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Research Article

Quality Function Deployment Method under Interval Neutrosophic Environment for Sustainable Supplier Selection

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Abstract

Background and Objective: With increased worldwide awareness of environmental protection, green purchasing has become an important issue for companies to gain environmental sustainability. This study proposes a new Quality Function Deployment (QFD) method based on score, accuracy and certainty functions under interval neutrosophic environment for sustainable supplier selection. Several economic, environmental and social criteria are considered in the decision process. **Materials and Method:** In the proposed approach, the interval neutrosophic set (INS) is applied to assess the importance of the "WHATs", "HOWs", "HOWs"-"WHATs" correlation scores and the impact of each potential supplier. This study applies the score, the accuracy and the certainty functions to rank the alternatives. **Results:** Two numerical examples are used to compare the proposed approach with two others QFD approaches demonstrating its advantages and applicability. The result indicates that the proposed method is efficient and more general compared with those of relevant studies. **Conclusion:** This study has developed the QFD approach using the INS to evaluate sustainable suppliers. The proposed method has great application potential in solving multi-criteria decision making (MCDM) problems in the INS.

Key words: Sustainable supplier selection, interval neutrosophic set, quality function deployment, score function, accuracy function, certainty function

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Data Availability: All relevant data are within the paper and its supporting information files.

INTRODUCTION

Evaluating and selecting sustainable supplier plays an importance role for companies to reduce the purchasing cost of materials, increase quality of products and enhance their competitive advantages in the global market. Historically, supplier selection was mainly based on economic criteria[1-7]. Now a days, with increasing concern towards environmental protection and sustainable development, it becomes important for company to integrate the environmental and social criteria into their supply chain activities. Several economic, environmental and social criteria are engaged in the assessment and selection of an ideal sustainable supplier such as product price, logistics cost, ISO quality system installed, on-time delivery, production facilities and capacity, financial position, etc.[8-10]. Consequently, the sustainable supplier selection is regarded as a multiple criteria decision-making (MCDM) problem.

However, the majority of sustainable supplier selection criteria is generally evaluated by personal judgment and thus might suffer from subjectivity. To solve this problem, Zadeh[11] proposed the Fuzzy Set (FS) theory, which is one of the most effective tools for processing fuzzy information. However, the disadvantage of fuzzy set theory is that it only has a membership and is unable to express non-membership. On the basis of fuzzy set, Atanassov[12,13] proposed the Intuitionistic Fuzzy Set (IFS) by adding a non-membership function. The IFSs can only handle incomplete information not the indeterminate information and inconsistent information. However, in practice, the decision information is often incomplete, indeterminate and inconsistent information. In order to process this kind of information, Smarandache[14] further introduced the Neutrosophic Set (NS) by adding an independent indeterminacy-membership on the basis of IFS. The NS which is a generalization of classical set, fuzzy set and intuitionistic fuzzy set, handles indeterminate data, whereas the fuzzy set and the intuitionistic fuzzy set fail to work when the relations are indeterminate. Since the NS is difficult to be directly used in real-life applications, Wang *et al.*[15] proposed the concept of single-valued NS and provided its theoretic operations and properties.

Now a days, QFD is a quality management technique that is used to convert judgments about degree of importance of requirements into degree of importance of criteria related to those requirements. It has gained wide application to support decision making problems when the aim is to prioritize a list of objectives (HOW) based on a list of requirements (WHAT). Many QFD approaches have been proposed to select and evaluate supplier in the literature[8-10,16-18]. Bhattacharya *et al.*[16] presented a concurrent engineering approach integrating analytic hierarchy process (AHP) with QFD in combination with cost factor measure has been delineated to rank and subsequently select suppliers under multiple, conflicting in nature criteria environment within a value-chain framework. The sensitivity of the proposed methodology was elucidated considering a parameter called objective factor decision weight. Dursun and Karsak[17] presented a fuzzy multi-criteria group decision making approach based on the QFD concept for supplier selection. Their proposed algorithm enables to consider the impacts of inner dependence among supplier assessment criteria. Lima-Junior and Carpinetti[18] presented a new approach to aid the choice and weighting of criteria to be used in the supplier selection process. Their proposed approach combined the fuzzy QFD procedure for weighting the criteria with a procedure for evaluating the difficulty of data collection so as to portray the criteria in a classification grid. Based on the judgments of three decision makers, the proposed method was applied in an automotive company to revise the criteria used as well as their weighting. Yazdani *et al.*[8] proposed an integrated approach for sustainable supplier selection by considering various environmental performance requirements and criteria. In their approach, QFD model was used to establish a central relationship matrix in order to identify degree of relationship between each pair of supplier selection criteria and customer requirements. Then, the complex proportional assessment was applied to prioritize and rank the alternative suppliers. Parkouhi *et al.*[9] developed a conceptual framework for supplier's management which involves selection, segmentation and development of resilient suppliers. The grey DEMATEL method was employed to analyze the structural relationships and to determine the weights of criteria. Grey Simple Additive Weighting method was exploited to prioritize alternatives and finally to segment them.

