A new integrated generalized multi-criteria group decision making approach for green supplier selection

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CHRONICLE	ABSTRACT
	Green supplier selection is an important group decision making problem that includes not only economic criteria, but also environment and society criteria incorporating vagueness and imprecision. This paper proposes a new integrated quality function deployment (QFD) and technique for order preference by similarity to ideal solution (TOPSIS) using generalized fuzzy numbers. The proposed approach initially identifies the features that the purchased product should possess in order to satisfy the company's needs ("WHATs"), and then it seeks to establish the relevant supplier assessment criteria ("HOWs"). Then, the importance of the ''WHATs'', ''HOWs'', ''HOWs''-''WHATs'' correlation scores, and the impact of each potential green suppliers are determined based on generalized fuzzy numbers. The study applies the TOPSIS approach to rank the green suppliers. A numerical example is used to illustrate the advantages and applicability of the proposed approach.

1. Introduction

Owing to the recently escalated changes in the world's climate, selecting green supplier is one of the critical issues of companies to pursue the business strategy and remain in a competitive position (Van et al., 2018). To select the right suppliers, companies must take into account economic criteria (e.g., product price, payment terms, delivery time, quality, materials, financial capability), and more recently to criteria related to the environment and society (e.g., pollution production, resource consumption, eco-design, green product, management commitment, commitment to health and safety of employees, social responsibility). Therefore, green supplier selection (GSS) can be viewed as a multiple-criteria group decision-making (MCGDM) problem that involves many unmeasurable and conflicting criteria. To solve the uncertainty of information, fuzzy sets theory proposed by Zadeh (1965) was frequently used in the existing studies for GSS. Many fuzzy MCGDM techniques have been proposed in the literature to tackle the problem of GSS. Among them, fuzzy technique for order preference by similarity to ideal solution (TOPSIS), fuzzy Analytical Hierarchy Process (AHP), fuzzy analytic network process (ANP), best-worst method (BWM) (Sadjadi & Karimi, 2018), fuzzy quality function deployment (QFD) and their integration are the most popular approaches to evaluate and select the suppliers. Hashemi et al. (2015) integrated green supplier selection approach with analytic network process and improved grey relational analysis. Qin et al. (2017) extended the TODIM (an acronym in Portuguese of interactive and MCDM) technique to solve GSS problems within the context of interval type-2 fuzzy sets. Hamdan and Cheaitou (2017) proposed a supplier selection and order allocation model that took into account all-unit quantity discounts and variable availability of suppliers. Fuzzy TOPSIS, AHP, and a bi-objective integer linear programming model were applied. Their model was solved using the weighted comprehensive

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criterion method and the branch-and-cut algorithm by implementing it in MATLAB R2014a. Lo et al. (2018) proposed a novel model that integrates the BWM, modified fuzzy TOPSIS, and fuzzy multi-objective linear programming (FMOLP) to solve problems in GSS and order allocation. Three dimensions and many criteria were used in their proposed approach including supplier performance (product quality, green manufacturing, service flexibility), environmental protection (environmental performance, innovation capability, green logistic) and supplier risk (labor intensive, financial stability, supplier reputation, information safety). Their proposed approach was applied to solve the GSS in the case of an electronics manufacturing firm in Taiwan. Gupta et al. (2019) proposed a fuzzy MCDM based framework that is used to evaluate GSS by using an integrated fuzzy AHP with the other three techniques namely Multi-Attributive Border Approximation Area Comparison (MABAC), Weighted Aggregated Sum-Product Assessment (WASPAS) and TOPSIS. Six environmental criteria (environmental management system, green image, staff environment training, eco-design, pollution control, and resource consumption) and three conventional criteria (price, quality and service level) was employed in their approach. A real-world case study of the automotive industry in India was deliberated to exhibit the proposed framework applicability. Haeri and Rezaei (2019) developed a grey-based GSS model for uncertain environments using both economic and environmental criteria. Javad et al. (2020) employed the BWM and fuzzy TOPSIS to select GSS in the case of Khouzestan steel company. The BWM was used to rank the criteria of GSS. Then, the fuzzy TOPSIS was applied to select the most effective suppliers among set of alternative suppliers. Gao et al. (2020) proposed a consensus model based on probabilistic linguistic preference relation to solve the problem of GSS. Many criteria and sub-criteria were used in their model including environmental protection capability (pollutant emission control level, green product, environmental management certification, level of disposal of hazardous chemicals, green competitiveness), product quality (reject rate, quality assessment, warranties and claim policies), technology capability (technology level, capability of design) and product cost (product price, transportation cost).

