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New Integrated Quality Function Deployment Approach Based on Interval Neutrosophic Set for Green Supplier Evaluation and Selection

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Abstract: Green supplier evaluation and selection plays a crucial role in the green supply chain management of any organization to reduce the purchasing cost of materials and increase the flexibility and quality of products. An interval neutrosophic set (INS)—which is a generalization of fuzzy sets, intuitionistic fuzzy sets (IFS) and neutrosophic sets (NS)—can better handle the incomplete, indeterminate and inconsistent information than the other sets. This paper proposes a new integrated Quality Function Deployment (QFD) in support of the green supplier evaluation and selection process. In the proposed approach, INS is 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 normalized weighted rating is then defined and the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) method is developed to obtain a final ranking of green suppliers. A case study is applied to demonstrate the efficiency and computational procedure of the proposed method.

Keywords: quality function deployment; TOPSIS; interval neutrosophic; green supplier selection

1. Introduction

The selection of the right suppliers is among the important supply chain issues for making company operations efficient [1]. Owing to the recently escalated changes in the world's climate, green supplier selection is considered a key element for companies to help protect the world environment and to maintain their competitive advantages in the global market. Traditional approaches have considered economic criteria such as cost, quality, flexibility, technology and delivery in supplier evaluation policy. In the sustainable approach to supplier evaluation and selection, environmental and social criteria—such as environmental commitment, recyclable packages, social responsibility, ethical issues and legal compliance and commitment to health and safety of employees—should also be considered when measuring supplier performance [2]. Therefore, green supplier evaluation and selection can be regarded as a multiple criteria decision-making (MCDM) problem [3,4].

Despite the growing work of green supplier selection, existent studies have focused on aspects of supplier selection in terms of some internal criteria in general. External criteria, such as customer opinions or requirements (CRs), have not been considered [1]. Additionally, most studies have focused only on the economic efficiency of suppliers rather than the environmental issues in the supplier selection process [5]. However, considering environmental and social criteria has become critical due to the increasing awareness of environmental issues and governmental regulations in supply chain management. Table 1 shows the most commonly used criteria to evaluate the performance of green supplier selection.

Table 1. Green supplier selection and evaluation criteria.

Criteria	Sub-Criteria	Sub-Sub-Criteria/Definition	References
Economic criteria	Cost	Product price, logistics cost, payment terms	[1,6–12]
	Quality	ISO quality system installed, quality award, repair and return rate	[1,8,9,13,14]
	Delivery	Lead time, on-time delivery, safety and security of components	[1,9,15–17]
	Technology	Communication and e-commerce systems, production facilities and capacity	[8,9,17]
	Flexibility	Product volume changes, using flexible machines	[8,9,18–20]
	Financial capability	Financial position and economic stability	[1,13]
	Culture	Vendor's image, Mutual Trust	[7,16,20]
	Innovativeness	New launch of products and/or technologies	[21]
	Relationship	Relationship closeness	[18–20]
Environmental criteria	Pollution production	Air pollutants, waste water	[1,8,11,22,23]
	Pollution control	Remediation, end-of-pipe controls	[22,24,25]
	Resource consumption	Consumption of resources in terms of raw material, energy and water	[22,23]
	Eco-design	Design for resource efficiency, design of products for reuse, recycle and recovery of material	[1,11,19,23,26,27]
	Environmental management system	Environmental certificates, green process planning	[1,11,19,22–28]
	Green image	Ratio of green customers to total customers	[24,25,27]
	Green competencies	Ability to alter product for reducing the impact on natural resources	[24–26,28]
	Green product	Use of recycled and nontoxic materials, green packaging	[26,28]
	Staff environmental training	Staff training on environmental issues	[28]
	Management commitment	Commitment of senior managers to support and improve green supply chain management initiatives	[1,26,28]
	Green Technology	The application of the environmental science to conserve the natural environment and resources	[26]
Social criteria		Social responsibility	[2,13,29–31]
		Energy and resource efficiency	[2]
		Ethical issues and legal complain	[2]
		Commitment to health and safety of employees	[2,23,30]

Many researchers and practitioners have proposed various MCDM models to evaluate and choose appropriate supplier. Among them, analytic hierarchy process (AHP) [32–35], Analytic Network Process (ANP) [36], Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) [37–39], Quality Function Deployment (QFD) [10,40–43]; AHP-TOPSIS combined approach [44–46], QFD and Step-wise Weight Assessment Ratio Analysis (SWARA) [1], AHP and VlseKriterijuska Optimizacija I Komoromisno Resenje (VIKOR) [47], AHP and QFD [2,48], QFD and MCDM [49]; AHP-TOPSIS-QFD [50] have been successfully applied to optimize the supplier evolution process.