However, most of existing studies have used the crisp or fuzzy numbers to evaluate and select the suppliers. There exist limited studied on the application of QFD technique under neutrosophic environment for sustainable supplier selection and evaluation[10]. As a result, this study proposes a new QFD approach for supporting sustainable supplier selection and evaluation.

MATERIALS AND METHODS

Definition 1

Neutrosophic Set (NS)[14]: Let X be a space of points and let $x \in X$. A NS $\overline{S}$ in X is characterized by a truth membership function $T_{\bar{S}}$, an indeterminacy membership function $I_{\bar{S}}$ and a falsehood membership function $F_{\bar{S}}$. The $T_{\bar{S}}$, $I_{\bar{S}}$ and $F_{\bar{S}}$ are real standard or non-standard subsets of $]0^-, 1^+[$.

To use NS in some real-life applications, such as engineering and scientific problems, it is necessary to consider the interval [0, 1] instead of $]0^-, 1^+[$, for technical applications.

The NS can be represented as:

$$\bar{S} = \{(x, T_{\bar{S}}(x), I_{\bar{S}}(x), F_{\bar{S}}(x)): x \in X\}$$

where, one has that $0 < \sup T_{\bar{S}}(x) + \sup I_{\bar{S}}(x) + \sup F_{\bar{S}}(x) \leq 33$ and $T_{\bar{S}}$, $I_{\bar{S}}$ and $F_{\bar{S}}$ are subsets of the unit interval [0, 1].

Definition 2

Single valued neutrosophic set[15]: Let X be a universe of discourse, with a generic element in X denoted by x. A single valued NS A in X is $A = \{x(T_A(x), I_A(x), F_A(x)) \mid x \in X\}$, where, $T_A(x)$, $I_A(x)$ and $F_A(x)$ are the truth-membership function, indeterminacy-membership function and the falsity-membership function, respectively. For each point x in X, we have $T_A(x)$, $I_A(x)$, $F_A(x) \in [0, 1]$ and $0 \leq T_A(x) + I_A(x) + F_A(x) \leq 3$.

Definition 3

Interval neutrosophic set[15,19]: Let X be a universe of discourse, with a generic element in X denoted by x. AINS*A* in X is $A = \{x\ (T_A(x), I_A(x), F_A(x)) \mid x \in X\}$, where, $T_A(x)$, $I_A(x)$ and $F_A(x)$ are the truth-membership function, indeterminacy-membership function and the falsity-membership function, respectively. For each point x in X, IT has $T_A(x)$, $I_A(x)$, $F_A(x) \subseteq [0, 1]$ and $0 \leq \sup T_A(x) + \sup I_A(x) + \sup F_A(x) \leq 3$. For convenience, it can use $x = ([T^L, T^U], [I^L, I^U], [F^L, F^U])$ to represent a value in INS and call interval neutrosophic value (INV).

Definition 4

Operational rules of the INV[19]: 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 operational rules are then defined as follows:

The complement of x is:

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

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

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

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

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

Definition 5: Let $x = ([T_1^L, T_1^U], [I_1^L, I_1^U], [F_1^L, F_1^U])$ be an INV. Then, the score function, accuracy function and certainty function for the INVs*x* are defined, respectively, as follows[20]:

$$S(x) = (4 + T_1^L + T_1^U - I_1^L - I_1^U - F_1^L - F_1^U) / 6 \tag{6}$$

$$H(x) = (T_1^L + T_1^U - F_1^L - F_1^U) / 2 \tag{7}$$

$$C(x) = (T_1^L + T_1^U) / 2 \tag{8}$$

The bigger the score, accuracy and certainty functions, the greater the corresponding INN.

Definition 6: 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. Then, the ranking method can be defined as follows:

- If $S(x) \succ S(y)$, then $x \succ y$
- If $S(x) = S(y)$ and $H(x) = H(y)$, then $x \succ y$
- If $S(x) = S(y)$, $H(x) = H(y)$ and $C(x) = C(y)$, then $x \succ y$

PROPOSED QFD METHOD

This section proposes the QFD model based on score, accuracy and certainty functions under interval neutrosophic environment for evaluate and select the sustainable supplier. The procedure of the proposed approach is as the following:

Determining the relative importance of the "WHATs": Let $w_{it} = ([T_{it}^L, T_{it}^U], [I_{it}^L, I_{it}^U], [F_{it}^L, F_{it}^U]), i = 1,..., k, t = 1,..., n$ be the weight assigned by decision-maker D_t to criterion C_i. The average weight $w_i = ([T_i^L, T_i^U], [I_i^L, I_i^U], [F_i^L, F_i^U])$ can be evaluated using the operational rules of the INS as follows:

$$w_i = (\frac{1}{n}) \otimes (w_{i1} \oplus w_{i2} \oplus ... \oplus w_{in}) \tag{9}$$