Lately, several researchers have employed the QFD in supplier selection. Bhattacharya et al. (2010) presented a concurrent engineering approach integrating AHP with QFD in combination with cost factor measure (CFM) to rank and subsequently select candidate-suppliers under multiple, conflicting-in-nature criteria environment within a value-chain framework. Dursun and Karsak (2013) proposed a QFD approach for supplier selection process. In their approach, the upper and the lower bounds of the weights of supplier assessment criteria and ratings of suppliers were computed by using the fuzzy weighted average (FWA) method. Karsak and Dursun (2014) developed a novel fuzzy MCGDM framework for supplier selection integrating QFD and data envelopment analysis (DEA). The lower and upper bounds of the weights of supplier assessment criteria were identified by adopting fuzzy weighted average (FWA) method that enables the fusion of imprecise and subjective information expressed as linguistic variables. An imprecise DEA methodology was implemented for supplier selection, which employs the weights of supplier assessment criteria computed by FWA utilizing the data from the HOQ and the supplier ratings with respect to supplier assessment criteria. Yazdani et al. (2017) developed an integrated approach for evaluating supplier performance and selecting the best supplier while considering both traditional and green supplier selection criteria simultaneously. An attempt was made to evaluate and rank ten alternative green suppliers for a reputed Iranian dairy company using the integrated approach consisting of decision-making trial and evaluation laboratory (DEMATEL), QFD model, complex proportional assessment (COPRAS) and multi-objective optimization on the basis of ratio analysis (MOORA) methods.

Van et al. (2018) proposed a new integrated QFD approach in support of the green supplier evaluation and selection process. Interval neutrosophic sets was used to assess the relative importance of the characteristics that the purchased product should have (internal variables "WHATs") in order to satisfy the company's needs, the relevant supplier assessment criteria (external variables "HOWs"), the "HOWs"-"WHATs" correlation scores, the resulting weights of the "HOWs" and the impact of each potential supplier. The TOPSIS method was further applied to obtain a final ranking of green suppliers. Do et al. (2019) proposed a new QFD method based on score, accuracy and certainty functions under interval neutrosophic environment for sustainable supplier selection. Several economic, environmental and social criteria were considered in their decision process. Although many approaches have been proposed for supplier selection process in literature, most of these approaches used normal fuzzy numbers to select the suppliers. However, in many cases it is not possible to restrict the membership function to the normal form. As a result, this study proposes a new integrated QFD-TOPIS approach for supporting GSS using generalized fuzzy numbers. In the proposed integrated approach, the relative importance of the "WHATs'', the "HOWs" - "WHATs" correlation scores, the resulting weights of the "HOWs", and the impact of each potential green suppliers, are assessed in generalized fuzzy numbers. Then, the TOPSIS technique is applied to obtain a final ranking of alternatives. Finally, this study uses a numerical example demonstrating the efficiency of the proposed approach. The organization of this paper is as follows. Section 2 introduces the concepts of fuzzy sets, generalized fuzzy numbers, and their operations. Section 3 presents the proposed integrated MCGDM approach. A numerical example is used to show the procedure and advantage of the proposed method in Section 4. Finally, conclusion is given in Section 5.

2. Preliminaries

2.1. Fuzzy sets

$$A = \{(x, f_A(x)) \mid x \in U\}$$

where U is the universe of discourse, A is a fuzzy set in U, $f_A(x)$ is defined as a membership function $f_A(x) \in [0,1]$, for $f_A(x), \forall x \in U$, indicates the degree of x in A.