In the supplier selection model, the majority of the criteria are generally evaluated by personal judgment and therefore might be subjective. To solve this problem, Zadeh [51] proposed fuzzy sets theory, which is one of the most effective tools for processing vague information. However, this theory is disadvantaged by its membership and inability to express non-membership. Atanassov [52,53] introduced the intuitionistic fuzzy sets (IFSs) by adding a non-membership function. The IFSs can only handle incomplete information and not indeterminate and inconsistent information. On the basis of IFSs, Smarandache [54,55] proposed the neutrosophic set (NS) by adding an independent indeterminacy-membership. The NS, a generalization of fuzzy set and IFSs, can handle incomplete, indeterminate and inconsistent information. Given that the practical application of NS is difficult, Wang [56] proposed a single valued neutrosophic set (SVNS), which is an instance of the NS. The concept of SVNS has been widely applied to various problems in decision-making, education, artificial intelligence, medical diagnosis and so on. In certain real-life situations, using exact numbers to describe the degree of truth, falsity and indeterminacy about a particular statement is infeasible. Therefore, Wang [57] and Zhang [58] proposed interval neutrosophic sets (INSs) and presented the set-theoretic operators of INSs. The theoretical and practical work in INSs has rapidly progressed. Chi and Liu [59] extended the TOPSIS method for multiple attribute decision-making problems using INSs and the maximizing deviation method. Ye [60] defined the Hamming and Euclidean distances and proposed the similarity measures between INSs based on the relationship between similarity measures and distances. Zhang [58] defined the improved operations for INSs. A method for MCDM problems was explored after applying aggregation operators. Şahin [61] proposed the concept of interval neutrosophic cross-entropy, which was then established in an MCDM problem in which the alternative criteria are characterized by INS.

Ye [60] proposed the concept of an interval neutrosophic linguistic set and developed some new aggregation operators for the interval neutrosophic linguistic information. A decision-making method was then presented to manage decision-making problems. Broumi [62] extended the TOPSIS method to deal with the interval neutrosophic uncertain linguistic information.

Quality function deployment (QFD) recently became a widely used quality management tool in product design and development. The QFD is used to receive customer feedback throughout the product planning, development, engineering and manufacturing stages of any product [41]. This technique helps organizations allocate resources and coordinate skills based on customer needs and thus, it decreases production costs and reduces the cycle [63]. The traditional QFD is only used for decision-making problems with crisp numbers and many extended versions of QFD were proposed to deal with fuzzy information. Various QFD approaches using crisp and fuzzy numbers have been presented in the literature [2,10,40–43,48–50]. However, there exist few studies on the application of the QFD technique in a neutrosophic environment [64] and, thus far, no research has extended QFD for INS.

As a result, this study proposes a new integrated QFD-based INS for supporting the green supplier evaluation and selection process. In the proposed 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 supplier are assessed in INS. The technique for order performance by similarity to ideal solution (TOPSIS) is developed based on INS to obtain a final ranking of alternatives. A case study is further used to illustrate the computational procedure of the proposed approach.

The rest of this paper is organized as follows: Basic notions of NSs, INSs and their operations are discussed in Section 2; the QFD procedures on INSs are demonstrated in Section 3; an application of the procedures for green supplier evaluation and selection in a real case study is illustrated in Section 4; and conclusions of this research and recommendations for further studies are explained in Section 5.

2. Preliminary

Definition 1. *Neutrosophic Set (NS)*

Let U be a universe of discourse and a set N ⊂ U, such that

$$\mathrm{N} = \{\mathrm{x}(\ \mathrm{T_A(x)}, \mathrm{I_A(x)}, \mathrm{F_A(x)}\ ), \mathrm{x} \in \mathrm{U}\ \},$$

where $\mathrm{T_A(x)}, \mathrm{I_A(x)}, \mathrm{F_A(x)} \subseteq [0, 1]$ are real subsets, for all x ∈ U, is called a neutrosophic set (NS) [65]. If $\mathrm{T_A(x)}, \mathrm{I_A(x)}, \mathrm{F_A(x)} \in [0, 1]$ are real (crisp) numbers, for all x ∈ U, then N is called a *single-valued neutrosophic set* (SVNS).

If $\mathrm{T_A(x)}, \mathrm{I_A(x)}, \mathrm{F_A(x)} \subseteq [0, 1]$ are real intervals, for all x ∈ U, then N is called a *interval-valued neutrosophic set* [57].

Definition 2. *Operational Rules of the Interval Neutrosophic Value*

Let $x = ([T_1^L, T_1^U], [I_1^L, I_1^U], [F_1^L, F_1^U])$ and $y = ([T_2^L, T_2^U], [I_2^L, I_2^U], [F_2^L, F_2^U])$ be two interval neutrosophic value. The operational rules of interval neutrosphic value are then defined as follows:

The complement of x is

$$\overline{x} = ([F_1^L, F_1^U], [1 - I_1^U, 1 - I_1^L], [T_1^L, T_1^U]) \quad (1)$$

$$x \oplus y = ([T_1^L + T_2^L - T_1^L T_2^L, T_1^U + T_2^U - T_1^U T_2^U], [I_1^L I_2^L, I_1^U I_2^U], [F_1^L F_2^L, F_1^U F_2^U] \quad (2)$$

$$x \otimes y = \begin{array}{l} ([T_1^L T_2^L, T_1^U T_2^U], [I_1^L + I_2^L - I_1^L I_2^L, I_1^U + I_2^U - I_1^U I_2^U], \\ [F_1^L + F_2^L - F_1^L F_2^L, F_1^U + F_2^U - F_1^U F_2^U]) \end{array} \quad (3)$$

$$nx = ([1-(1-T_1^L)^n, 1-(1-T_1^U)^n], [(I_1^L)^n, (I_1^U)^n], [(F_1^L)^n, (F_1^U)^n]),\ n > 0 \quad (4)$$

$$x^n = ([(T_1^L)^n, (T_1^U)^n], [1-(1-I_1^L)^n, 1-(1-I_1^U)^n], [1-(1-F_1^L)^n, 1-(1-F_1^U)^n]), n > 0 \quad (5)$$

Definition 3. *Distance between two Neutrosophic Values*

Let $x = ([T_1^L, T_1^U], [I_1^L, I_1^U], [F_1^L, F_1^U])$ and $y = ([T_2^L, T_2^U], [I_2^L, I_2^U], [F_2^L, F_2^U])$ be two INVs. The Hamming and Euclidian distances between x and y are defined respectively as follows:

$$\begin{array}{rl} d_H(x,y) & = \frac{1}{6}(|T_1^L - T_2^L| + |T_1^U - T_2^U| + |I_1^L - I_2^L| \\ & +|I_1^U - I_2^U| + |F_1^L - F_2^L| + |F_1^U - F_2^U|) \end{array} \quad (6)$$

$$d_E(x,y) = \sqrt{\frac{1}{6}\left(\begin{array}{c} (T_1^L - T_2^L)^2 + (T_1^U - T_2^U)^2 + (I_1^L - I_2^L)^2 \\ +(I_1^U - I_2^U)^2 + (F_1^L - F_2^L)^2 + (F_1^U - F_2^U)^2 \end{array} \right)} \quad (7)$$

3. QFD Model Development Using Interval Neutrosophic Sets

In this section, the QFD model is developed for green supplier selection and evaluation using INSs (as shown in Figure 1).

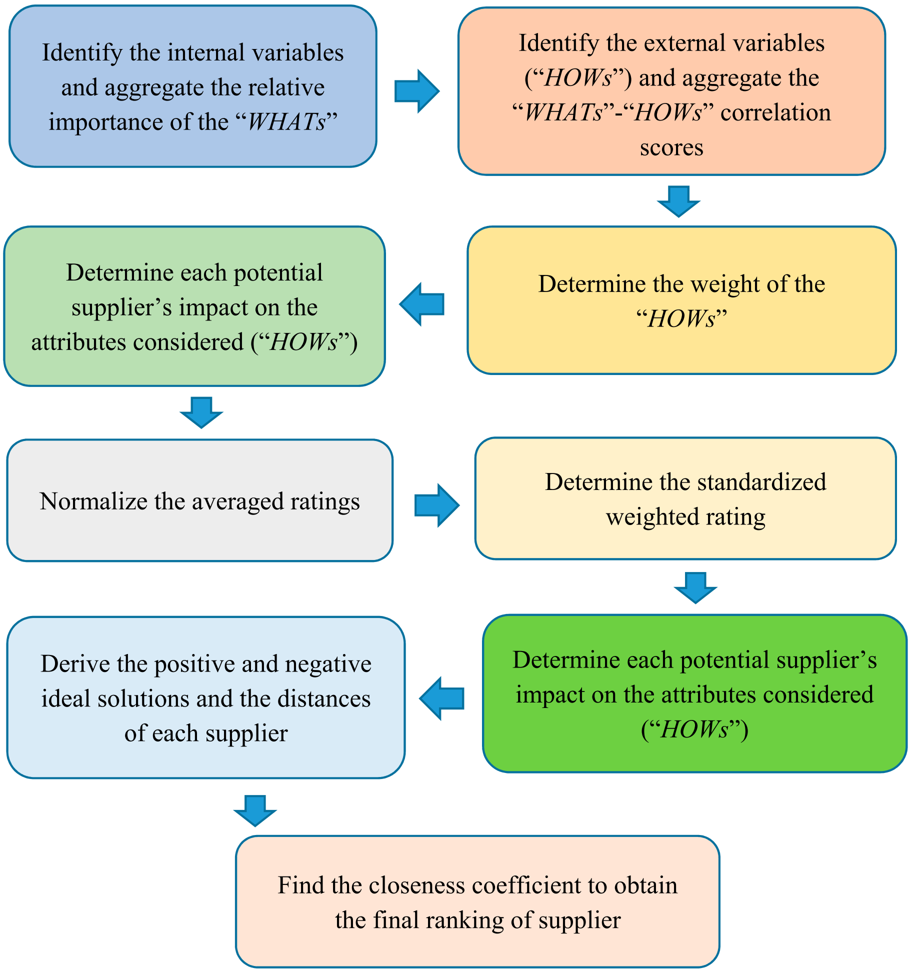

Figure 1. The procedure of the proposed Quality Function Deployment (QFD) model.