Where:

$$T_i^L = 1-\left(1-\sum_{t=1}^{n} T_{it}^L\right)^{\frac{1}{n}};\ T_i^U = 1-\left(1-\sum_{t=1}^{n} T_{it}^U\right)^{\frac{1}{n}}$$

$$I_i^L = \left(\sum_{t=1}^{n} I_{it}^L\right)^{\frac{1}{n}};\ I_i^U = \left(\sum_{t=1}^{n} I_{it}^U\right)^{\frac{1}{n}}$$

$$F_i^L = \left(\sum_{t=1}^{n} F_{it}^L\right)^{\frac{1}{n}};\ F_i^U = \left(\sum_{t=1}^{n} F_{it}^U\right)^{\frac{1}{n}}$$

Determining the "WHATs"-"HOWs" correlation scores: Let $x_{ijt} = ([T_{ijt}^L, T_{ijt}^U], [I_{ijt}^L, I_{ijt}^U], [F_{ijt}^L, F_{ijt}^U]),\quad i = 1,...,k, j = 1,\dots,m, t = 1,...,n,$ be the suitability rating assigned by decision-maker D_t for "WHATs" criteria C_i and "HOWs" criteria C_j. The averaged suitability rating, $x_{ij} = ([T_{ij}^L, T_{ij}^U], [I_{ij}^L, I_{ij}^U], [F_{ij}^L, F_{ij}^U])$ can be evaluated using the operational rules of the INS, as follows:

$$x_{ij} = \frac{1}{n} \otimes (x_{ij1} \oplus x_{ij2} \oplus .... \oplus x_{ijt}) \quad (10)$$

Where:

$$T_{ij}^L = 1-\left(1-\sum_{t=1}^{n} T_{ijt}^L\right)^{\frac{1}{n}};\ T_{ij}^U = 1-\left(1-\sum_{t=1}^{n} T_{ijt}^U\right)^{\frac{1}{n}}$$

$$I_{ij}^L = \left(\sum_{t=1}^{n} I_{ijt}^L\right)^{\frac{1}{n}};\ I_{ij}^U = \left(\sum_{t=1}^{n} I_{ijt}^U\right)^{\frac{1}{n}}$$

$$F_{ij}^L = \left(\sum_{t=1}^{n} F_{ijt}^L\right)^{\frac{1}{n}};\ F_{ij}^U = \left(\sum_{t=1}^{n} F_{ijt}^U\right)^{\frac{1}{n}}$$

Determine the weights of the "HOWs" criteria: The weights of the "HOWs" are calculated by averaging the aggregate ratings x_{ij} correlation scores with the aggregate weights of the "WHATs" w_i as follows:

$$W_j = (\frac{1}{k})\sum_{i=1}^{k}(w_i x_{ij}) = \left(\left[1-(1-\sum_{i=1}^{k} T_{ij}^L T_i^L)^{1/k}, 1-(1-\sum_{i=1}^{k} T_{ij}^U T_i^U)^{1/k}\right],\right.$$
$$\left.\left[(\sum_{i=1}^{k} I_{ij}^L I_i^L)^{1/k}, (\sum_{i=1}^{k} I_{ij}^U I_i^U)^{1/k}\right], \left[(\sum_{i=1}^{k} F_{ij}^L F_i^L)^{1/k}, (\sum_{i=1}^{k} F_{ij}^U F_i^U)^{1/k}\right]\right) \quad (11)$$

Determine each potential supplier impact on the attributes considered "HOWs": Let $SR_{hjt} = ([T_{hjt}^L, T_{hjt}^U], [I_{hjt}^L, I_{hjt}^U], [F_{hjt}^L, F_{hjt}^U]),$ $h = 1,\dots,s,\ j = 1,\dots,m,\ t = 1,\dots,n$ be the suitability rating assigned to supplier A_h by decision-maker D_t for "HOWs" criteria C_j. The averaged suitability rating, $SR_{hj} = ([T_{hj}^L, T_{hj}^U], [I_{hj}^L, I_{hj}^U], [F_{hj}^L, F_{hj}^U]),$ can be evaluated as:

$$G_{hj} = \frac{1}{n} \otimes (G_{hj1} \oplus G_{hj2} \oplus ... \oplus G_{hjn}) \quad (12)$$

Where:

$$T_{hj}^L = 1-\left(1-\sum_{t=1}^{n} T_{hjt}^L\right)^{1/n};\ T_{hj}^U = 1-\left(1-\sum_{t=1}^{n} T_{hjt}^U\right)^{1/n}$$

$$I_{hj}^L = \left(\sum_{t=1}^{n} I_{hjt}^L\right)^{1/n};\ I_{hj}^U = \left(\sum_{t=1}^{n} I_{hjt}^U\right)^{1/n}$$

$$F_{hj}^L = \left(\sum_{t=1}^{n} F_{hjt}^L\right)^{1/n};\ F_{hj}^U = \left(\sum_{t=1}^{n} F_{hjt}^U\right)^{1/n}$$