2.2. Generalized fuzzy numbers

$A = (a_1, a_2, a_3, a_4; \varpi_A), 0 < \varpi_A \leq 1$ is a generalized trapezoidal fuzzy number, where $w_A \in (0,1]$, a_1, a_2, a_3 and a_4 are real numbers. If $\varpi_A = 1$, then the generalized trapezoidal fuzzy number A is called a normal trapezoidal fuzzy number and denoted as $A = (a_1, a_2, a_3, a_4; 1)$. If $a_2 = a_3$ then A become generalized triangular fuzzy number, and can be denoted as $A = (a_1, a_2, a_4; \varpi_A)$. The membership function $\mu_A(x)$ of the generalized trapezoidal fuzzy number A satisfies the following conditions (Chen, 1985; Hsieh & Chen, 1999):

(a) $\mu_A(x)$ is a continuous to $[0, \varpi]$;

(b) $\mu_A(x) = 0$ for all $x \in (-\infty, a_1]$;

(c) $\mu_A(x)$ is strictly increasing on $[a_1, a_2]$;

(d) $\mu_A(x) = w$, for all $x \in [a_2, a_3]$;

(e) $\mu_A(x)$ is strictly decreasing on $[a_3, a_4]$;

(f) $\mu_A(x) = 0$, for all $x \in (a_4, \infty]$

2.3. Arithmetic operations on generalized fuzzy numbers

Let A and B are two trapezoidal fuzzy numbers, i.e., $A = (a_1, a_2, a_3, a_4; \varpi_A)$ and $B = (b_1, b_2, b_3, b_4; \varpi_B)$ where $a_1, a_2, a_3, a_4, b_1, b_2, b_3$ and b_4 are real values, $0 \leq \varpi_A, \varpi_B \leq 1$. Some arithmetic operators between the A and B are defined as follows (Chen, 1985):

(i). Addition $(+)$:

$$A(+)B = (a_1, a_2, a_3, a_4; \varpi_A)(+)(b_1, b_2, b_3, b_4; \varpi_B) = (a_1 + b_1, a_2 + b_2, a_3 + b_3, a_4 + b_4; \min(\varpi_A, \varpi_B)) \qquad (1)$$

(ii). Subtraction $(-)$:

$$A(-)B = (a_1, a_2, a_3, a_4; \varpi_A)(-)(b_1, b_2, b_3, b_4; \varpi_B) = (a_1 - b_4, a_2 - b_3, a_3 - b_2, a_4 - b_1; \min(\varpi_A, \varpi_B)) \qquad (2)$$

(iii). Multiplication $(\times)$:

$$A(\times)B = (a_1, a_2, a_3, a_4; \varpi_A)(\times)(b_1, b_2, b_3, b_4; \varpi_B) = (a_1 \times b_1, a_2 \times b_2, a_3 \times b_3, a_4 \times b_4; \min(\varpi_A, \varpi_B)) \qquad (3)$$

(iv). Division $(/)$:

$$A(/)B = (a_1, a_2, a_3, a_4; \varpi_A)(/)(b_1, b_2, b_3, b_4; \varpi_B) = (a_1 / b_4, a_2 / b_3, a_3 / b_2, a_4 / b_1; \min(\varpi_A, \varpi_B)) \qquad (4)$$

where $a_1, a_2, a_3, a_4, b_1, b_2, b_3$ and b_4 be non-zero positive real numbers

2.4. Linguistic variables and fuzzy numbers

Table 1 shows the linguistic variables representing by generalized triangular fuzzy number s of the ratings of alternatives and the importance weights of criteria.

