C17	((0;0.01;0.01;0.01;1;1),(0;0.01;0.01;0.01;0.9;0.9))	((0;0.01;0.01;0.01;1;1),(0.01;0.01;0.01;0.01;0.9;0.9))	((0.01;0.01;0.01;0.02;1;1),(0.01;0.01;0.01;0.01;0.9;0.9))
C2			
C21	((0.01;0.01;0.01;0.01;1;1),(0.01;0.01;0.01;0.01;0.9;0.9))	((0.01;0.01;0.01;0.02;1;1),(0.01;0.01;0.01;0.01;0.9;0.9))	((0.02;0.02;0.02;0.02;1;1),(0.02;0.02;0.02;0.02;0.9;0.9))
C22	((0;0;0;0;1;1),(0;0;0;0;0.9;0.9))	((0;0;0;0.01;1;1),(0;0;0;0;0.9;0.9))	((0;0;0;0.01;1;1),(0;0;0;0.01;0.9;0.9))
C23	((0;0.01;0.01;0.01;1;1),(0;0.01;0.01;0.01;0.9;0.9))	((0;0;0;0.01;1;1),(0;0;0;0;0.9;0.9))	((0;0;0;0.01;1;1),(0;0;0;0;0.9;0.9))
C24	((0;0;0;0;1;1),(0;0;0;0;0.9;0.9))	((0;0;0;0;1;1),(0;0;0;0;0.9;0.9))	((0;0;0;0;1;1),(0;0;0;0;0.9;0.9))
C25	((0;0;0;0;1;1),(0;0;0;0;0.9;0.9))	((0;0;0;0;1;1),(0;0;0;0;0.9;0.9))	((0;0;0;0;1;1),(0;0;0;0;0.9;0.9))
C26	((0;0;0;0.01;1;1),(0;0;0;0.01;0.9;0.9))	((0.01;0.01;0.01;0.01;1;1),(0.01;0.01;0.01;0.01;0.9;0.9))	((0.01;0.01;0.01;0.01;1;1),(0.01;0.01;0.01;0.01;0.9;0.9))
C3			
C31	((0.02;0.03;0.03;0.05;1;1),(0.02;0.03;0.03;0.04;0.9;0.9))	((0.03;0.05;0.05;0.06;1;1),(0.04;0.05;0.05;0.06;0.9;0.9))	((0.06;0.07;0.07;0.08;1;1),(0.06;0.07;0.07;0.07;0.9;0.9))
C33	((0;0.01;0.01;0.02;1;1),(0.01;0.01;0.01;0.02;0.9;0.9))	((0.02;0.03;0.03;0.03;1;1),(0.02;0.03;0.03;0.03;0.9;0.9))	((0.03;0.04;0.04;0.04;1;1),(0.03;0.04;0.04;0.04;0.9;0.9))
C34	((0.01;0.02;0.02;0.03;1;1),(0.02;0.02;0.02;0.03;0.9;0.9))	((0.02;0.03;0.03;0.04;1;1),(0.03;0.03;0.03;0.04;0.9;0.9))	((0.03;0.04;0.04;0.05;1;1),(0.03;0.04;0.04;0.04;0.9;0.9))
C35	((0;0.01;0.01;0.01;1;1),(0;0.01;0.01;0.01;0.9;0.9))	((0.01;0.01;0.01;0.01;1;1),(0.01;0.01;0.01;0.01;0.9;0.9))	((0.01;0.01;0.01;0.01;1;1),(0.01;0.01;0.01;0.01;0.9;0.9))
C4			
C41	((0.01;0.01;0.01;0.01;1;1),(0.01;0.01;0.01;0.01;0.9;0.9))	((0.01;0.01;0.01;0.01;1;1),(0.01;0.01;0.01;0.01;0.9;0.9))	((0.01;0.01;0.01;0.01;1;1),(0.01;0.01;0.01;0.01;0.9;0.9))