Determine the weighted rating: The weighted ratings $V_h = ([\dot{T}_h^L, \dot{T}_h^U], [\dot{I}_h^L, \dot{I}_h^U], [\dot{F}_h^L, \dot{F}_h^U])$ are calculated by multiplying the averaged suitability rating r_{ij} with its associated weights W_j as follows:

$$V_h = \frac{1}{j} \otimes [(r_{h1} \otimes W_1) \oplus \cdots \oplus (r_{hm} \otimes W_m)],\ h = 1,\dots,s, j = 1,\dots,m \quad (13)$$

Where:

$$\dot{T}_h^L = 1-\left(1-\sum_{h=1}^{m} T_{hj}^L\right)^{1/j};\ \dot{T}_h^U = 1-\left(1-\sum_{j=1}^{m} T_{hj}^U\right)^{1/j}$$

$$\dot{I}_h^L = \left(\sum_{j=1}^{m} I_{hj}^L\right)^{1/k};\ \dot{I}_h^U = \left(\sum_{j=1}^{m} I_{hj}^U\right)^{1/k}$$

Ranking the alternatives: Using the Eq. 6-8, the modified score function, the accuracy function and the certainty function of the weighted ratings are as the following:

$$S(V_h) = (4 + \dot{T}_h^L + \dot{T}_h^U - \dot{I}_h^L - \dot{I}_h^U - \dot{F}_h^L - \dot{F}_h^U) / 6 \quad (14)$$

$$H(V_h) = (\dot{T}_h^L + \dot{T}_h^U - \dot{F}_h^L - \dot{F}_h^U) / 2 \quad (15)$$

$$C(V_h) = (\dot{T}_h^L + \dot{T}_h^U) / 2 \quad (16)$$

Let V_1 and V_2 be any two INSs. Then, the ranking method can be defined as follows:

- If $S(V_1) \succ S(V_2)$, then $V_1 \succ V_2$
- If $S(V_1) = S(V_2)$ and $H(V_1) = H(V_2)$, then $V_1 \succ V_2$
- If $S(V_1) = S(V_2)$, $H(V_1) = H(V_2)$ and $C(V_1) \succ C(V_2)$, then $V_1 \succ V_2$
- If $S(V_1) = S(V_2)$, $H(V_1) = H(V_2)$ and $C(V_1) = C(V_2)$, then $V_1 \succ V_2$

COMPARISON OF THE PROPOSED METHOD AND OTHER QFD METHODS

Example 1: This section compares the proposed approach with another QFD approach under neutrosophic environment to demonstrate its advantages and applicability. It reconsiders the example investigated by Van *et al.*[10], in which a Transportation Parts Company Limited in northern Vietnam desires to evaluate and select the sustainable suppliers, which are evaluated by a committee of four experts against six "WHATs" and six "HOWs" criteria. Table 1 shows the linguistic ratings of alternatives and importance weights of criteria.

Using the proposed ranking method and the data presented in Table 2-6 in the work of Van *et al.*[10], the modified score function, the accuracy function and the certainty function of the sustainable suppliers are shown in Table 2.

According to this table, the ranking order of the four suppliers is $A_3 \succ A_2 \succ A_1 \succ A_4$. So the best supplier is A_3. The result is the same as that of Van *et al.*[10].

Example 2: This section compares the proposed approach with another QFD approach to demonstrate its advantages and applicability by reconsidering the example investigated by Bevilacqua *et al.*[21]. In this example, three decision makers ($D_1,\cdots, D_3$) have been appointed to evaluate 10 suppliers ($A_1,\cdots, A_{10}$) based on six "WHATs" criteria, i.e., conformity (W_1), cost (W_2), punctuality (W_3), efficacy (W_4), availability (W_5), programming (W_6) and seven "HOWs" criteria, i.e., experience of the sector (H_1), capacity for innovation (H_2), quality system certification (H_3), flexibility of response to the customer's requests (H_4), financial stability (H_5), ability to manage orders on-line (H_6), geographical position (H_7).

Aggregate the importance weights of the "WHATs": Table 2 displayed the importance weights of the "WHATs" criteria from the decision-makers based on the data presented in Table 1 in the work of Bevilacqua *et al.*[21]. The aggregated weights of the "WHATs" criteria are obtained by Eq. 9 and Table 1 as shown in the last column of Table 3.

Aggregate the "HOWs"-"WHATs" correlation scores: Table 4 presents the suitability ratings assigned by decision-maker based on the data presented in Table 2 in the work of Bevilacqua *et al.*[21]. The aggregated ratings of "HOWs"-"WHATs" correlation scores are obtained by Eq. 10 and Table 1, as shown in the last column of Table 4.