The steps of the proposed QFD model are as follows:

3.1. Identify the Characteristics That the Product Being Purchased Must Have (Internal Variables or "WHATs") to Meet the Company's Needs and Aggregate the Relative Importance of "WHATs"

The characteristics that the products or services being purchased must have (internal variables or "*WHATs*") can be identified from the literature review and experts' opinions (or decision-makers). After determining the "*WHATs*" factors, the decision-makers further identify their importance weights.

Let $w_{pq} = ([T^L_{pq}, T^U_{pq}], [I^L_{pq}, I^U_{pq}], [F^L_{pq}, F^U_{pq}])$ be the weight assigned by decision-maker D_q to criterion C_p, $p = 1, \ldots, n$; $q = 1, \ldots, h$. With the operational rules of the INS, the average weight $w_p = ([T^L_p, T^U_p], [I^L_p, I^U_p], [F^L_p, F^U_p])$ can be evaluated as:

$$w_p = (\frac{1}{h}) \otimes (w_{p1} \oplus w_{p2} \oplus \ldots \oplus w_{ph}) \quad (8)$$

where

$$T^L_p = 1 - \left(1 - \sum_{q=1}^{h} T^L_{pq}\right)^{\frac{1}{h}}; T^U_p = 1 - \left(1 - \sum_{q=1}^{h} T^U_{pq}\right)^{\frac{1}{h}}$$

$$I^L_p = \left(\sum_{q=1}^{h} I^L_{pq}\right)^{\frac{1}{h}}; I^U_p = \left(\sum_{q=1}^{h} I^U_{pq}\right)^{\frac{1}{h}}$$

$$F^L_p = \left(\sum_{q=1}^{h} F^L_{pq}\right)^{\frac{1}{h}}; F^U_p = \left(\sum_{q=1}^{h} F^U_{pq}\right)^{\frac{1}{h}}$$

3.2. Identify the Criteria Relevant to Supplier Assessment (External Variables or "HOWs") and Aggregate the "WHATs"-"HOWs" Correlation Scores

The supplier assessment criteria are defined from a careful review of the supply management literature and expert opinion. The "*WHATs*"-"*HOWs*" correlation scores are then defined.

Let $x_{pmq} = ([T^L_{pmq}, T^U_{pmq}], [I^L_{pmq}, I^U_{pmq}], [F^L_{pmq}, F^U_{pmq}])$, $p = 1, \ldots, n, m = 1, \ldots, t$, $q = 1, \ldots, h$ be the suitability rating assigned by decision-maker D_q for "*WHATs*" criteria C_p and "*HOWs*" criteria C_m. With the operational rules of the INS, the averaged suitability rating, $x_{pm} = ([T^L_{pm}, T^U_{pm}], [I^L_{pm}, I^U_{pm}], [F^L_{pm}, F^U_{pm}])$, can be evaluated as:

$$x_{pm} = \frac{1}{h} \otimes (x_{pm1} \oplus x_{pm2} \oplus \ldots \oplus x_{pmq} \oplus \ldots \oplus x_{pmh}), \quad (9)$$

where

$$T^L_{pm} = 1 - \left(1 - \sum_{q=1}^{h} T^L_{pmq}\right)^{\frac{1}{h}}; T^U_{pm} = 1 - \left(1 - \sum_{q=1}^{h} T^U_{pmq}\right)^{\frac{1}{h}}$$

$$I^L_{pm} = \left(\sum_{q=1}^{h} I^L_{pmq}\right)^{\frac{1}{h}}; I^U_{p} = \left(\sum_{q=1}^{h} I^U_{pmq}\right)^{\frac{1}{h}}$$

$$F^L_{pm} = \left(\sum_{q=1}^{h} F^L_{pmq}\right)^{\frac{1}{h}}; F^U_{pm} = \left(\sum_{q=1}^{h} F^U_{pmq}\right)^{\frac{1}{h}}$$

3.3. Determine the Weights of the "HOWs" Criteria

The weights of the "*HOWs*" are calculated by averaging the aggregate ratings x_{pm} correlation scores with the aggregate weights of the "*WHATs*" w_p as follows:

$$W_m = (\tfrac{1}{n})\sum_{p=1}^{n}(w_p x_{pm}) = \left(\left[1-(1-\sum_{p=1}^{n}T_{pm}^{L}T_{P}^{L})^{1/n}, 1-(1-\sum_{p=1}^{n}T_{pm}^{U}T_{P}^{U})^{1/n}\right], \left[(\sum_{p=1}^{n}I_{pm}^{L}I_{P}^{L})^{1/n}, (\sum_{p=1}^{n}I_{pm}^{U}I_{P}^{U})^{1/n}\right], \left[(\sum_{p=1}^{n}F_{pm}^{L}F_{P}^{L})^{1/n}, (\sum_{p=1}^{n}F_{pm}^{U}F_{P}^{U})^{1/n}\right]\right) \quad (10)$$

