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Optimization Decision of Supplier Selection in Green Procurement under the Mode of Low Carbon Economy

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Abstract

Under the background of economic globalization, selecting a path of low-carbon economic development and developing green supply chains are the inevitable choice of realizing the sustainable development for the enterprises. In this paper, we investigate the optimization decision problem of supplier selection in green procurement under the mode of low carbon economy. Concretely, we construct a new evaluation system for green supplier selection by considering commercial criterion and environmental criterion, and then present a decision method with 2-tuple linguistic assessments for green supplier selection. In this proposed decision method, all original decision data are transformed into linguistic 2-tuples, and then a ranking method based on 2-tuple weighted averaging (*TWA*) operator and 2-tuple ordered weighted averaging (*TOWA*) operator is presented to rank all alternative suppliers. Moreover, we provide an application decision making example of green supplier selection and compare our method with the method of linguistic 2-tuple Technique for Order Preference by Similarity to an Ideal Solution (LT-TOPSIS) to demonstrate the practicality and effectiveness of our decision method.

Keywords: Supplier selection; Low carbon economy; Green procurement; Linguistic 2-tuple; TOWA operator

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1. Introduction

With the intensification of market competition, people pay more and more attention to the environment pollution and low carbon economy. A low carbon economy (LCE) is an economy based on low carbon power sources that therefore has a minimal output of greenhouse gas (GHG) emissions into the environment biosphere, but specifically refers to the greenhouse gas carbon dioxide [1, 2]. In the background of coordinated development of economy and environment, green supply chain management (GSCM) is developed rapidly and is considered as an important way for enterprises to achieve sustainable development [3]. It is of great practical significance for enterprises to solve environmental problems and achieve sustainable development through the implementation of GSCM [4, 5]. GSCM will enable enterprises to obtain economic benefits while also to get social environmental benefits.

In the GSCM under a low-carbon economy mode, the competition means of enterprises have developed gradually from quality competition, service competition and brand competition to green competition, and the international green trade barriers are threatening the export of our products and directly affect the competitiveness of our business in the global market. Faced with the pressure from a variety of competitions, the enterprises must do green reformation for the whole supply chain starting from raw material procurement to strengthen their competitiveness. As a source of green reformation, green procurement is the key to the success of reformation. Green procurement is the procurement practice which considers environmental factors together with a series of actions such as reducing procurement costs, reducing carbon emissions, protecting the environment and resources, and so on. Green procurement is an efficient procurement, which considers that how to reduce negative impaction on environment that bring from procurement, and meanwhile to meet the requirements of products and services for the buyers under the condition of costs controlling.

In the green procurement management, one of the important activities is the supplier selection, especially to select green suppliers in line with the sustainable development strategy. Suppliers are in the upstream of the whole supply chain, and their activities will be passed to each node of the whole supply chain. The role of green suppliers on cost savings and environmental protection can be passed through to all nodes of the downstream in supply chain, so as to improve the overall efficiency of the supply chain. In this sense, supplier evaluation and selection plays a pivotal role in the overall green supply chain, which will directly affect the competitiveness of enterprises and the operating results of the entire green supply chain. Therefore, to present a scientific and reliable evaluation system and evaluation method for green supplier selection is a very important problem with realistic significance.

Up to now, there are many scholars proposed a number of different evaluation methods and models to solve the problem of supplier evaluation and selection. To sum up, they are mainly divided into three categories. The first one is the qualitative evaluation methods [6] like intuitive judgment method, Delphi method, negotiation method, and so on. These methods are simple and easy to operate, but they are too subjective and lack of science and rationality, and most of them make decision making based on experience or some certainty attributes. Thus, the qualitative methods are gradually replaced by the quantitative selection methods in the practice. The second one is the quantitative selection methods, such as benefit-cost analysis method [7, 8], analytic network process (ANP) [9, 10], data envelopment analysis (DEA) [11], Green DEA [12], VIseKriterijumska Optimizacija I Kompromisno Resenje (VIKOR) method [13, 14], techniques for order preferences by similarity to ideal solution (TOPSIS) [15, 16], grey relational analysis model [17, 18], two-level genetic algorithm [19], believable rough set approach [20], new normalized goal programming [21], multi-objective linear programming [22], mixed integer programming [23, 24], multi-objective integer linear programming [25]. These quantitative selection methods have more obvious advantages than the qualitative selection methods, and can solve specific problems under the deterministic environment, but the quantitative selection methods are generally based on deterministic evaluation attributes, and are difficult to quantify some qualitative attributes, and then unable to meet all requirements of processing uncertain information in supply chain environment. The last one is the combination of quantitative and qualitative methods, such as analytic hierarchy process (AHP) [26, 27], fuzzy AHP [28], D-AHP [29], fuzzy TOPSIS [30, 31], hybrid model including fuzzy ANP and fuzzy

TOPSIS [32], integrated method including fuzzy AHP and fuzzy TOPSIS [33], hybrid method including AHP, DEA and neural network (NN) [34], integrated method including artificial neural network (ANN), DEA and ANP [35], and so on. The combination of quantitative and qualitative methods can solve more decision problems of supply selection with the uncertainty under the complex and changeable situation by more scientific and rational way.

Obviously, the study of supplier evaluation and selection has been a hot research topic of supply chain management, and the recent research has the following trend. Firstly, the evaluation attributes and index system gradually become systematic, diverse and comprehensive. Secondly, the evaluation methods and models tended to be more and more reasonable from the original mainly qualitative judgment, and gradually to develop into the direction of the combination of qualitative and quantitative methods. On model applications, the single methods are replaced gradually by the combination methods formed by multiple single methods. Thirdly, the evaluation object gradually refined from the original general studies to steer specific industries and specific supplier evaluation. And some studies have proposed different evaluation index systems for different industries and suppliers.

From the comprehensive analysis of existing methods of supplier selection, we can conclude that quality, price/cost, flexibility, delivery time, service ability and supplier's reputation are the main evaluation criteria to be considered in most methods for selecting the best fit supplier. However, not many studies have considered the environmental performance and the related issues for supplier evaluation and selection. Even though there are a few methods to consider environmental factors, most of them are based on the assumption of complete and certain decision-making information. However, in the practical decision making of supplier selection, it is difficult to get the supplier's precise data and information of environmental performance for the buyer when considering the environmental attributes such as environment treatment input and low carbon emissions. The evaluation results of these attributes are given often only in the form of linguistic fuzzy variable (such as better, good, bad or very high, high, low). This fact puts forward a challenge to the existing supplier selection methods. In essence, mainly because there are often incomplete information sharing between suppliers and buyer, coupled with the complexity of the decision-making environment, thus lead to a certain fuzzification and uncertainty to the carbon emissions data. Therefore, how to deal with fuzzification and uncertainty under a complex and fuzzy situation in the green supplier selection process is the focus of our study.