C42	((0.01;0.02;0.02;0.03;1;1),(0.02;0.02;0.02;0.02;0.9;0.9))	((0.02;0.03;0.03;0.04;1;1),(0.02;0.03;0.03;0.03;0.9;0.9))	((0.02;0.03;0.03;0.04;1;1),(0.03;0.03;0.03;0.04;0.9;0.9))
C44	((0.02;0.03;0.03;0.05;1;1),(0.03;0.03;0.03;0.04;0.9;0.9))	((0.01;0.03;0.03;0.04;1;1),(0.02;0.03;0.03;0.03;0.9;0.9))	((0.03;0.05;0.05;0.06;1;1),(0.04;0.05;0.05;0.05;0.9;0.9))
C5			
C51	((0.02;0.02;0.02;0.03;1;1),(0.02;0.02;0.02;0.03;0.9;0.9))	((0.02;0.03;0.03;0.04;1;1),(0.03;0.03;0.03;0.03;0.9;0.9))	((0.01;0.02;0.02;0.02;1;1),(0.01;0.02;0.02;0.02;0.9;0.9))
C52	((0;0;0;0;1;1),(0;0;0;0;0.9;0.9))	((0;0;0;0;1;1),(0;0;0;0;0.9;0.9))	((0;0;0;0;1;1),(0;0;0;0;0.9;0.9))
C54	((0;0;0;0.01;1;1),(0;0;0;0.01;0.9;0.9))	((0;0;0;0;1;1),(0;0;0;0;0.9;0.9))	((0;0;0;0;1;1),(0;0;0;0;0.9;0.9))
C56	((0.02;0.03;0.03;0.04;1;1),(0.02;0.03;0.03;0.03;0.9;0.9))	((0.01;0.02;0.02;0.03;1;1),(0.01;0.02;0.02;0.02;0.9;0.9))	((0;0.01;0.01;0.02;1;1),(0.01;0.01;0.01;0.02;0.9;0.9))
C57	((0;0;0;0;1;1),(0;0;0;0;0.9;0.9))	((0;0;0;0;1;1),(0;0;0;0;0.9;0.9))	((0;0;0;0;1;1),(0;0;0;0;0.9;0.9))
C58	((0;0;0;0.01;1;1),(0;0;0;0;0.9;0.9))	((0.01;0.01;0.01;0.01;1;1),(0.01;0.01;0.01;0.01;0.9;0.9))	((0.01;0.01;0.01;0.01;1;1),(0.01;0.01;0.01;0.01;0.9;0.9))
C59	((0.01;0.02;0.02;0.03;1;1),(0.01;0.02;0.02;0.02;0.9;0.9))	((0;0;0;0.01;1;1),(0;0;0;0.01;0.9;0.9))	((0;0;0;0.01;1;1),(0;0;0;0.01;0.9;0.9))
C6			
C61	((0;0.01;0.01;0.02;1;1),(0.01;0.01;0.01;0.01;0.9;0.9))	((0.01;0.01;0.01;0.02;1;1),(0.01;0.01;0.01;0.02;0.9;0.9))	((0.01;0.02;0.02;0.03;1;1),(0.01;0.02;0.02;0.02;0.9;0.9))
C62	((0.02;0.03;0.03;0.04;1;1),(0.02;0.03;0.03;0.03;0.9;0.9))	((0.03;0.04;0.04;0.05;1;1),(0.03;0.04;0.04;0.04;0.9;0.9))	((0.03;0.05;0.05;0.05;1;1),(0.04;0.05;0.05;0.05;0.9;0.9))
C63	((0;0;0;0.01;1;1),(0;0;0;0;0.9;0.9))	((0;0;0;0.01;1;1),(0;0;0;0.01;0.9;0.9))	((0;0.01;0.01;0.01;1;1),(0;0.01;0.01;0.01;0.9;0.9))