3.4. Determine Each Potential Supplier Impact on the Attributes Considered "HOWs"

Let $G_{jmq} = ([T_{jmq}^{L}, T_{jmq}^{U}], [I_{jmq}^{L}, I_{jmq}^{U}], [F_{jmq}^{L}, F_{jmq}^{U}])$, $j = 1, \ldots, s$, $m = 1, \ldots, t$, $q = 1, \ldots, h$ be the suitability rating assigned to supplier A_j, by decision-maker D_q, for "*HOWs*" criteria C_m. The averaged suitability rating, $G_{jm} = ([T_{jm}^{L}, T_{jm}^{U}], [I_{jm}^{L}, I_{jm}^{U}], [F_{jm}^{L}, F_{jm}^{U}])$, can be evaluated as:

$$G_{jm} = \frac{1}{h} \otimes (G_{jm1} \oplus G_{jm2} \oplus \ldots \oplus G_{jmq} \oplus \ldots \oplus G_{jmh}), \quad (11)$$

where

$$T_{jm}^{L} = 1 - \left(1 - \sum_{q=1}^{h} T_{jmq}^{L}\right)^{1/h}; T_{jm}^{U} = 1 - \left(1 - \sum_{q=1}^{h} T_{jmq}^{U}\right)^{1/h}$$

$$I_{jm}^{L} = \left(\sum_{q=1}^{h} I_{jmq}^{L}\right)^{1/h}; I_{jm}^{U} = \left(\sum_{q=1}^{h} I_{jmq}^{U}\right)^{1/h}$$

$$F_{jm}^{L} = \left(\sum_{q=1}^{h} F_{jmq}^{L}\right)^{1/h}; F_{jm}^{U} = \left(\sum_{q=1}^{h} F_{jmq}^{U}\right)^{1/h}.$$

3.5. Normalize the Averaged Ratings

The "*HOWs*" criteria are generally classified into two types. The benefit type is characterized as "the larger the better," whereas the cost type is characterized as "the smaller the better." To eliminate the influence of the criteria, we need to convert cost to benefit type.

Suppose the standardized matrix is expressed by $R_{jm} = [r_{jm}]$, where $r_{jm} = ([\dot{T}_{jm}^{L}, \dot{T}_{jm}^{U}], [\dot{I}_{jm}^{L}, \dot{I}_{jm}^{U}], [\dot{F}_{jm}^{L}, \dot{F}_{jm}^{U}])$, then we have

$$\begin{cases} r_{jm} = G_{jm} \;\; if\ the\ criterion\ m\ is\ benefit\ type \\ r_{jm} = \overline{G}_{jm} \;\; if\ the\ criterion\ m\ is\ cost\ type \end{cases}$$

3.6. Determine the Standardized Weighted Rating

The standardized weighted ratings $V_j = ([\dot{T}_{j}^{L}, \dot{T}_{j}^{U}], [\dot{I}_{j}^{L}, \dot{I}_{j}^{U}], [\dot{F}_{j}^{L}, \dot{F}_{j}^{U}])$, are calculated by multiplying the standardized averaged suitability rating r_{jm} with its associated weights W_m as follows:

$$V_j = \frac{1}{m} \otimes [(r_{j1} \otimes W_1) \oplus \cdots \oplus (r_{jt} \otimes W_t)],\ j = 1, \ldots, s, m = 1, \ldots, t. \quad (12)$$

where,

$$\dot{T}_{j}^{L} = 1 - \left(1 - \sum_{m=1}^{t} T_{jm}^{L}\right)^{1/m}; \dot{T}_{j}^{U} = 1 - \left(1 - \sum_{m=1}^{t} T_{jm}^{U}\right)^{1/m}$$

$$\dot{I}_{j}^{L} = \left(\sum_{m=1}^{t} I_{jm}^{L}\right)^{1/m}; \dot{I}_{j}^{U} = \left(\sum_{m=1}^{t} I_{jm}^{U}\right)^{1/m}.$$

3.7. Derive A^+, A^-, d_h^+ and d_h^-

The positive and negative ideal solutions are obtained respectively as follows:

$$A_j^+ = ([1,1],[0,0],[0,0]) \tag{13}$$

$$A_j^- = ([0,0],[1,1],[1,1]) \tag{14}$$

The distances of each alternative $A_j, j = 1, \ldots, s$ from A^+ and A^- are calculated as:

$$d_j^+ = \sqrt{\sum_{j=1}^{s} (V_j - A^+)^2} \tag{15}$$

$$d_j^- = \sqrt{\sum_{j=1}^{s} (V_j - A^-)^2} \tag{16}$$

where d_j^+ is the shortest distance of alternative A_j, and d_j^- is the farthest distance of alternative A_j.

3.8. Find the Closeness Coefficient and Ranking Order of Alternatives

The closeness coefficient of each alternative with respect to interval neutrosophic ideal solutions is calculated as:

$$CC_j = \frac{d_j^-}{d_j^+ + d_j^-} \tag{17}$$

According to descending order of the closeness coefficient value, the raking order of each alternative can be identified.