In this paper, we focus on investigating the problem of supplier selection in the green procurement under the background of low carbon economy and green supply chain management. A new evaluation system for green supplier selection is constructed by considering the attributes under commercial criterion and environmental criterion. Then an optimization decision method with 2-tuple linguistic assessments is designed for selecting green suppliers. Our contribution is thus to provide a theoretical basis and decision-making reference to help firms select green suppliers in green supply chain management under a complex and fuzzy information environment.

The rest of this paper is organized as follows. Section 2 proposes an evaluation system for green supplier selection by considering the commercial criterion and the environmental criterion. Section 3 presents a multi-attribute group decision making method with 2-tuple linguistic assessments for green supplier selection under a fuzzy uncertainty information environment. Section 4 provides an application decision making example of green supplier selection and compares our method with the method of LT-TOPSIS to demonstrate the practicality and effectiveness of our decision method. Section 5 concludes the paper.

2. Evaluation System of Green Supplier Selection

Suppliers' environmental performance also determines the environmental performance of purchasers. Therefore, when dealing with the problem of green supplier selection, we not only consider the commercial criterion in the traditional supplier selection, such as product quality, price, delivery time, suppliers' reputation, service quality (including cooperative attitude and after-sales service), but also consider the environmental performance of suppliers [1, 2, 12, 31, 34], namely, (1) environmental quality criterion: pollutant emissions level in the production, rate of reaching the standard for main attributes of environmental quality, the consumption of environmental resources, level of poisonous and harmful material use, recycling utilization level of waste material, and so on. (2) Environmental management criterion: the establishment of environmental management system, discharge payment, pollution treatment and control, and so on. (3) Environmental input criterion: costs of clean production technology development, investment of environmental technology development and maintenance personnel, costs of education and training of staffs, and so on. This paper presents a new evaluation system for green supplier selection by considering both the commercial criterion and the environmental criterion. The detailed evaluation system is shown in Table 1.

Table 1. Evaluation system of green supplier selection

Attribute	Sub-attribute
Commercial criterion	A_1 Quality A_2 Price A_3 Delivery time A_4 On-time delivery rate A_5 After-sales service A_6 Supplier reputation
Environmental criterion	A_7 Carbon emissions A_8 Level of wastewater discharge A_9 Level of solid waste generation A_{10} Noise level A_{11} Recycling utilization level of waste material A_{12} Level of poisonous and harmful material utilization A_{13} Level of clean energy utilization A_{14} Level of environmental protection input A_{15} Level of environmental management

A_1 quality, refers the level of supplier to meet the quality standards. Here we use the rate of qualified products to reflect the product quality level. Rate of qualified products is equal to the number of qualified products divided by total production. The specific calculation formula is as follows.

Rate of qualified products $=(N - N_1)/N*100\%$,

where N is the total procurement quantity within a certain period T, and N_1 is the quantity of inferior-quality product within T. Qualified level of products can be characterized by the standard of the quality system such as the international ISO standard, or other established norms.

A_2 Price, is a core attribute in supplier evaluation, refers to the selling price of unit goods for a supplier. Usually, suppliers will submit the values directly to the buyer in the form of precise values in conjunction with their actual input costs.

A_3 Delivery time is the time taken by a supplier to deliver the goods to a buyer under contract. This time can be either early, on-time or late, as it is affected by production, transportation, and inventory.

A_4 On-time delivery rate, refers to the percentage of the number of on time delivery in total number of delivery within a certain time. The specific calculation formula is as follows.

On-time delivery rate =(The number of on time delivery within a certain time / The total number of delivery within a certain time)*100%.

A_5 After-sales service level, refers to a series of services include product introduction, delivery, installation, commissioning, maintenance, technical training, on-site service and consulting given by the supplier after winning the contract. A good supplier must have good service attitude, timely service and high customer satisfaction.

A_6 Supplier reputation is an important attribute which is related to the success of fulfilling the procurement contract. A supplier with good reputation has good peer evaluation, and can always fulfill the procurement contract to provide high-quality products within a specified time.

A_7 Carbon emissions, refers to carbon emissions of per unit of output, which is equal to the value of total carbon emissions divided by total production.

A_8 Level of wastewater discharge. Decrement rate of wastewater discharge is used to measure the level of wastewater discharge for a firm. This can be quantified as Decrement rate of wastewater discharge

a_1=(wastewater discharge amount in current period − wastewater discharge amount in prior period)/ wastewater discharge amount in prior period.

Table 2: Scale and type for evaluation attributes

Attribute	Evaluation scale for performance values	Attribute type
A_1 Quality	Precise real number	benefit
A_2 Price	Precise real number	cost
A_3 Delivery time	Precise real number	cost
A_4 On-time delivery rate	Precise real number	benefit
A_5 After-sales service	Worst, Poor, Acceptable, Good, Best	benefit
A_6 Supplier reputation	Worst, Poor, Acceptable, Good, Best	benefit
A_7 Carbon emissions	Precise real number	cost
A_8 Level of wastewater discharge	Worst(a_1<20%), Poor(20%≤a_1<50%), Acceptable(70%≤a_1 <80%), Good(50%≤a_1<70%), Best(a_1≥80%)	benefit
A_9 Level of solid waste generation	Worst(a_2<20%), Poor(20%≤a_2<50%), Acceptable(50%≤a_2 <70%), Good(70%≤a_2<80%), Best(a_2≥80%)	benefit
A_{10} Noise level	Worst(a_3≥90dB); Poor(80dB≤a_3<90dB); Acceptable(60dB ≤a_3<80dB); Good50(dB≤a_3<60dB); Best(a_3<50dB)	benefit
A_{11} Recycling utilization level of waste material	Worst(a_4<40%); Poor(40%≤a_4<60%); Acceptable(60%≤ a_4<80%); Good(80%≤a_4<90%); Best(a_4≥90%)	benefit
A_{12} Level of poisonous and harmful material utilization	Worst(a_5≥15%); Poor(12%≤a_5<15%); Acceptable(8%≤a_5 <12%); Good(4%≤a_5<8%); Best(a_5<4%)	benefit
A_{13} Level of clean energy utilization	Worst(a_6<70%); Poor(70%≤a_6<80%); Acceptable(80%≤ a_6<90%); Good(90%≤a_6<95%); Best(a_6≥95%)	benefit
A_{14} Level of environmental protection input	Worst(a_7<2%); Poor(2%≤a_7<3%); Acceptable(3%≤a_7 <4%); Good(4%≤a_7<5%); Best(a_7≥5%)	benefit
A_{15} Level of environmental management	Worst, Poor, Acceptable, Good, Best	benefit