Table 1: Linguistic ratings of alternatives and importance weight of criteria

Linguistic ratings of alternatives		Importance weights of criteria	
Linguistic variables	INSs	Linguistic varibales	INSs
Very Low (VL)	([0.1, 0.2], [0.6, 0.7], [0.6, 0.7])	Unimportant (UI)/ Very Low (VL)	([0.1, 0.2], [0.4, 0.5], [0.6, 0.7])
Low (L)	([0.2, 0.3], [0.5, 0.6], [0.6, 0.7])	Ordinary Important (OI)/ Low (L)	([0.2, 0.4], [0.5, 0.6], [0.4, 0.5])
Medium (M)	([0.3, 0.5], [0.4, 0.6],[0.4, 0.5])	Important (I)/ Medium (M)	([0.4, 0.6], [0.4, 0.5], [0.3, 0.4])
High (H)	([0.5, 0.6], [0.4, 0.5], [0.3, 0.4])	Very Important (VI)/ High (H)	([0.6, 0.8], [0.3, 0.4], [0.2, 0.3])
Very High (VH)	([0.6, 0.7], [0.2, 0.3], [0.2, 0.3])	Absolutely Important (AI)/ Very High (VH)	([0.7, 0.9], [0.2, 0.3], [0.1, 0.2])

Table 2: Modified score, accuracy and certainty function of each supplier

Suppliers	Score function	Accuracy function	Certainty function	Ranking
A_1	0,237	-0,499	0,196	3
A_2	0,238	-0,500	0,193	2
A_3	0,254	-0,472	0,207	1
A_4	0,236	-0,505	0,191	4

Table 3: Aggregated weights of the "WHATs" criteria

	Decision makers			
"WHATs"	D_1	D_2	D_3	w_i
W_1	VH	VH	H	([0,670, 0,874], [0,229, 0,3], [0,126, 0,2])
W_2	M	L	M	([0,340, 0,542], [0,431, 0,5], [0,330, 0,4])
W_3	H	M	M	([0,476, 0,683], [0,363, 0,5], [0,262, 0,4])
W_4	M	M	L	([0,340, 0,542], [0,431, 0,5], [0,330, 0,4])
W_5	L	VL	L	([0,200, 0,273], [0,271, 0,3], [0,252, 0,3])
W_6	M	L	L	([0,273, 0,476], [0,464, 0,6], [0,363, 0,5])

Table 4: Aggregated ratings of "HOWs"-"WHATs" correlation scores

		Decision makers			
"WHATs"	"HOWs"	D_1	D_2	D_3	r_{ij}
W_1	H_1	VH	H	H	([0,900, 0,952], [0,032, 0,075], [0,018, 0,048])
	H_2	VH	VH	VH	([0,936, 0,973], [0,008, 0,027], [0,008, 0,027])
	H_3	L	VL	VL	([0,352, 0,552], [0,180, 0,294], [0,216, 0,343])
	H_4	M	L	L	([0,552, 0,755], [0,100, 0,216], [0,144, 0,245])
	H_5	L	VL	VL	([0,352, 0,552], [0,180, 0,294], [0,216, 0,343])
	H_6	H	H	H	([0,875, 0,936], [0,064, 0,125], [0,027, 0,064])
	H_7	L	L	L	([0,488, 0,657], [0,125, 0,216], [0,216, 0,343])
W_2	H_1	M	M	L	([0,608, 0,825], [0,080, 0,216], [0,096, 0,175])
	H_2	H	H	M	([0,825, 0,920], [0,064, 0,150], [0,036, 0,080])
	H_3	VH	VH	VH	([0,936, 0,973], [0,008, 0,027], [0,008, 0,027])
	H_4	L	L	L	([0,488, 0,657], [0,125, 0,216], [0,216, 0,343])
	H_5	M	M	M	([0,657, 0,875], [0,064, 0,216], [0,064, 0,125])
	H_6	L	L	VL	([0,424, 0,608], [0,150, 0,252], [0,216, 0,343])
	H_7	M	M	H	([0,755, 0,900], [0,064, 0,180], [0,048, 0,100])
W_3	H_1	H	M	H	([0,825, 0,920], [0,064, 0,150], [0,036, 0,080])
	H_2	M	M	M	([0,657, 0,875], [0,064, 0,216], [0,064, 0,125])
	H_3	L	L	L	([0,488, 0,657], [0,125, 0,216], [0,216, 0,343])
	H_4	H	VH	VH	([0,920, 0,964], [0,016, 0,045], [0,012, 0,036])
	H_5	L	L	L	([0,488, 0,657], [0,125, 0,216], [0,216, 0,343])
	H_6	VH	VH	VH	([0,936, 0,973], [0,008, 0,027], [0,008, 0,027])
	H_7	H	H	H	([0,875, 0,936], [0,064, 0,125], [0,027, 0,064])
W_4	H_1	H	H	VH	([0,900, 0,952], [0,032, 0,075], [0,018, 0,048])
	H_2	VH	VH	VH	([0,936, 0,973], [0,008, 0,027], [0,008, 0,027])
	H_3	M	L	L	([0,552, 0,755], [0,100, 0,216], [0,144, 0,245])
	H_4	H	VH	VH	([0,920, 0,964], [0,016, 0,045], [0,012, 0,036])
	H_5	L	L	L	([0,488, 0,657], [0,125, 0,216], [0,216, 0,343])
	H_6	M	VL	H	([0,685, 0,840], [0,096, 0,210], [0,072, 0,140])
	H_7	L	VL	VL	([0,352, 0,552], [0,180, 0,294], [0,216, 0,343])
W_5	H_1	H	H	H	([0,875, 0,936], [0,064, 0,125], [0,027, 0,064])
	H_2	H	H	M	([0,825, 0,920], [0,064, 0,150], [0,036, 0,080])
	H_3	L	L	L	([0,488, 0,657], [0,125, 0,216], [0,216, 0,343])
	H_4	M	M	M	([0,657, 0,875], [0,064, 0,216], [0,064, 0,125])
	H_5	L	VL	VL	([0,352, 0,552], [0,180, 0,294], [0,216, 0,343])
	H_6	H	H	H	([0,875, 0,936], [0,064, 0,125], [0,027, 0,064])
	H_7	VL	VL	VL	([0,271, 0,488], [0,216, 0,343], [0,216, 0,343])
W_6	H_1	H	M	H	([0,825, 0,920], [0,064, 0,150], [0,036, 0,080])
	H_2	VH	VH	H	([0,920, 0,964], [0,016, 0,045], [0,012, 0,036])
	H_3	VL	L	L	([0,424, 0,608], [0,150, 0,252], [0,216, 0,343])
	H_4	H	VH	VH	([0,920, 0,964], [0,016, 0,045], [0,012, 0,036])
	H_5	M	M	M	([0,657, 0,875], [0,064, 0,216], [0,064, 0,125])
	H_6	H	H	VH	([0,900, 0,952], [0,032, 0,075], [0,018, 0,048])
	H_7	H	H	VH	([0,900, 0,952], [0,032, 0,075], [0,018, 0,048])