4. Application of the Proposed Model for Green Supplier Evaluation and Selection

This section applies the proposed QFD method for green supplier evaluation and selection to the case of Transportation Parts Company Limited in northern Vietnam.

After preliminary screening, four green suppliers (A_1–A_4) are chosen for further evaluation. A committee of four company managers (D_1–D_4) conducts the evaluation and selection of green suppliers. As a result of discussions with the company, six fundamental characteristics required in products or services purchased from green suppliers are determined. The committee members were carefully selected from the company's top managers and the head of the supply chain management department. These characteristics can be listed as: "affordable price (W_1)," "product conformity (W_2)," "availability and accessibility (W_3)," "amount of emission of pollution and hazardous material (W_4)," "eco-design (W_5)," and "social responsibility (W_6)." The six criteria relevant to supplier assessment are identified as: "financial stability (H_1)," "quality (H_2)," "delivery time (H_3)," "corporate social responsibility (H_4)," "environmental management systems (H_5)," and "pollution control (H_6)." The computational procedure is summarized as follows:

4.1. Aggregate the Importance Weights of the "WHATs"

After determining the internal variables or "*WHATs*" criteria, the decision-makers are asked to determine the level of importance of each criterion using INS, V = {UI, OI, I, VI, AI}, where UI = Unimportant = ([0.1, 0.2], [0.4, 0.5], [0.6, 0.7]), OI = Ordinary Important = ([0.2, 0.4], [0.5, 0.6], [0.4, 0.5]), I = Important = ([0.4, 0.6], [0.4, 0.5], [0.3, 0.4]), VI = Very Important = ([0.6, 0.8], [0.3, 0.4], [0.2, 0.3]) and AI = Absolutely Important = ([0.7, 0.9], [0.2, 0.3], [0.1, 0.2]). Table 2 displays the importance weights of the "*WHATs*" criteria from the decision-makers. The aggregated weights of the "*WHATs*" criteria are obtained by Equation (8), as shown in the last column of Table 2.

Table 2. Aggregated weights of the "*WHATs*" criteria.

"WHATs"	Decision-Makers				w_i
	D_1	D_2	D_3	D_4	
W_1	AI	AI	VI	VI	([0.654, 0.859], [0.245, 0.346], [0.141, 0.245])
W_2	VI	VI	AI	AI	([0.654, 0.859], [0.245, 0.346], [0.141, 0.245])
W_3	I	VI	VI	I	([0.510, 0.717], [0.346, 0.447], [0.245, 0.346])
W_4	I	VI	I	VI	([0.557, 0.762], [0.322, 0.423], [0.221, 0.322])
W_5	I	VI	I	VI	([0.458, 0.664], [0.372, 0.473], [0.271, 0.372])
W_6	VI	VI	I	VI	([0.557, 0.762], [0.322, 0.423], [0.221, 0.322])

4.2. Aggregate the "HOWs"-"WHATs" Correlation Scores

Assume that the decision-makers use the linguistic rating set $S = \{VL, L, M, H, VH\}$ where VL = Very Low = ([0.1, 0.2], [0.6, 0.7], [0.6, 0.7]), L = Low = ([0.2, 0.3], [0.5, 0.6], [0.6, 0.7]), M = Medium = ([0.3, 0.5], [0.4, 0.6], [0.4, 0.5]), H = High = ([0.5, 0.6], [0.4, 0.5], [0.3, 0.4]) and VH = Very High = ([0.6, 0.7], [0.2, 0.3], [0.2, 0.3]) to evaluate the ratings of "*HOWs*"-"*WHATs*" correlation scores. Table 3 presents the aggregated ratings of "*HOWs*"-"*WHATs*" correlation scores from the decision-makers using Equation (9).

Table 3. Aggregated ratings of "HOWs"-"WHATs" correlation scores.