A_9 Level of solid waste generation. Decrement rate of solid waste generation amount is used to measure the level of solid waste generation, and which refers to the control of the remaining sludge and industrial waste from metal processing, smelting, casting, power production of raw materials and water treatment. It can be expressed as decrement rate of solid waste generation amount a_2 =(solid waste generation amount in current period−solid waste generation amount in prior period)/ solid waste generation amount in prior period.

A_{10} Noise level. Noise will affect the producers, transporters, users and the environment during the entire life cycle of the product. Usually, the allowable range of environmental noise a_3 is 50 to 80 dB (Standard of Environmental Noise of Urban Area GB3096-93).

A_{11} Recycling utilization level of waste material. Recycling utilization rate of waste material is used to measure the recycling utilization level, which refers to the percentage of recycling utilization amount of waste material to total generation amount of waste material, i.e., recycling utilization rate of waste material a_4=(recycling utilization amount of waste material/total generation amount of waste material). Generally, to realize the material integration, energy integration and water resources integration, the recycling utilization rate of waste material a_4 should be at least 80%.

A_{12} Level of poisonous and harmful material utilization, refers to the percentage of the usage quantity of poisonous and harmful material in total usage quantity of all material within a certain time. According to the relative regulations of clean energy utilization, the usage rate of poisonous and harmful material a_5 should be far less than 15%.

A_{13} Level of clean energy utilization, refers to the percentage of the usage quantity of clean energy in total usage quantity of all energy within a certain time. The higher the proportion of clean energy utilization, the less the environmental pollution is. The usage rate of clean energy a_6 should be more than 85% for an enterprise in green supply chain.

A_{14} Level of environmental protection input, which can be measured by the percentage of total investment of environmental protection to the total investment of the firm within a certain period of time, i.e., Investment rate of environmental protection a_7 =(total investment of environmental protection within a certain time period /total investment of the firm in the same period). Generally, SSCM requires that a firm's investment rate a_7 for environmental protection should be more than 3.0%.

A_{15} Level of environmental management, which is mainly measured by the development and implementation of environmental management systems and related regulations, and the level of environmental information management. A good supplier should have a perfect environment management system and regulation, and the implementation is very good, and the data monitoring for environment is realized.

The above 15 attributes form the evaluation index system to evaluate and select the green supplier. These attributes can be divided into qualitative attributes and quantitative attributes. The values of quantitative attributes can be given in the form of precise real numbers by the buyer or by the supplier himself. For the qualitative attribute, the buyer can synthetically consider the performance of each attribute and provide the evaluation value for each alternative supplier in the form of fuzzy linguistic variables namely, "Worst, Poor, Acceptable, Good, Best". The detailed scale for the performance values of attribute is shown in Table 2. In addition, the above15 attributes can be classified as either benefit type or cost type. The detailed classification information is also shown in Table 2.

3. Optimization Decision Making Method of Green Supplier Selection

3.1. *Problem description*

The problem of green supplier selection under the background of low carbon economy and green supply chain management is described as follows. Suppose that there is a firm wants to procure G_0 units goods, and n alternative suppliers participate in the supply competition. The set of the alternative suppliers is denoted as $C=\{C_1,C_2,\ldots,C_n\}$. The above 15 evaluation attributes listed in Table 1 section 2 are used to evaluate n alternative suppliers. Let the set of evaluation attribute be $A=\{A_1,A_2,\ldots,A_{15}\}$, and the set of weights for these attributes be $W=\{w_1, w_2, \ldots, w_{13}\}$, which satisfies the conditions $0\le w_j\le 1$ and $\sum_{j=1}^{15} w_j=1$.

In the supplier selection decision making, l experts are invited to evaluate and give the performance results for all alternative suppliers. The weight set of experts is denoted as $V=\{v_1, v_2, \ldots, v_l\}$, such that $0\le v_k\le 1$ and $\sum_{k=1}^{l} v_k=1$. The attribute value for alternative supplier C_i (i=1, 2, …, n) with respect to attribute A_j (j=1, 2, …,15) given by expert k (k=1, 2, …, l) is denoted as x_{ij}^k. We set N_1={1, 2, 3, 4, 7}, N_2={ 5, 6, 8, 9, 10, 11, 12, 13, 14, 15}. From the evaluation scale for performance values of attributes in Table 2, we know that when $j\in N_1$, x_{ij}^k is a precise real number; and when $j\in N_2$, x_{ij}^k is a linguistic fuzzy variable, i.e., Worst, Poor, Acceptable, Good, Best. The original decision matrix determined by the expert k is denoted as $X_k=(x_{ij}^k)_{i\times 15}$, ($k$=1, 2, …, l; i=1, 2, …, n). Then our task is to select optimal green supplier according to the information in the l original decision matrixes $X_1, X_2\ldots, X_l$.

3.2. *The linguistic 2-tuple*

The 2-tuple fuzzy linguistic model was developed by Herrera and Martínez [36]. Since the 2-tuple linguistic model can express any counting of information in the universe of discourse and avoid the information loss in the process of linguistic information processing, it has been widely studied and applied in decision making [36, 37]. Next we give some relative definitions, operations and properties of linguistic 2-tuple.

The definition of linguistic 2-tuple is proposed based on a finite linguistic term set with odd cardinality S and the concept of symbolic translation α, where $S=\{s_0,s_1,\ldots,s_t\}$ is formed by t+1 linguistic fuzzy variables $s_0,s_1,\ldots,s_t$, where s_k is the k-th element in S, and it satisfies the following characteristics.

(i) The property of ordering, i.e., $s_k\ge s_l$ if and only if $k\ge l$.

(ii) Negation operator. $Neg(s_k)=s_l$, such that $l=t-k$.

(iii) Max operator and Min operator. $\max(s_k,s_l)=s_k$, if and only if $k\ge l$; $\min(s_k,s_l)=s_k$, if and only if $k\le l$.