Table 5: Aggregated importance weights of "HOWs"

Criteria	W_j
H_1	([0,183, 0,340], [0,599, 0,720], [0,501, 0,627])
H_2	([0,197, 0,369], [0,553, 0,687], [0,471, 0,603])
H_3	([0,094, 0,206], [0,659, 0,765], [0,650, 0,760])
H_4	([0,154, 0,303], [0,591, 0,721], [0,541, 0,664])
H_5	([0,078, 0,194], [0,680, 0,795], [0,666, 0,772])
H_6	([0,179, 0,327], [0,602, 0,716], [0,511, 0,637])
H_7	([0,121, 0,250], [0,663, 0,772], [0,605, 0,721])

Aggregate the importance weights of the "HOWs": The value for weight of each attribute "HOWs" can be obtained using Eq. 11 as shown in Table 5.

Determine each potential supplier' impacts on the attributes considered the "HOWs": Table 6 shows the suitability rating of each "HOWs" factor on 10 suppliers by 3 decision makers based on the data presented in Table 3 in the work of Bevilacqua *et al.*[21]. The averaged rating of each "HOWs" can be obtained by Eq. 12 and Table 1 as shown in the last column of Table 6.

Determine the weighted rating: Using Eq. 13, the weighted ratings V_h can be obtained as shown in Table 7.