"*WHATs*"	"*HOWs*"	Decision-Makers				r_{ij}
		D_1	D_2	D_3	D_4	
W_1	H_1	H	M	H	H	([0.456, 0.577], [0.4, 0.523], [0.322, 0.423])
	H_2	H	H	VH	H	([0.527, 0.628], [0.336, 0.44], [0.271, 0.372])
	H_3	M	H	H	H	([0.456, 0.577], [0.4, 0.523], [0.322, 0.423])
	H_4	H	H	H	M	([0.456, 0.577], [0.4, 0.523], [0.322, 0.423])
	H_5	VH	VH	VH	H	([0.577, 0.678], [0.238, 0.341], [0.221, 0.322])
	H_6	M	H	M	H	([0.408, 0.553], [0.4, 0.548], [0.346, 0.447])
W_2	H_1	H	M	H	H	([0.456, 0.577], [0.4, 0.523], [0.322, 0.423])
	H_2	VH	H	H	H	([0.527, 0.628], [0.336, 0.44], [0.271, 0.372])
	H_3	VH	H	VH	VH	([0.577, 0.678], [0.238, 0.341], [0.221, 0.322])
	H_4	H	H	M	H	([0.456, 0.577], [0.4, 0.523], [0.322, 0.423])
	H_5	H	VH	VH	H	([0.553, 0.654], [0.283, 0.387], [0.245, 0.346])
	H_6	M	H	M	M	([0.356, 0.527], [0.4, 0.573], [0.372, 0.473])
W_3	H_1	M	L	L	M	([0.252, 0.408], [0.447, 0.6], [0.49, 0.592])
	H_2	H	M	H	H	([0.456, 0.577], [0.4, 0.523], [0.322, 0.423])
	H_3	H	H	H	H	([0.5, 0.6], [0.4, 0.5], [0.3, 0.4])
	H_4	H	M	H	H	([0.456, 0.577], [0.4, 0.523], [0.322, 0.423])
	H_5	H	VH	H	H	([0.527, 0.628], [0.336, 0.44], [0.271, 0.372])
	H_6	M	L	M	M	([0.276, 0.456], [0.423, 0.6], [0.443, 0.544])
W_4	H_1	M	M	L	M	([0.276, 0.456], [0.423, 0.6], [0.443, 0.544])
	H_2	VH	H	H	H	([0.527, 0.628], [0.336, 0.44], [0.271, 0.372])
	H_3	M	H	H	M	([0.408, 0.553], [0.4, 0.548], [0.346, 0.447])
	H_4	H	H	M	H	([0.456, 0.577], [0.4, 0.523], [0.322, 0.423])
	H_5	M	H	H	H	([0.456, 0.577], [0.4, 0.523], [0.322, 0.423])
	H_6	VH	VH	H	H	([0.553, 0.654], [0.283, 0.387], [0.245, 0.346])
W_5	H_1	VH	H	H	H	([0.527, 0.628], [0.336, 0.44], [0.271, 0.372])
	H_2	H	VH	VH	H	([0.553, 0.654], [0.283, 0.387], [0.245, 0.346])
	H_3	H	H	M	H	([0.456, 0.577], [0.4, 0.523], [0.322, 0.423])
	H_4	VH	H	VH	H	([0.553, 0.654], [0.283, 0.387], [0.245, 0.346])
	H_5	VH	VH	H	VH	([0.577, 0.678], [0.238, 0.341], [0.221, 0.322])
	H_6	H	H	H	H	([0.5, 0.6], [0.4, 0.5], [0.3, 0.4])
W_6	H_1	H	VH	H	H	([0.527, 0.628], [0.336, 0.44], [0.271, 0.372])
	H_2	H	M	H	M	([0.408, 0.553], [0.4, 0.548], [0.346, 0.447])
	H_3	VH	H	VH	H	([0.553, 0.654], [0.283, 0.387], [0.245, 0.346])
	H_4	H	VH	H	H	([0.527, 0.628], [0.336, 0.44], [0.271, 0.372])
	H_5	VH	H	H	VH	([0.553, 0.654], [0.283, 0.387], [0.245, 0.346])
	H_6	M	M	H	H	([0.408, 0.553], [0.4, 0.548], [0.346, 0.447])

4.3. Aggregate the Importance Weights of the "HOWs"

The value for weight of each attribute "*HOWs*" can be obtained using Equation (10), as shown in Table 4.

Table 4. Aggregated importance weights of "*HOWs*."

Criteria	W_j
H_1	([0.239, 0.426], [0.578, 0.717], [0.481, 0.619])
H_2	([0.248, 0.474], [0.548, 0.682], [0.432, 0.576])
H_3	([0.281, 0.473], [0.547, 0.683], [0.434, 0.578])
H_4	([0.272, 0.46], [0.565, 0.698], [0.446, 0.587])
H_5	([0.307, 0.5], [0.51, 0.645], [0.405, 0.552])
H_6	([0.236, 0.431], [0.573, 0.72], [0.476, 0.614])

4.4. Determine Each Potential Supplier's Impacts on the Attributes Considered the "HOWs"

Using Equation (11), the suitability rating of each "*HOWs*" factor on four suppliers, based on four participants and its averaged value, can be obtained as shown in Table 5.

Table 5. Aggregated ratings of each "HOWs" factors in four suppliers.