Specially, in this paper, the linguistic term set can be written as

S={s_0= Worst, s_1=Poor, s_2= Acceptable, s_3=Good, s_4= Best }

From the linguistic term set with odd cardinality S, a dual combination (s_k, a_k) which is called linguistic 2-tuple is used to express the linguistic information, where $a \in [-0.5, 0.5)$ is a numerical value representing the value of symbolic translation which is defined by Herrera and Martinez [30] in the following Definition 1.

Definition 1. Let β be the result of an aggregation of the indexes of a set of labels assessed in a linguistic term set *S*, i.e., the result of a symbolic aggregation operation. $\beta \in [0, t]$, being *t*+1 the cardinality of *S*. Let *I* = round (β) and $\alpha = \beta - i$ be two values such that $i \in [0, t]$ and $a \in [-0.5, 0.5)$, where round $(\cdot)$ is the usual rounding operation. Then α is called a symbolic translation.

Herrera and Martinez [36] also defined the transformation function between the numeric values and 2-tuples, and the transformation function between the linguistic fuzzy variables and 2-tuples. The following Definition 2 and Definition 3 give the detailed transformation functions.

Definition 2. Let $S = \{s_0, s_1, \dots, s_t\}$ be a known linguistic term set, and $\beta \in [0, t]$ be a real number which is a value supporting the result of a symbolic aggregation operation, then $\beta \in [0, t]$ can be transformed into an equivalent linguistic 2-tuple by the following function Δ:

$$\Delta : [0, t] \to S \times [-0.5, 0.5), \ \Delta(\beta) = (s_k, a_k),$$

where

$$\begin{cases} k = round(\beta) \\ a_k = \beta - k, \quad a_k \in [-0.5, 0.5) \end{cases}$$

and "round" is the usual rounding operation. Conversely, for a known linguistic 2-tuple (s_k, a_k), there is an inverse function Δ^{-1} such that from a 2-tuple (s_k, a_k) it returns its equivalent numerical value $\beta \in [0, t]$, i.e.,

$$\Delta^{-1} : S \times [-0.5, 0.5) \to [0, t],$$

$$\Delta^{-1}(s_k, a_k) = k + a_k = \beta .$$

Definition 3. Let $s_k \in S$ be a linguistic fuzzy variable, then its corresponding linguistic 2-tuple can be obtained by the following function θ.

$$\theta : S \to S \times [-0.5, 0.5),$$

$$\theta(s_k) = (s_k, 0), \ s_k \in S .$$

Definition 3 means that the corresponding linguistic 2-tuple for a linguistic fuzzy variable $s_k \in S$ is just $(s_k, 0)$.

Especially, for a numerical value $\beta \in [0,1]$, the following Definition 4 [37] is presented based on Defintion 2 to transform it into a linguistic 2-tuple.

Definition 4. Let $S = \{s_0, s_1, \dots, s_t\}$ be a known linguistic evaluation set, and $\beta \in [0,1]$ be a real number which is a value supporting the result of a symbolic aggregation operation, then $\beta \in [0,1]$ can be transformed into an equivalent linguistic 2-tuple by function Δ:

$$\Delta : [0,1] \to S \times [-0.5, 0.5),$$

$$\Delta(\beta) = (s_k, a_k),$$

where

$$\begin{cases} k = round(\beta \cdot t) \\ a_k = \beta \cdot t - k, \quad a_k \in [-0.5, 0.5) \end{cases}$$

and "round" is the usual rounding operation. Conversely, for a 2-tuple (s_k, a_k), there exists an inverse function Δ^{-1} such that from a 2-tuple (s_k, a_k) it returns its equivalent numerical value $\beta \in [0,1]$, i.e.,

$$\Delta^{-1} : S \times [-0.5, 0.5) \to [0,1],$$

$$\Delta^{-1}(s_k, a_k) = \frac{k + a_k}{t} = \beta .$$

In addition, the following Definition 5 gives some frequently-used operations of linguistic 2-tuples.

Definition 5. Let (s_k, a_k) and (s_l, a_l) be any two linguistic 2-tuples, their relative operations are defined as follows.

(1) Comparison operations.

If $k > l$, then $(s_k, a_k) > (s_l, a_l)$. If $k = l$, there are three cases, i.e., (i) if $a_k = a_l$, then $(s_k, a_k) = (s_l, a_l)$; (ii) if $a_k < a_l$, then $(s_k, a_k) < (s_l, a_l)$ (iii) if $a_k > a_l$, then $(s_k, a_k) > (s_l, a_l)$.

(2) Negation operator.

$Neg(s_k, a_k) = \Delta(t - (\Delta^{-1}(s_k, a_k)))$, where *g*+1 is the cardinality of *S*, $S = \{s_0, s_1, \dots, s_t\}$.

(3) Max operator and Min operator.

If $(s_k, a_k) \geq (s_l, a_l)$, then

$$\max\{(s_k, a_k), (s_l, a_l)\} = (s_k, a_k),$$

$$\min\{(s_k, a_k), (s_l, a_l)\} = (s_l, a_l).$$

(4) Distance operator.

$d((s_k, a_k), (s_l, a_l)) = \Delta\left|\Delta^{-1}(s_k, a_k) - \Delta^{-1}(s_l, a_l)\right|$ is called the distance between (s_k, a_k) and (s_l, a_l).

Moreover, for multiple 2-tuples (s_1, a_1), (s_2, a_2), …, (s_n, a_n), the following *TAA* operator, *TWA* operator and *TOWA* operator are presented to aggregate them.

Definition 6. Let *H*={ (s_1, a_1), (s_2, a_2), …, (s_n, a_n) } be a set of linguistic 2-tuples, then the 2-tuple arithmetic averaging (*TAA)* operator is defined as

$$TAA((s_1,a_1),(s_2,a_2),\ldots,(s_n,a_n))=\Delta\left(\frac{1}{n}\sum_{j=1}^{n}\Delta^{-1}(s_j,a_j)\right).$$

Definition 7. Let H={ (s_1,a_1) , (s_2,a_2) , …, (s_n,a_n) } be a set of linguistic 2-tuples, and W={w_1, w_2, …, w_n} is the weight vector of 2-tuples (s_j,a_j) , $j=1,2,\ldots,n$, which satisfies $0\le w_j\le 1$ and $\sum_{j=1}^{n}w_j=1$, then the 2-tuple weighted averaging (*TWA)* operator is defined as

$$TWA_W((s_1,a_1),(s_2,a_2),\ldots,(s_n,a_n))$$
$$=\Delta\left(\sum_{j=1}^{n}w_j\Delta^{-1}(s_j,a_j)\right)$$

From Definition 6 and Definition 7, we can see that if we set the weight vector of 2-tuples (s_j,a_j) as $w_j=\frac{1}{n}$ ($j=1,2,\ldots,n$) in the above *TWA* operator, then the *TWA* operator is just become the *TAA* operator. For this sense, the *TAA* operator is a particular case of *TWA* operator.