Table 1
Ratings of alternatives and importance weights of criteria

Ratings		Importance weights	
Linguistic variables	GTFNs	Linguistic variables	GTFNs
Very Low (VL)	(0.1, 0.2, 0.3; 0.6)	Unimportant (UI)	(0.0, 0.2, 0.4; 0.6)
Low (Po)	(0.2, 0.3, 0.4; 0.7)	Ordinary Important (OI)	(0.3, 0.4, 0.5; 0.7)
Middle (M)	(0.3, 0.5, 0.7; 0.8)	Important (I)	(0.4, 0.5, 0.6; 0.8)
High (H)	(0.5, 0.7, 0.9; 0.9)	Very Important (VI)	(0.5, 0.7, 0.9; 0.9)
Very High (VH)	(0.8, 0.9, 1.0; 1.0)	Absolutely Important (AI)	(0.8, 0.9, 1.0; 0.9)

3. Proposed integrated generalized multi-criteria group decision making approach for green supplier selection

In this study, a new integrated MCGDM approach using generalized fuzzy numbers is developed for green supplier selection is proposed to select and rank the green suppliers. The procedure of the proposed approach is characterized by the following steps:

(i) Identifying the purchased product's characteristics must have ("WHAT") in order to meet the company's needs and the green supplier selection criteria ("HOW");
(ii) Determining the importance weight of the "WHATs";
(iii) Determining the "WHAT"-"HOW" correlation scores;
(iv) Determining the importance weight of the "HOWs";
(v) Determining each potential green supplier's impact on the attributes considered ("HOWs");
(vi) Determining the weighted rating of green suppliers;
(vii) Ranking the green suppliers using TOPSIS technique.

3.1. Identifying the purchased product's characteristics must have ("WHAT") and the green supplier selection criteria ("HOW")

Many studies in supply chain management have mentioned the required criteria of products purchased from green suppliers by the company and the green supplier assessment criteria ("HOW"). Five "*WHATs*" criteria have been considered in this study including green product (W_1), cost (W_2), punctuality of deliveries (W_3), efficacy of corrective action (W_4), eco-design (W_5). The green supplier selection criteria ("HOWs") are used in this study including experience of the sector (H_1), commitment to health and safety of employees (H_2), quality system certification (H_3), social responsibility (H_4), financial stability (H_5), ability to manage orders on-line (H_6).

3.2. Determining the relative importance of the "WHATs"

Let $w_{it} = (a_{it}, b_{it}, c_{it}; \varpi_{it}), i = 1, \ldots, k, t = 1, \ldots, n$ be the weights assigned by decision makers D_t to "WHATs'' criteria C_i. The averaged weight $w_i = (a_i, b_i, c_i; \varpi_w)$ of criterion C_i assessed by the committee of n decision makers can be evaluated as:

$$w_i = (1/n) \otimes (w_{i1} \oplus w_{i2} \oplus \ldots \oplus w_{in}) \tag{5}$$

where $a_i = (1/n)\sum_{t=1}^{n} a_{it}, b_i = (1/n)\sum_{t=1}^{n} b_{it}, c_i = (1/n)\sum_{t=1}^{n} c_{it}, \varpi_w = \min(\varpi_{it})$.

3.3. Determining the "WHATs"-"HOWs" correlation scores

Let $r_{ijt} = (d_{ijt}, e_{ijt}, f_{ijt}; \varpi_{ijt})$, $i = 1, \ldots, k, j = 1, \ldots, m, t = 1, \ldots, n,$ be the suitability rating assigned by decision maker D_t, for "WHATs" criteria C_i and "HOWs" criteria C_j. The averaged suitability rating $r_{ij} = (d_{ij}, e_{ij}, f_{ij}; \varpi_r)$, can be evaluated as:

$$r_{ij} = (1/n) \otimes (r_{ij1} \oplus r_{ij2} \oplus \ldots \oplus r_{ijn}) \tag{6}$$

where $d_{ij} = \frac{1}{n}\sum_{t=1}^{n} d_{ijt}$, $e_{ij} = \frac{1}{n}\sum_{t=1}^{n} e_{ijt}$, $f_{ij} = \frac{1}{n}\sum_{t=1}^{n} f_{ijt}$, and $\varpi_r = \min(\varpi_{ijt})$.