"*HOWs*"	Suppliers	Decision-Makers				G_{jm}
		D_1	D_2	D_3	D_4	
H_1	A_1	M	M	H	M	([0.085, 0.225], [0.747, 0.879], [0.674, 0.799])
	A_2	M	H	M	H	([0.097, 0.236], [0.747, 0.872], [0.661, 0.789])
	A_3	VH	H	H	H	([0.126, 0.267], [0.72, 0.841], [0.621, 0.761])
	A_4	H	H	H	VH	([0.126, 0.267], [0.72, 0.841], [0.621, 0.761])
H_2	A_1	H	H	H	H	([0.5, 0.6], [0.4, 0.5], [0.3, 0.4])
	A_2	H	H	M	H	([0.456, 0.577], [0.4, 0.523], [0.322, 0.423])
	A_3	H	H	H	VH	([0.126, 0.267], [0.72, 0.841], [0.621, 0.761])
	A_4	M	H	M	H	([0.408, 0.553], [0.4, 0.548], [0.346, 0.447])
H_3	A_1	M	H	H	H	([0.456, 0.577], [0.4, 0.523], [0.322, 0.423])
	A_2	H	M	M	M	([0.085, 0.225], [0.747, 0.879], [0.674, 0.799])
	A_3	H	VH	H	H	([0.126, 0.267], [0.72, 0.841], [0.621, 0.761])
	A_4	L	M	M	M	([0.276, 0.456], [0.423, 0.6], [0.443, 0.544])
H_4	A_1	H	VH	H	H	([0.126, 0.267], [0.72, 0.841], [0.621, 0.761])
	A_2	H	M	H	H	([0.456, 0.577], [0.4, 0.523], [0.322, 0.423])
	A_3	VH	H	H	VH	([0.553, 0.654], [0.283, 0.387], [0.245, 0.346])
	A_4	H	H	H	H	([0.5, 0.6], [0.4, 0.5], [0.3, 0.4])
H_5	A_1	H	M	H	M	([0.097, 0.236], [0.747, 0.872], [0.661, 0.789])
	A_2	H	H	M	H	([0.456, 0.577], [0.4, 0.523], [0.322, 0.423])
	A_3	H	VH	VH	H	([0.553, 0.654], [0.283, 0.387], [0.245, 0.346])
	A_4	H	H	H	VH	([0.126, 0.267], [0.72, 0.841], [0.621, 0.761])
H_6	A_1	H	H	H	H	([0.5, 0.6], [0.4, 0.5], [0.3, 0.4])
	A_2	H	VH	H	VH	([0.553, 0.654], [0.283, 0.387], [0.245, 0.346])
	A_3	L	M	M	L	([0.059, 0.176], [0.764, 0.888], [0.733, 0.842])
	A_4	H	M	M	H	([0.097, 0.236], [0.747, 0.872], [0.661, 0.789])

4.5. Normalize the Averaged Ratings and Weights of the "HOWs"

For simplicity and practicality, all the fuzzy numbers in this paper are defined on the closed interval [0, 1]. Consequently, the normalization procedure is no longer needed.

4.6. Determine the Standardized Weighted Rating

Using Equation (12), the standardized weighted ratings V_j can be obtained as shown in Table 6.

Table 6. Normalized weighted ratings of each supplier.

Suppliers	V_j
A_1	([0.124, 0.268], [0.727, 0.852], [0.626, 0.764])
A_2	([0.121, 0.266], [0.724, 0.85], [0.624, 0.762])
A_3	([0.135, 0.279], [0.703, 0.828], [0.607, 0.75])
A_4	([0.119, 0.263], [0.724, 0.849], [0.627, 0.765])

4.7. Derive S^+, S^-, d_h^+ and d_h^-

As shown in Table 7, the distance of each alternative from S^+ and S^- can be calculated by Equations (13)–(16).

Table 7. Distance measurement.

Suppliers	d^+	d^-
A_1	0.768	0.251
A_2	0.767	0.252
A_3	0.751	0.268
A_4	0.768	0.251

4.8. Find the Closeness Coefficient and Ranking Order of Each Supplier

The closeness coefficients of a supplier can be calculated by Equation (17), as shown in Table 8. Results show that supplier A_1, with the largest closeness coefficient value, is defined as the best supplier for this company. Therefore, the ranking order of the four suppliers is $A_3 \succ A_2 \succ A_1 \succ A_4$.

Table 8. Closeness coefficients of alternatives.

Suppliers	Closeness Coefficient	Ranking
A_1	0.247	3
A_2	0.248	2
A_3	0.263	1
A_4	0.246	4

The INSs are a further generalization of fuzzy, intuitionistic fuzzy and NSs. Hence, the proposed approach in this paper is more typical in applications than the existing QFD approaches [2,40–44,49–51]. Furthermore, the proposed approach can be used to solve not only decision-making problems with incomplete information but also those with indeterminate or inconsistent information.

5. Discussion and Conclusions

Neutrosophic value can better express uncertain, imprecise, incomplete and inconsistent information than other types of fuzzy sets. The main objective of this research is to propose the new integrated QFD approach in INS and to apply it to green supplier selection and evaluation. In the proposed approach, the relative importance of the "*WHATs*," the "*HOWs*"-"*WHATs*" correlation scores, the weights of the "*HOWs*," and the impact of each potential supplier were assessed in INS. The normalized and standardized weighted ratings were then defined and the TOPSIS technique based on INS was presented to rank the alternatives. Finally, the proposed integrated QFD approach was applied to supplier selection and evaluation in the case of Transportation Parts Company Limited in northern Vietnam. Four decision-makers, six "*WHATs*" and six "*HOWs*" evaluation and selection criteria—which include not only the economic criteria but also environmental and social criteria—were used in the decision process. It was demonstrated throughout the detailed calculation in the application that the proposed integrated approach is efficient and is also more generally compared with the approaches of relevant studies.

Future work should use the AHP method to define the importance weight of "*WHATs*" and apply the proposed QFD approach to solve more complex problems in real life.

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