Combining with the *TWA* operator and *OWA* operator [38], Herrera and Martinez [36] developed a 2-tuple ordered weighted averaging (*TOWA*) operator.

Definition 8. Let H={ (s_1,a_1) , (s_2,a_2) , …, (s_n,a_n) } be a set of linguistic 2-tuples, then the 2-tuple ordered weighted averaging (*TOWA)* operator is defined as

$$TOWA_\omega((s_1,a_1),(s_2,a_2),\ldots,(s_n,a_n))$$
$$=\Delta\left(\sum_{j=1}^{n}\omega_j\Delta^{-1}(s_{\tau(j)},a_{\tau(j)})\right)$$

where ω = {ω_1, ω_2, …, ω_n} is the weighted vector correlating with *TOWA*, which satisfies $0\le\omega_j\le 1$ and $\sum_{j=1}^{n}\omega_j=1$. ($\tau(1)$, $\tau(2)$, …, $\tau(n)$) is a permutation of (1, 2, ... , n) which satisfies $(s_{\tau(j-1)},a_{\tau(j-1)})\ge(s_{\tau(j)},a_{\tau(j)})$ for any j.

For the above weighted vector correlating with *TOWA* ω = {ω_1, ω_2, …, ω_n}, Yager [39] gave a common useful method, i.e., get rid of the maximum value and the minimum value in H={ (s_1,a_1) , (s_2,a_2) , …, (s_n,a_n) }, and then assign the same weight to the rest of the values, that is

$$\omega=\{\omega_1,\omega_2,\ldots,\omega_n\}$$
$$=(0,\frac{1}{n-2},\frac{1}{n-2},\ldots,\frac{1}{n-2},\frac{1}{n-2},0).$$

Later, Xu [40] developed a Normal distribution based method to determine the weighted vector ω correlating with *TOWA*. He gave the weighted vector as follows.

$$\omega_j=\frac{1}{\sqrt{2\pi\sigma_n}}e^{-[(j-\mu_n)^2/2\sigma_n^2]},\ j=1,2,\ldots,n,$$

where μ_n is the mean of the collection of 1, 2, ... , n, and $\sigma_n(\sigma_n>0)$ is the standard deviation of the collection of 1, 2, ... , n. μ_n and σ_n are obtained by the following formulas, respectively:

$$\mu_n=\frac{1}{n}\cdot\frac{n(1+n)}{2}=\frac{1+n}{2},$$
$$\sigma_n=\sqrt{\frac{1}{n}\sum_{i=1}^{n}(i-\mu_n)^2}.$$

3.3. *The decision method with 2-tuple linguistic assessments for green supplier selection*

In this section, we propose a decision method with 2-tuple linguistic assessments based on section 3.2 to solve the problem of green supplier selection. The algorithm and decision process are given as follows.

Step 1: l experts make the comprehensive evaluation and give the performance results for all alternative suppliers. Then the original decision matrix determined by the expert k is denoted as $X_k=(x_{ij}^k)_{i\times 15}$, (k=1, 2, …, l; i=1, 2, …, n), where the evaluation value x_{ij}^k is a precise real number for any $j\in N_1$={1, 2, 3, 4, 7}, and x_{ij}^k is a linguistic fuzzy variable (Worst = s_0, Poor = s_1, Acceptable = s_2, Good = s_3, Best = s_4) for any $j\in N_2$={ 5, 6, 8, 9, 10, 11, 12, 13, 14, 15}. Then l original decision matrixes X_1 , X_2 …, X_l are found.

Step 2: Data process for l original decision matrixes X_1 , X_2 …, X_l .

For the benefit type attributes, A_1 Quality and A_4 On-time delivery rate, which attribute values are in the forms of precise real numbers, the attribute value $x_{ij}\in R$ can be normalized by the following relation.

$$y_{ij}=\frac{x_{ij}-\min_i x_{ij}}{\max_i x_{ij}-\min_i x_{ij}}\quad i=1,2,\ldots,n,\ j=1,4.\qquad(1)$$

For the cost type attributes, A_2 Price, A_3 Delivery time and A_7 Carbon emissions, the attribute value $x_{ij}\in R$ can be normalized be the following rule

$$y_{ij}=\frac{\max_i x_{ij}-x_{ij}}{\max_i x_{ij}-\min_i x_{ij}}\quad i=1,2,\ldots,n,\ j=2,3,7.\qquad(2)$$

After data process, l original decision matrixes X_1 , X_2 …, X_l becomes l new decision matrixes Y_1 , Y_2 …, Y_l , where $Y_k=(y_{ij}^k)_{i\times 15}$, and

$$y_{ij}^k = \begin{cases} \lambda \in [0,1] \in R, \quad j = 1,2,3,4,7;\ k = 1,2,\ldots,l \\ s_k \in S,\ j = 5,6,8,9,10,11,12,13,14,15 \end{cases}$$

Step 3: Use the transformation method in Definition 3 and Definition 4 to transform each decision matrix $Y_k = (y_{ij}^k)_{i\times 15}$ into linguistic 2-tuple decision matrix $\widetilde{Z}_k = ((s_{ij}^k, a_{ij}^k))_{n\times 15}$, k=1, 2, …, l; i=1, 2, …, n.

Step 4: Use the *TWA* operator in Definition 7 to aggregate all evaluation values under 15 evaluation attributes in matrix $\widetilde{Z}_k = ((s_{ij}^k, a_{ij}^k))_{n\times 15}$ into one overall evaluation value r_i^k of the alternative C_i (i=1, 2, …, n) corresponding to the expert k, i.e.,

$$r_i^k = (s_i^k, a_i^k) = TWA_W((s_{i1}^k, a_{i1}^k), (s_{i2}^k, a_{i2}^k), \ldots, s_{i,15}^k, a_{i,15}^k))$$

$$= \Delta\left(\sum_{j=1}^{15} w_j \Delta^{-1}(s_{ij}^k, a_{ij}^k)\right), \quad k=1, 2, \ldots, l,$$

where W = {w_1, w_2, …, w_{15}} is the weight vector of 15 evaluation attributes which satisfies $0 \le w_j \le 1$ and $\sum_{j=1}^{15} w_j = 1$.