3.4. Determining the weights of the "HOWs" criteria

The weights of the "HOWs" are calculated by averaging the aggregate weighted r_{ij} correlation scores with the aggregate weights of the "WHATs" w_i as follows:

$$W_j = \frac{1}{k} \otimes [(r_{j1} \otimes w_1) \oplus \ldots \oplus (r_{jk} \otimes w_k)] \tag{7}$$

3.5. Determining each potential green suppliers' impact on the attributes considered "HOWs"

Let $PS_{hjt} = (g_{hjt}, h_{hjt}, k_{hjt}; \varpi_{hjt})$, $h = 1, \ldots, s, j = 1, \ldots, m, t = 1, \ldots, n,$ be the suitability rating assigned to green suppliers A_h, by decision maker D_t, for "HOWs" criteria C_j. The averaged suitability rating $PS_{hj} = (g_{hj}, h_{hj}, k_{hj})$, can be evaluated as:

$$PS_{hj} = (1/n) \otimes (sr_{hj1} \oplus sr_{hj2} \oplus \ldots \oplus sr_{hjn}) \tag{8}$$

where $g_{hj} = \frac{1}{n}\sum_{t=1}^{n} g_{hjt}$, $h_{hj} = \frac{1}{n}\sum_{t=1}^{n} h_{hjt}$, $k_{hj} = \frac{1}{n}\sum_{t=1}^{n} k_{hjt}$, and $\varpi_{PS} = \min(\varpi_{hjt})$

3.6. Determining the weighted rating of green suppliers

The weighted ratings T_h are calculated by multiplying the averaged suitability rating PS_{hj} with its associated weights W_j as follows:

$$T_h = \frac{1}{m} \otimes [(PS_{h1} \otimes W_1) \oplus \cdots \oplus (PS_{hm} \otimes W_m)], \quad h = 1, \ldots, s, \ j = 1, \ldots, m. \tag{9}$$

3.7. Determining T^+, T^-, d_h^+ and d_h^-

The fuzzy positive-ideal solution (FPIS, T^+) and fuzzy negative-ideal solution (FNIS, T^-) are obtained as follows:

$$T^+ = (1,1,1; \varpi_{PS}\} \tag{10}$$

$$T^- = (0,0,0; \varpi_{PS}) \tag{11}$$

The distances of each alternative $T_h, h = 1, \ldots, s$ from T^+ and T^- are calculated as:

$$d_h^+ = \sqrt{\sum_{j=1}^{n} (T_h - T^+)^2} \tag{12}$$

$$d_h^- = \sqrt{\sum_{j=1}^{n} (T_h - T^-)^2} \tag{13}$$

where d_h^+ represents the shortest distance of alternative T_h, and d_h^- represents the farthest distance of alternative T_h.

3.8. Determining the closeness coefficient

The closeness coefficient of each alternative, which is usually defined to determine the ranking order of all alternatives, is calculated as:

$$CC_h = \frac{d_h^-}{d_h^+ + d_h^-} \tag{14}$$

A higher value of the closeness coefficient indicates that an alternative is closer to *PIS* and farther from *NIS* simultaneously. The closeness coefficient of each alternative is used to determine the ranking order of all alternatives and identify the best one among a set of given feasible alternatives.

4. A numerical example for green supplier selection

This section applies the proposed integrated generalized MCGDM to solve a green suppliers selection problem. Assume that the manufacturing company needs to evaluate and rank their suppliers. After an initial screening, four green suppliers A_1, A_2, A_3 and A_4 are chosen for further evaluation. A committee of three decision-makers, D_1, D_2 and D_3 is formed to determine the most suitable green suppliers.

4.1. Aggregating the importance weights of "WHATs"

The importance and aggregated weights of the five "WHATs" criteria from the three decision makers are obtained by the quantified linguistic variables from Table 1 and Eq. (5), and expressed in Table 2.

Table 2
The importance weights of the "WHATs" criteria and their aggregated weights

"WHATs"	Decision makers			w_i
	D_1	D_2	D_3	
W_1	AI	AI	VI	(0.70, 0.83, 0.97;0.90)
W_2	VI	VI	AI	(0.60, 0.77, 0.93;0.90)
W_3	I	VI	VI	(0.47, 0.63, 0.80;0.80)
W_4	VI	VI	I	(0.47, 0.63, 0.80;0.80)
W_5	I	I	I	(0.40, 0.50, 0.60;0.80)

4.2. Aggregating the "HOWs"-"WHATs" correlation scores

Based on the quantified linguistic variables from Table 1 and using Eq. (6), the linguistic values and aggregated ratings of "HOWs"-"WHATs" can be obtained as shown in Tables 3.