Table 6. *Cont.*

Criteria	Supplier 1	Supplier 2	Supplier 3
C64	((0.02;0.03;0.03;0.04;1;1),(0.03;0.03;0.03;0.04;0.9;0.9))	((0.02;0.02;0.02;0.03;1;1),(0.02;0.02;0.02;0.03;0.9;0.9))	((0.01;0.02;0.02;0.02;1;1),(0.01;0.02;0.02;0.02;0.9;0.9))
C65	((0.04;0.05;0.05;0.07;1;1),(0.05;0.05;0.05;0.06;0.9;0.9))	((0.01;0.03;0.03;0.05;1;1),(0.02;0.03;0.03;0.04;0.9;0.9))	((0.02;0.04;0.04;0.05;1;1),(0.03;0.04;0.04;0.05;0.9;0.9))
C7			
C71	((0;0;0;0;1;1),(0;0;0;0;0.9;0.9))	((0;0;0;0.01;1;1),(0;0;0;0;0.9;0.9))	((0;0;0;0.01;1;1),(0;0;0;0.01;0.9;0.9))
C72	((0;0.01;0.01;0.01;1;1),(0.01;0.01;0.01;0.01;0.9;0.9))	((0;0.01;0.01;0.01;1;1),(0;0.01;0.01;0.01;0.9;0.9))	((0;0;0;0.01;1;1),(0;0;0;0.01;0.9;0.9))
C73	((0;0;0;0.01;1;1),(0;0;0;0;0.9;0.9))	((0;0.01;0.01;0.01;1;1),(0.01;0.01;0.01;0.01;0.9;0.9))	((0.01;0.01;0.01;0.01;1;1),(0.01;0.01;0.01;0.01;0.9;0.9))
C74	((0;0;0;0;1;1),(0;0;0;0;0.9;0.9))	((0;0;0;0.01;1;1),(0;0;0;0.01;0.9;0.9))	((0;0.01;0.01;0.01;1;1),(0;0.01;0.01;0.01;0.9;0.9))
C75	((0;0;0;0;1;1),(0;0;0;0;0.9;0.9))	((0;0;0;0;1;1),(0;0;0;0;0.9;0.9))	((0;0;0;0;1;1),(0;0;0;0;0.9;0.9))
C76	((0;0;0;0;1;1),(0;0;0;0;0.9;0.9))	((0;0;0;0;1;1),(0;0;0;0;0.9;0.9))	((0;0;0;0;1;1),(0;0;0;0;0.9;0.9))
C77	((0;0;0;0;1;1),(0;0;0;0;0.9;0.9))	((0;0.01;0.01;0.01;1;1),(0;0.01;0.01;0.01;0.9;0.9))	((0;0;0;0.01;1;1),(0;0;0;0.01;0.9;0.9))
C8			
C81	((0;0;0;0;1;1),(0;0;0;0;0.9;0.9))	((0;0;0;0;1;1),(0;0;0;0;0.9;0.9))	((0;0;0;0;1;1),(0;0;0;0;0.9;0.9))
C82	((0;0;0;0;1;1),(0;0;0;0;0.9;0.9))	((0;0;0;0;1;1),(0;0;0;0;0.9;0.9))	((0;0;0;0;1;1),(0;0;0;0;0.9;0.9))
C83	((0;0;0;0;1;1),(0;0;0;0;0.9;0.9))	((0;0;0;0;1;1),(0;0;0;0;0.9;0.9))	((0;0;0;0;1;1),(0;0;0;0;0.9;0.9))
C84	((0.01;0.01;0.01;0.01;1;1),(0.01;0.01;0.01;0.01;0.9;0.9))	((0;0.01;0.01;0.01;1;1),(0.01;0.01;0.01;0.01;0.9;0.9))	((0;0;0;0.01;1;1),(0;0;0;0.01;0.9;0.9))
C85	((0;0;0;0.01;1;1),(0;0;0;0;0.9;0.9))	((0;0.01;0.01;0.01;1;1),(0;0.01;0.01;0.01;0.9;0.9))	((0;0.01;0.01;0.01;1;1),(0.01;0.01;0.01;0.01;0.9;0.9))
C86	((0;0;0;0;1;1),(0;0;0;0;0.9;0.9))	((0;0;0;0;1;1),(0;0;0;0;0.9;0.9))	((0;0;0;0;1;1),(0;0;0;0;0.9;0.9))

Table 7. The rank values.

Criteria	Supplier 1	Supplier 2	Supplier 3
C1			
C11	3.8147	3.8376	3.8530
C12	3.8036	3.8177	3.8177
C13	3.8458	3.9168	3.9403
C14	3.8091	3.8263	3.8263
C15	3.8300	3.8459	3.8459
C16	3.8634	3.9136	3.9297
C17	3.8372	3.8505	3.8639
C2			
C21	3.8508	3.8720	3.9042
C22	3.8127	3.8189	3.8257
C23	3.8293	3.8239	3.8240
C24	3.8065	3.8018	3.8018
C25	3.8039	3.8025	3.8025
C26	3.8222	3.8758	3.8715
C3			
C31	3.9839	4.0811	4.2033
C32	3.8700	3.9454	4.0087
C33	3.9362	3.9932	4.0206
C34	3.8348	3.8762	3.8762
C4			
C41	3.8450	3.8721	3.8678
C42	3.9169	3.9658	3.9893
C43	3.9931	3.9527	4.0737
C5			
C51	3.9373	3.9839	3.8920
C52	3.8124	3.8017	3.8094
C53	3.8268	3.8105	3.8029
C54	3.9548	3.8930	3.8607
C55	3.8162	3.8061	3.8123
C56	3.8237	3.8379	3.8379
C57	3.8977	3.8133	3.8133
C6			
C61	3.8479	3.8734	3.8967
C62	3.9663	4.0345	4.0692
C63	3.8215	3.8283	3.8357
C64	3.9895	3.9415	3.8926
C65	4.1179	3.9531	4.0080
C7			
C71	3.8144	3.8220	3.8258
C72	3.8382	3.8325	3.8269
C73	3.8181	3.8376	3.8539
C74	3.8143	3.8257	3.8293
C75	3.8043	3.8094	3.8099
C76	3.8095	3.8246	3.8232
C77	3.8165	3.8295	3.8252
C8			
C81	3.8062	3.8066	3.8066
C82	3.8005	3.8009	3.8017
C83	3.8031	3.8022	3.8031
C84	3.8516	3.8360	3.8235
C85	3.8148	3.8298	3.8377
C86	3.8068	3.8045	3.8045

Hereafter, the positive ideal and negative ideal solutions are calculated for green suppliers. The closeness coefficient for each green supplier is computed and rankings are determined in decreasing order (Table 8). In IT2F TOPSIS, the larger the value of closeness coefficient, the higher the preference of the green supplier. We determined the greenest supplier as Supplier 3 based on five expert evaluations using the proposed BWM and IT2F TOPSIS model.