Step 5: Use the *TOWA* operator in Definition 8 to aggregate the overall evaluation value r_i^k corresponding to the expert k (k=1, 2, …, l) and get the collective overall evaluation value for alternative C_i, i=1, 2, …, n,

$$r_i = (s_i, a_i) = TOWA_\omega((s_i^1, a_i^1), (s_i^2, a_i^2), \ldots, (s_i^l, a_i^l))$$

$$= \Delta\left(\sum_{k=1}^{l} \omega_k \Delta^{-1}(s_i^{\tau(k)}, s_i^{\tau(k)})\right),$$

where ω={ω_1, ω_2, …, ω_n} is the weighted vector correlating with *TOWA*, such that $0 \le \omega_k \le 1$ and $\sum_{k=1}^{l} \omega_k = 1$. ($\tau(1)$, $\tau(2)$, …, $\tau(n)$) is a permutation of (1, 2, ... , n) which satisfies $(s_i^{\tau(k-1)}, s_i^{\tau(k-1)}) \ge (s_i^{\tau(k)}, s_i^{\tau(k)})$ for any k.

Step 6: Rank n alternative suppliers according to the value of 2-tuple $r_i = (s_i, a_i)$ (i=1, 2, …, n), and select the best green supplier(s). The greater the value of $r_i = (s_i, a_i)$, the better is alternative supplier i.

4. A Decision Example of Green Supplier Selection

In this section, we use a decision making example of green supplier selection to show how to implement our decision method and to demonstrate the effectiveness of our method.

Suppose that there is a firm wants to procure G_0 units goods, and 5 alternative suppliers participate in the supply competition, i.e., $C = \{C_1, C_2, C_3, C_4, C_5\}$. The 15 evaluation attributes listed in Table 1 are used to evaluate 5 alternative suppliers, i.e., A_1 Quality (%), A_2 Price ($/unit), A_3 Delivery time (days), A_4 On-time delivery rate (%), A_5 After-sales service, A_6 Supplier reputation, A_7 Carbon emissions (tons), A_8 Level of wastewater discharge, A_9 Level of solid waste generation, A_{10} Noise level, A_{11} Recycling utilization level of waste material, A_{12} Level of poisonous and harmful material utilization, A_{13} Level of clean energy utilization, A_{14} Level of environmental protection input, A_{15} Level of environmental management. Let the weight set of the 15 attributes be W = (w_1, w_2, ..., w_{15}) = (0.1, 0.15, 0.05, 0.05, 0.05, 0.05, 0.1, 0.05, 0.05, 0.05, 0.05, 0.05, 0.05, 0.1, 0.05).

Three experts are invited to participate in the evaluation decision for 5 alternative suppliers, and the weight vector of experts is V =(v_1, v_2, v_3)=(0.3, 0.4, 0.3). For the attributes of A_2 Price and A_3 Delivery time, the attribute values are submitted by the alternative suppliers directly to the buyer in the form of precise values in conjunction with their actual input costs and transportation capability. Moreover, the experts will determine the precise evaluation values for the attributes of A_1 Quality, A_4 On-time delivery rate and A_7 Carbon emissions (tons) according to each alternative supplier's relative historical statistical data. That is to say, the attribute values of A_1, A_2, A_3, A_4 and A_7 are all precise values and the same public information to three experts. The evaluation values of the rest ten attributes are given in the forms of s_0(Worst), s_1(Poor), s_2(Acceptable), s_3(Good) and s_4(Best) by all experts according to their experience, knowledge level, judgment, and so on. After evaluating the 15 attributes for all 5 suppliers by using the evaluation scale for performance values in Table 2, the expert k gives the original decision matrix $X_k = (x_{ji}^k)_{15\times 5}$. They are all listed in Tables 3–5. Based on the data information in original decision matrixes X_1, X_2, and X_3, the decision task is to evaluate all alternative suppliers and to select optimal green supplier.

4.1. *Decision making process*

Applying the decision method given by section 3.2, we give the decision making process for select optimal green supplier as follows.

(1) Use Eqns (1) and (2) to process the data in original decision matrixes X_1 , X_2 , and X_3 given by Tables 3–5, and 3 new decision matrixes Y_1, Y_2 and Y_3 are found (see Tables 6–8).

Table 3. Original decision matrix X_1

Attribute	C_1	C_2	C_3	C_4	C_5
A_1	96	93	89	95	90
A_2	180	160	165	150	175
A_3	25	18	30	20	22
A_4	95	96	85	98	92
A_5	s_2	s_3	s_2	s_4	s_3
A_6	s_3	s_4	s_3	s_3	s_1
A_7	85	82	85	80	88
A_8	s_3	s_4	s_2	s_4	s_1
A_9	s_2	s_4	s_4	s_3	s_2
A_{10}	s_2	s_3	s_4	s_4	s_3
A_{11}	s_2	s_3	s_2	s_4	s_2
A_{12}	s_3	s_3	s_2	s_3	s_3
A_{13}	s_2	s_3	s_1	s_4	s_3
A_{14}	s_3	s_4	s_2	s_4	s_3
A_{15}	s_2	s_3	s_3	s_4	s_1

Table 4. Original decision matrix X_2

Attribute	C_1	C_2	C_3	C_4	C_5
A_1	96	93	89	95	90
A_2	180	160	165	150	175
A_3	25	18	30	20	22
A_4	95	96	85	98	92
A_5	s_3	s_2	s_3	s_4	s_2
A_6	s_3	s_3	s_3	s_4	s_1
A_7	85	82	85	80	88
A_8	s_2	s_3	s_1	s_3	s_2
A_9	s_3	s_4	s_3	s_4	s_1
A_{10}	s_3	s_2	s_3	s_4	s_2
A_{11}	s_2	s_4	s_2	s_4	s_3
A_{12}	s_3	s_4	s_1	s_4	s_2
A_{13}	s_2	s_2	s_2	s_3	s_2
A_{14}	s_3	s_4	s_3	s_4	s_2
A_{15}	s_1	s_4	s_3	s_4	s_2