Table 3
The linguistic values and aggregated fuzzy rating of "HOWs"-"WHATs"

"HOWs"	"WHATs"	Decision makers			r_{ij}
		D_1	D_2	D_3	
W_1	H_1	H	H	H	(0.50, 0.70, 0.90;0.90)
	H_2	H	H	M	(0.43, 0.63, 0.83;0.80)
	H_3	VH	H	H	(0.60, 0.77, 0.93;0.90)
	H_4	H	VH	H	(0.60, 0.77, 0.93;0.90)
	H_5	H	H	H	(0.50, 0.70, 0.90;0.90)
	H_6	M	H	M	(0.37, 0.57, 0.77;0.80)
W_2	H_1	H	M	H	(0.43, 0.63, 0.83;0.80)
	H_2	H	VH	H	(0.60, 0.77, 0.93;0.90)
	H_3	M	H	VH	(0.53, 0.70, 0.87;0.80)
	H_4	H	H	M	(0.43, 0.63, 0.83;0.80)
	H_5	M	L	M	(0.27, 0.43, 0.60;0.70)
	H_6	M	H	M	(0.37, 0.57, 0.77;0.80)
W_3	H_1	M	L	L	(0.23, 0.37, 0.50;0.70)
	H_2	H	M	H	(0.43, 0.63, 0.83;0.80)
	H_3	H	H	H	(0.50, 0.70, 0.90;0.90)
	H_4	H	M	H	(0.43, 0.63, 0.83;0.80)
	H_5	H	H	H	(0.50, 0.70, 0.90;0.90)
	H_6	M	H	M	(0.37, 0.57, 0.77;0.80)
W_4	H_1	H	H	H	(0.50, 0.70, 0.90;0.90)
	H_2	M	H	H	(0.43, 0.63, 0.83;0.80)
	H_3	M	H	H	(0.43, 0.63, 0.83;0.80)
	H_4	VH	H	M	(0.53, 0.70, 0.87;0.80)
	H_5	M	H	H	(0.43, 0.63, 0.83;0.80)
	H_6	H	VH	H	(0.60, 0.77, 0.93;0.90)
W_5	H_1	VH	H	VH	(0.70, 0.83, 0.97;0.90)
	H_2	H	H	VH	(0.60, 0.77, 0.93;0.90)
	H_3	H	H	H	(0.50, 0.70, 0.90;0.90)
	H_4	H	H	VH	(0.60, 0.77, 0.93;0.90)
	H_5	H	VH	H	(0.60, 0.77, 0.93;0.90)
	H_6	H	VH	H	(0.60, 0.77, 0.93;0.90)

4.3. Aggregating the Importance Weights of the "HOWs"

The fuzzy value for weight of each attribute "HOW" can be obtained by using Eq. (7) as shown in Table 4.

Table 4
Average weighed of each "HOWs" as a triangular fuzzy number

HOWs	W_j
H_1	(0.246, 0.432, 0.670; 0.7)
H_2	(0.262, 0.460, 0.714; 0.8)
H_3	(0.275, 0.474, 0.728; 0.8)
H_4	(0.274, 0.470, 0.720; 0.8)
H_5	(0.237, 0.429, 0.675; 0.7)
H_6	(0.234, 0.427, 0.675; 0.8)

4.4. Determining each potential green supplier impacts on the attributes considered "HOWs"

Using Eq. (8) and Table 1, the suitability rating of each "HOWs" criterion on four green suppliers based on three decision makers and its averaged value can be obtained as shown in Table 5

Table 5
Linguistic values and aggregated fuzzy rating of each "HOW" criterion on four green suppliers