Table 8. The ranking of the supplier.

Supplier	Supplier 1	Supplier 2	Supplier 3
d^+	0.3591	0.2839	0.2181
d^-	0.2408	0.2334	0.3705
CC	0.4014	0.4512	0.6295
Rank	3	2	1

4.2. The Comparative Analysis

The proposed approach is compared with a benchmarking model to validate its effectiveness. This benchmarking model concerns with IT2F VIKOR. For both approaches, the importance weights of green supplier selection criteria are obtained from BWM. In the second phase of the model, both are applied to rank suppliers. Results of final scores and ranking orders of suppliers in this new benchmarking model are given in Table 9. According to Table 9, ranking orders of three suppliers remain the same with our proposed model (integrated BWM and IT2F TOPSIS) when maximum group utility value (v) is set to 0.5 or higher than 0.5. This result demonstrates that the proposed approach yields reasonable results and presents suitable outcomes to decision-making in green supplier selection.

Table 9. Q values and rankings for each supplier in terms of v value change.

Maximum Group Utility Value (v) in VIKOR	Q Value			Rank		
	Supplier 1	Supplier 2	Supplier 3	Supplier 1	Supplier 2	Supplier 3
v = 0.1	0.450	1.000	0.000	2	3	1
v = 0.1	0.505	0.934	0.000	2	3	1
v = 0.2	0.560	0.869	0.000	2	3	1
v = 0.3	0.615	0.803	0.000	2	3	1
v = 0.4	0.670	0.738	0.000	2	3	1
v = 0.5	0.725	0.672	0.000	3	2	1
v = 0.6	0.780	0.607	0.000	3	2	1
v = 0.7	0.835	0.541	0.000	3	2	1
v = 0.8	0.890	0.475	0.000	3	2	1
v = 0.9	0.945	0.410	0.000	3	2	1
v = 1.0	1.000	0.344	0.000	3	2	1

5. Conclusions

Selection of suppliers under green concept is a significant milestone for organizations that are moving towards a more environmental supply chain. In today's world, organizations are following new ways to reduce negative effects of their organizations to the environment and to reach a greener system. At this point, green supplier selection concept has gained great importance with its ability to incorporate environmental or green criteria into the classical supplier selection practices. In the literature, lots of approaches are proposed regarding supplier selection and green supplier selection. Integration of fuzzy set theory and its various versions with classical MCDM methods is the forefront in the modeling of green supplier selection.

Therefore, in this study, we propose a multi-phase approach for green supplier selection. First, the selection of criteria under green motivation through literature review and interviews with decision-makers is performed. In the second phase, weights of green supplier selection criteria are determined using BWM. Finally, to obtain ranking order of suppliers with respect to previously weighted criteria, an IT2F TOPSIS method is used. Moreover, a comparative study between the proposed approach and BWM-IT2F VIKOR is provided to validate effectiveness of the proposed approach. This study is considered as the first attempt in the literature that integrates BWM and IT2F TOPSIS. BWM is preferred in weighting the selection criteria since it is more efficient and easier for pairwise comparisons versus Analytic Hierarchy Process. Use of TOPSIS method extended with IT2FSs enables reflecting more uncertainty and ambiguity in the decision-making process as well as including a concept of similarity to ideal solution. The proposed multi-phase approach is applied to the green supplier selection process in a plastic injection molding facility in Turkey.

The proposed approach with its case study has also some limitations. First concerns the integrated methodology.

This study proposes an incorporation of BWM and IT2F TOPSIS for green supplier selection. However, other MCDM methods like VIKOR, PROMETHEE and Elimination Et Choix Traduisant la Realité (ELECTRE) can also be used for this study. Moreover, different versions of fuzzy set theory that have recently been popular, such as Pythagorean fuzzy sets, hesitant fuzzy sets and intuitionistic fuzzy sets, can also be applied to our case study. Secondly, in this study the case study in a single facility has been taken. Therefore, the proposed approach can be adapted from this facility or industry to another one. Future attempts can include the following: (1) A comparative framework can be developed that can highlight the optimal method in selection of green suppliers. (2) A broader and multi-facility data can be used in the problem.

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