Table 5. Original decision matrix X_3

Attribute	C_1	C_2	C_3	C_4	C_5
A_1	96	93	89	95	90
A_2	180	160	165	150	175
A_3	25	18	30	20	22
A_4	95	96	85	98	92
A_5	s_2	s_3	s_2	s_4	s_3
A_6	s_2	s_4	s_2	s_4	s_2
A_7	85	82	85	80	88
A_8	s_3	s_4	s_2	s_4	s_3
A_9	s_2	s_3	s_3	s_4	s_2
A_{10}	s_3	s_4	s_3	s_4	s_2
A_{11}	s_3	s_3	s_1	s_4	s_2
A_{12}	s_2	s_3	s_2	s_3	s_2
A_{13}	s_3	s_2	s_2	s_4	s_3
A_{14}	s_2	s_4	s_1	s_4	s_3
A_{15}	s_2	s_3	s_2	s_4	s_2

Table 6. Decision matrix Y_1

Attribute	C_1	C_2	C_3	C_4	C_5
A_1	1	0.571	0	0.857	0.143
A_2	0	0.667	0.5	1	0.167
A_3	0.417	1	0	0.833	0.667
A_4	0.769	0.846	0	1	0.538
A_5	s_2	s_3	s_2	s_4	s_3
A_6	s_3	s_4	s_3	s_3	s_1
A_7	0.375	0.75	0.375	1	0
A_8	s_3	s_4	s_2	s_4	s_1
A_9	s_2	s_4	s_4	s_3	s_2
A_{10}	s_2	s_3	s_4	s_4	s_3
A_{11}	s_2	s_3	s_2	s_4	s_2
A_{12}	s_3	s_3	s_2	s_3	s_3
A_{13}	s_2	s_3	s_1	s_4	s_3
A_{14}	s_3	s_4	s_2	s_4	s_3
A_{15}	s_2	s_3	s_3	s_4	s_1

Table 7. Decision matrix Y_2

Attribute	C_1	C_2	C_3	C_4	C_5
A_1	1	0.571	0	0.857	0.143
A_2	0	0.667	0.5	1	0.167
A_3	0.417	1	0	0.833	0.667
A_4	0.769	0.846	0	1	0.538
A_5	s_3	s_2	s_3	s_4	s_2
A_6	s_3	s_3	s_3	s_4	s_1
A_7	0.375	0.75	0.375	1	0
A_8	s_2	s_3	s_1	s_3	s_2
A_9	s_3	s_4	s_3	s_4	s_1
A_{10}	s_3	s_2	s_3	s_4	s_2
A_{11}	s_2	s_4	s_2	s_4	s_3
A_{12}	s_3	s_4	s_1	s_4	s_2
A_{13}	s_2	s_2	s_2	s_3	s_2
A_{14}	s_3	s_4	s_3	s_4	s_2
A_{15}	s_1	s_4	s_3	s_4	s_2

Table 8. Decision matrix Y_3

Attribute	C_1	C_2	C_3	C_4	C_5
A_1	1	0.571	0	0.857	0.143
A_2	0	0.667	0.5	1	0.167
A_3	0.417	1	0	0.833	0.667
A_4	0.769	0.846	0	1	0.538
A_5	s_2	s_3	s_2	s_4	s_3
A_6	s_2	s_4	s_2	s_4	s_2
A_7	0.375	0.75	0.375	1	0
A_8	s_3	s_4	s_2	s_4	s_3
A_9	s_2	s_3	s_3	s_4	s_2
A_{10}	s_3	s_4	s_3	s_4	s_2
A_{11}	s_3	s_3	s_1	s_4	s_2
A_{12}	s_2	s_3	s_2	s_3	s_2
A_{13}	s_3	s_2	s_2	s_4	s_3
A_{14}	s_2	s_4	s_1	s_4	s_3
A_{15}	s_2	s_3	s_2	s_4	s_2

Table 9. Linguistic 2-tuple decision matrix $\widetilde{Z}_1$

Attribute	C_1	C_2	C_3	C_4	C_5
A_1	$(s_4, 0)$	$(s_2, 0.286)$	$(s_0, 0)$	$(s_3, 0.429)$	$(s_1, -0.429)$
A_2	$(s_0, 0)$	$(s_3, -0.333)$	$(s_2, 0)$	$(s_4, 0)$	$(s_1, -0.333)$
A_3	$(s_2, -0.333)$	$(s_4, 0)$	$(s_0, 0)$	$(s_3, 0.333)$	$(s_3, -0.333)$
A_4	$(s_3, 0.077)$	$(s_3, 0.385)$	$(s_0, 0)$	$(s_4, 0)$	$(s_2, 0.154)$
A_5	$(s_2, 0)$	$(s_3, 0)$	$(s_2, 0)$	$(s_4, 0)$	$(s_3, 0)$
A_6	$(s_3, 0)$	$(s_4, 0)$	$(s_3, 0)$	$(s_3, 0)$	$(s_1, 0)$
A_7	$(s_2, -0.5)$	$(s_3, 0)$	$(s_2, -0.5)$	$(s_4, 0)$	$(s_0, 0)$
A_8	$(s_3, 0)$	$(s_4, 0)$	$(s_2, 0)$	$(s_4, 0)$	$(s_1, 0)$
A_9	$(s_2, 0)$	$(s_4, 0)$	$(s_4, 0)$	$(s_3, 0)$	$(s_2, 0)$
A_{10}	$(s_2, 0)$	$(s_3, 0)$	$(s_4, 0)$	$(s_4, 0)$	$(s_3, 0)$
A_{11}	$(s_2, 0)$	$(s_3, 0)$	$(s_2, 0)$	$(s_4, 0)$	$(s_2, 0)$
A_{12}	$(s_3, 0)$	$(s_3, 0)$	$(s_2, 0)$	$(s_3, 0)$	$(s_3, 0)$
A_{13}	$(s_2, 0)$	$(s_3, 0)$	$(s_1, 0)$	$(s_4, 0)$	$(s_3, 0)$
A_{14}	$(s_3, 0)$	$(s_4, 0)$	$(s_2, 0)$	$(s_4, 0)$	$(s_3, 0)$
A_{15}	$(s_2, 0)$	$(s_3, 0)$	$(s_3, 0)$	$(s_4, 0)$	$(s_1, 0)$