"HOWs"	Green suppliers	Decision makers			r_{ij}
		D_1	D_2	D_3	
H_1	A_1	H	H	H	(0.50, 0.70, 0.90;0.90)
	A_2	VH	H	VH	(0.70, 0.83, 0.97;0.90)
	A_3	H	H	H	(0.50, 0.70, 0.90;0.90)
	A_4	H	VH	H	(0.60, 0.77, 0.93;0.90)
H_2	A_1	M	H	M	(0.37, 0.57, 0.77;0.80)
	A_2	H	H	VH	(0.60, 0.77, 0.93;0.90)
	A_3	L	M	M	(0.27, 0.43, 0.60;0.70)
	A_4	M	H	M	(0.37, 0.57, 0.77;0.80)
H_3	A_1	VH	H	H	(0.60, 0.77, 0.93;0.90)
	A_2	H	H	VH	(0.60, 0.77, 0.93;0.90)
	A_3	H	M	H	(0.43, 0.63, 0.83;0.80)
	A_4	L	M	M	(0.27, 0.43, 0.60;0.70)
H_4	A_1	H	M	H	(0.43, 0.63, 0.83;0.80)
	A_2	H	H	H	(0.50, 0.70, 0.90;0.90)
	A_3	H	H	H	(0.50, 0.70, 0.90;0.90)
	A_4	H	VH	H	(0.60, 0.77, 0.93;0.90)
H_5	A_1	H	VH	VH	(0.70, 0.83, 0.97;0.90)
	A_2	L	H	M	(0.33, 0.50, 0.67;0.70)
	A_3	H	H	VH	(0.60, 0.77, 0.93;0.90)
	A_4	H	H	M	(0.43, 0.63, 0.83;0.80)
H_6	A_1	VH	H	H	(0.60, 0.77, 0.93;0.90)
	A_2	H	M	H	(0.43, 0.63, 0.83;0.80)
	A_3	VH	H	H	(0.60, 0.77, 0.93;0.90)
	A_4	M	H	H	(0.43, 0.63, 0.83;0.80)

4.5. Determining the normalized weighted rating

Using Eq. (9), the weighted ratings T_h can be obtained as shown in Table 6.

Table 6. Normalized weighted ratings of each green suppliers

Green suppliers	T_h
A_1	(0.135, 0.318, 0.619; 0.7)
A_2	(0.135, 0.315, 0.609; 0.7)
A_3	(0.122, 0.298, 0.591; 0.7)
A_4	(0.114, 0.283, 0.568; 0.7)

4.6. Determining T^+, T^-, d_h^+ and d_h^-

As shown in Table 7, the distance of each alternative from S^+ and S^- can be calculated by Eqs. (10)-(13).

Table 7
The distance measurement

Green suppliers	d^+	d^-
A_1	1.1656	0.7087
A_2	1.2600	0.6989
A_3	1.2701	0.6730
A_4	1.2730	0.6447

4.7. Determining the closeness coefficient and ranking order of each green supplier

The closeness coefficients of green suppliers can be calculated by Eq. (14), as shown in Table 8. The results show that the green supplier A_2 with the largest closeness coefficient value is defined as the best alternative for this company. Therefore, the ranking order of the four green suppliers is $A_1 \succ A_2 \succ A_3 \succ A_4$.

Table 9
Closeness coefficients of green suppliers

Green suppliers	Closeness coefficient	Ranking
A_1	0.3781	1
A_2	0.3568	2
A_3	0.3463	3
A_4	0.3362	4

5. Conclusions

This study proposed a novel integrated QFD-TOPSIS using generalized fuzzy numbers to support for green supplier evaluation and selection process. Using the proposed approach, the companies can determine the suitable green suppliers based on five criteria that are crucial to products "WHATs" and six green supplier evaluation criteria "HOWs". This study determined the relative importance of the "WHATs", the "HOWs"-"WHATs" correlation scores, the resulting weights of the "HOWs", and the impact of each potential green supplier using generalized triangular fuzzy numbers. Then, the fuzzy TOPSIS approach was applied to rank the green suppliers. A numerical example was used illustrating the advantages and applicability of the proposed approach.

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