Table 6: Aggregated ratings of each "HOWs" factors in 10 suppliers

		Decision makers			
"HOWs"	Suppliers	D_1	D_2	D_3	G_{hj}
H_1	A_1	M	L	M	([0,608, 0,825], [0,080, 0,216], [0,096, 0,175])
	A_2	H	H	H	([0,875, 0,936], [0,064, 0,125], [0,027, 0,064])
	A_3	L	M	VL	([0,496, 0,720], [0,120, 0,252], [0,144, 0,245])
	A_4	M	M	L	([0,608, 0,825], [0,080, 0,216], [0,096, 0,175])
	A_5	VH	VH	VH	([0,936, 0,973], [0,008, 0,027], [0,008, 0,027])
	A_6	H	VH	VH	([0,920, 0,964], [0,016, 0,045], [0,012, 0,036])
	A_7	VL	L	VL	([0,352, 0,552], [0,180, 0,294], [0,216, 0,343])
	A_8	L	L	H	([0,680, 0,804], [0,100, 0,180], [0,108, 0,196])
	A_9	M	M	M	([0,657, 0,875], [0,064, 0,216], [0,064, 0,125])
	A_{10}	H	H	H	([0,875, 0,936], [0,064, 0,125], [0,027, 0,064])
H_2	A_1	L	M	L	([0,552, 0,755], [0,100, 0,216], [0,144, 0,245])
	A_2	H	M	M	([0,755, 0,900], [0,064, 0,180], [0,048, 0,100])
	A_3	VH	H	VH	([0,920, 0,964], [0,016, 0,045], [0,012, 0,036])
	A_4	H	H	H	([0,875, 0,936], [0,064, 0,125], [0,027, 0,064])
	A_5	VH	VH	VH	([0,936, 0,973], [0,008, 0,027], [0,008, 0,027])
	A_6	L	VL	L	([0,424, 0,608], [0,150, 0,252], [0,216, 0,343])
	A_7	M	M	M	([0,657, 0,875], [0,064, 0,216], [0,064, 0,125])
	A_8	M	H	M	([0,755, 0,900], [0,064, 0,180], [0,048, 0,100])
	A_9	H	H	H	([0,875, 0,936], [0,064, 0,125], [0,027, 0,064])
	A_{10}	VL	L	VL	([0,352, 0,552], [0,180, 0,294], [0,216, 0,343])
H_3	A_1	M	L	M	([0,608, 0,825], [0,080, 0,216], [0,096, 0,175])
	A_2	M	M	H	([0,755, 0,900], [0,064, 0,180], [0,048, 0,100])
	A_3	VH	VH	H	([0,920, 0,964], [0,016, 0,045], [0,012, 0,036])
	A_4	VL	VL	L	([0,352, 0,552], [0,180, 0,294], [0,216, 0,343])
	A_5	VL	VL	VL	([0,271, 0,488], [0,216, 0,343], [0,216, 0,343])
	A_6	M	M	L	([0,608, 0,825], [0,080, 0,216], [0,096, 0,175])
	A_7	VH	VH	VH	([0,936, 0,973], [0,008, 0,027], [0,008, 0,027])
	A_8	H	H	H	([0,875, 0,936], [0,064, 0,125], [0,027, 0,064])
	A_9	M	M	L	([0,608, 0,825], [0,080, 0,216], [0,096, 0,175])
	A_{10}	M	M	H	([0,755, 0,900], [0,064, 0,180], [0,048, 0,100])
H_4	A_1	M	M	H	([0,755, 0,900], [0,064, 0,180], [0,048, 0,100])
	A_2	VH	VH	H	([0,920, 0,964], [0,016, 0,045], [0,012, 0,036])
	A_3	L	L	L	([0,488, 0,657], [0,125, 0,216], [0,216, 0,343])
	A_4	VL	VL	L	([0,352, 0,552], [0,180, 0,294], [0,216, 0,343])
	A_5	H	H	H	([0,875, 0,936], [0,064, 0,125], [0,027, 0,064])
	A_6	M	M	M	([0,657, 0,875], [0,064, 0,216], [0,064, 0,125])
	A_7	H	VH	VH	([0,920, 0,964], [0,016, 0,045], [0,012, 0,036])
	A_8	VL	VL	L	([0,352, 0,552], [0,180, 0,294], [0,216, 0,343])
	A_9	L	H	L	([0,680, 0,804], [0,100, 0,180], [0,108, 0,196])
	A_{10}	L	L	VL	([0,424, 0,608], [0,150, 0,252], [0,216, 0,343])
H_5	A_1	M	M	M	([0,657, 0,875], [0,064, 0,216], [0,064, 0,125])
	A_2	VH	VH	VH	([0,936, 0,973], [0,008, 0,027], [0,008, 0,027])
	A_3	L	L	L	([0,488, 0,657], [0,125, 0,216], [0,216, 0,343])
	A_4	H	H	H	([0,875, 0,936], [0,064, 0,125], [0,027, 0,064])
	A_5	M	M	L	([0,608, 0,825], [0,080, 0,216], [0,096, 0,175])
	A_6	H	H	VH	([0,900, 0,952], [0,032, 0,075], [0,018, 0,048])
	A_7	L	L	L	([0,488, 0,657], [0,125, 0,216], [0,216, 0,343])
	A_8	H	H	H	([0,875, 0,936], [0,064, 0,125], [0,027, 0,064])
	A_9	VL	VL	VL	([0,271, 0,488], [0,216, 0,343], [0,216, 0,343])
	A_{10}	VH	VH	H	([0,920, 0,964], [0,016, 0,045], [0,012, 0,036])
H_6	A_1	VL	L	L	([0,424, 0,608], [0,150, 0,252], [0,216, 0,343])
	A_2	VL	L	VL	([0,352, 0,552], [0,180, 0,294], [0,216, 0,343])
	A_3	VL	L	L	([0,424, 0,608], [0,150, 0,252], [0,216, 0,343])
	A_4	VL	VL	VL	([0,271, 0,488], [0,216, 0,343], [0,216, 0,343])
	A_5	L	L	M	([0,552, 0,755], [0,100, 0,216], [0,144, 0,245])
	A_6	VL	VL	VL	([0,271, 0,488], [0,216, 0,343], [0,216, 0,343])
	A_7	M	M	H	([0,755, 0,900], [0,064, 0,180], [0,048, 0,100])
	A_8	VH	VH	VH	([0,936, 0,973], [0,008, 0,027], [0,008, 0,027])
	A_9	VL	VL	L	([0,352, 0,552], [0,180, 0,294], [0,216, 0,343])
	A_{10}	VL	VL	M	([0,433, 0,680], [0,144, 0,294], [0,144, 0,245])

Table 6: Continue

		Decision makers			
"HOWs"	Suppliers	D_1	D_2	D_3	G_{hj}
H_7	A_1	VL	M	L	([0,496, 0,720], [0,120, 0,252], [0,144, 0,245])
	A_2	L	L	M	([0,552, 0,755], [0,100, 0,216], [0,144, 0,245])
	A_3	VL	L	VL	([0,352, 0,552], [0,180, 0,294], [0,216, 0,343])
	A_4	VH	H	H	([0,900, 0,952], [0,032, 0,075], [0,018, 0,048])
	A_5	VL	VL	M	([0,433, 0,680], [0,144, 0,294], [0,144, 0,245])
	A_6	VL	VL	L	([0,352, 0,552], [0,180, 0,294], [0,216, 0,343])
	A_7	L	M	L	([0,552, 0,755], [0,100, 0,216], [0,144, 0,245])
	A_8	VL	VL	L	([0,352, 0,552], [0,180, 0,294], [0,216, 0,343])
	A_9	VL	VL	L	([0,352, 0,552], [0,180, 0,294], [0,216, 0,343])
	A_{10}	VL	VL	M	([0,433, 0,680], [0,144, 0,294], [0,144, 0,245])

Table 7: Weighted ratings of each supplier

Suppliers	V_h
A_1	([0,037, 0,117], [0,791, 0,896], [0,772, 0,867])
A_2	([0,056, 0,147], [0,766, 0,873], [0,723, 0,832])
A_3	([0,043, 0,116], [0,785, 0,880], [0,768, 0,865])
A_4	([0,044, 0,121], [0,798, 0,891], [0,756, 0,856])
A_5	([0,058, 0,147], [0,765, 0,870], [0,723, 0,832])
A_6	([0,041, 0,118], [0,788, 0,888], [0,759, 0,858])
A_7	([0,049, 0,136], [0,769, 0,876], [0,741, 0,845])
A_8	([0,052, 0,136], [0,781, 0,878], [0,737, 0,843])
A_9	([0,040, 0,114], [0,803, 0,897], [0,769, 0,865])
A_{10}	([0,040, 0,114], [0,797, 0,892], [0,763, 0,861])

Table 8: Modified score, accuracy and certainty function of each supplier

Suppliers	Score function	Accuracy function	Certainty function	Ranking
A_1	0,1377	-0,743	0,077	9
A_2	0,1682	-0,676	0,102	2
A_3	0,1435	-0,737	0,080	7
A_4	0,1439	-0,724	0,082	6
A_5	0,1692	-0,675	0,103	1
A_6	0,1444	-0,729	0,080	5
A_7	0,1587	-0,701	0,092	3
A_8	0,1582	-0,696	0,094	4
A_9	0,1366	-0,740	0,077	10
A_{10}	0,1402	-0,735	0,077	8

Ranking the alternatives: Using the Eq. 14-16, the modified score function, the accuracy function and the certainty function of the suitable suppliers are shown in Table 8.

According to this Table 8, the ranking order of the 10 suppliers is $A_5 \succ A_2 \succ A_7 \succ A_8 \succ A_6 \succ A_4 \succ A_3 \succ A_{10} \succ A_1 \succ A_9$. Obviously, the results in Bevilacqua[21] conflicted with ours in this paper. The reason for the difference is in the proposed method: INS was used to measure the ratings of the suppliers and the importance weights of criteria.

DISCUSSION

Sustainable supplier selection and evaluation plays an importance role for companies to enhance the company competence in the market by decreasing the purchasing cost of materials and enhancing the quality of products. To select the suitable sustainable supplier, several economic, environmental and social criteria are needed to involve in the decision process[6,7,10]. Literature review indicated that the majority of sustainable supplier selection criteria is generally evaluated by personal judgment and thus might suffer from subjectivity[5,9]. To solve this problem, this paper proposed the new QFD method based on the score, the accuracy and the certainty function under INS. 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 supplier are assessed in INS. Two numerical examples have given to compare the proposed approach with two others QFD approaches illustrating its advantages and applicability. It shows that the proposed approach is simple and easy to use and more general compared with those of relevant studies[10,21].

CONCLUSION

The INS can better express the incomplete, indeterminate and inconsistent information than the fuzzy set, interval valued fuzzy set, intuitionistic fuzzy set and so on. This paper proposed the new QFD method to solve the sustainable supplier selection under INS. To illustrate the advantages and applicability of the proposed method, comparing examples were given. In the future, the QFD approach could be extended by integrating with other methods such as Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), analytic hierarchy process (AHP) method under neutrosophic environment and give the application of the proposed approach to the other fields.

SIGNIFICANCE STATEMENT

This study proposes a new Quality Function Deployment (QFD) method for sustainable supplier selection under interval neutrosophic environment. In the proposed method, the score, accuracy and certainty functions are applied to rank the sustainable supplier. This study will help companies to reduce the purchasing cost of materials, increase quality of products and enhance their competitive advantages in the global market.

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