Table 10. Linguistic 2-tuple decision matrix $\widetilde{Z}_2$

Attribute	C_1	C_2	C_3	C_4	C_5
A_1	$(s_4, 0)$	$(s_2, 0.286)$	$(s_0, 0)$	$(s_3, 0.429)$	$(s_1, -0.429)$
A_2	$(s_0, 0)$	$(s_3, -0.333)$	$(s_2, 0)$	$(s_4, 0)$	$(s_1, -0.333)$
A_3	$(s_2, -0.333)$	$(s_4, 0)$	$(s_0, 0)$	$(s_3, 0.333)$	$(s_3, -0.333)$
A_4	$(s_3, 0.077)$	$(s_3, 0.385)$	$(s_0, 0)$	$(s_4, 0)$	$(s_2, 0.154)$
A_5	$(s_3, 0)$	$(s_2, 0)$	$(s_3, 0)$	$(s_4, 0)$	$(s_2, 0)$
A_6	$(s_3, 0)$	$(s_3, 0)$	$(s_3, 0)$	$(s_4, 0)$	$(s_1, 0)$
A_7	$(s_2, -0.5)$	$(s_3, 0)$	$(s_2, -0.5)$	$(s_4, 0)$	$(s_0, 0)$
A_8	$(s_2, 0)$	$(s_3, 0)$	$(s_1, 0)$	$(s_3, 0)$	$(s_2, 0)$
A_9	$(s_3, 0)$	$(s_4, 0)$	$(s_3, 0)$	$(s_4, 0)$	$(s_1, 0)$
A_{10}	$(s_3, 0)$	$(s_2, 0)$	$(s_3, 0)$	$(s_4, 0)$	$(s_2, 0)$
A_{11}	$(s_2, 0)$	$(s_4, 0)$	$(s_2, 0)$	$(s_4, 0)$	$(s_3, 0)$
A_{12}	$(s_3, 0)$	$(s_4, 0)$	$(s_1, 0)$	$(s_4, 0)$	$(s_2, 0)$
A_{13}	$(s_2, 0)$	$(s_2, 0)$	$(s_2, 0)$	$(s_3, 0)$	$(s_2, 0)$
A_{14}	$(s_3, 0)$	$(s_4, 0)$	$(s_3, 0)$	$(s_4, 0)$	$(s_2, 0)$
A_{15}	$(s_1, 0)$	$(s_4, 0)$	$(s_3, 0)$	$(s_4, 0)$	$(s_2, 0)$

Table 11. Linguistic 2-tuple decision matrix $\widetilde{Z}_3$

Attribute	C_1	C_2	C_3	C_4	C_5
A_1	$(s_4, 0)$	$(s_2, 0.286)$	$(s_0, 0)$	$(s_3, 0.429)$	$(s_1, -0.429)$
A_2	$(s_0, 0)$	$(s_3, -0.333)$	$(s_2, 0)$	$(s_4, 0)$	$(s_1, -0.333)$
A_3	$(s_2, -0.333)$	$(s_4, 0)$	$(s_0, 0)$	$(s_3, 0.333)$	$(s_3, -0.333)$
A_4	$(s_3, 0.077)$	$(s_3, 0.385)$	$(s_0, 0)$	$(s_4, 0)$	$(s_2, 0.154)$
A_5	$(s_2, 0)$	$(s_3, 0)$	$(s_2, 0)$	$(s_4, 0)$	$(s_3, 0)$
A_6	$(s_2, 0)$	$(s_4, 0)$	$(s_2, 0)$	$(s_4, 0)$	$(s_2, 0)$
A_7	$(s_2, -0.5)$	$(s_3, 0)$	$(s_2, -0.5)$	$(s_4, 0)$	$(s_0, 0)$
A_8	$(s_3, 0)$	$(s_4, 0)$	$(s_2, 0)$	$(s_4, 0)$	$(s_3, 0)$
A_9	$(s_2, 0)$	$(s_3, 0)$	$(s_3, 0)$	$(s_4, 0)$	$(s_2, 0)$
A_{10}	$(s_3, 0)$	$(s_4, 0)$	$(s_3, 0)$	$(s_4, 0)$	$(s_2, 0)$
A_{11}	$(s_3, 0)$	$(s_3, 0)$	$(s_1, 0)$	$(s_4, 0)$	$(s_2, 0)$
A_{12}	$(s_2, 0)$	$(s_3, 0)$	$(s_2, 0)$	$(s_3, 0)$	$(s_2, 0)$
A_{13}	$(s_3, 0)$	$(s_2, 0)$	$(s_2, 0)$	$(s_4, 0)$	$(s_3, 0)$
A_{14}	$(s_2, 0)$	$(s_4, 0)$	$(s_1, 0)$	$(s_4, 0)$	$(s_3, 0)$
A_{15}	$(s_2, 0)$	$(s_3, 0)$	$(s_2, 0)$	$(s_4, 0)$	$(s_2, 0)$

(2) Use the transformation method in Definition 3 and Definition 4 to transform decision matrixes Y_1, Y_2 and Y_3 into linguistic 2-tuple decision matrix $\widetilde{Z}_k = ((s_{ji}^k, a_{ji}^k))_{15\times 5}$, k=1, 2, 3 (see Tables 9–11).

(3) Use the *TWA* operator in Definition 7 to aggregate all evaluation values under 15 evaluation attributes in matrix $\widetilde{Z}_k=((s_{ji}^k,a_{ji}^k))_{15\times 5}$ into one overall evaluation value $r_i^k=(s_i^k,a_i^k)$ of the alternative supplier C_i (i=1, 2, 3, 4, 5) corresponding to the expert k, k=1, 2, 3, the computation results are as follows.

$$r_1^1=(s_1^1,a_1^1)=(s_2,\ 0.137),\ r_2^1=(s_2^1,a_2^1)=(s_3,\ 0.198),$$

$$r_3^1=(s_3^1,a_3^1)=(s_2,\ -0.2),\ r_4^1=(s_4^1,a_4^1)=(s_4,\ -0.26),$$

$$r_5^1=(s_5^1,a_5^1)=(s_2,\ -0.35);\ r_1^2=(s_1^2,a_1^2)=(s_2,\ 0.187),$$

$$r_2^2=(s_2^2,a_2^2)=(s_3,\ 0.098),\ r_3^2=(s_3^2,a_3^2)=(s_2,\ -0.2),$$

$$r_4^2=(s_4^2,a_4^2)=(s_4,\ -0.19),\ r_5^2=(s_5^2,a_5^2)=(s_1,\ 0.448);$$

$$r_1^3=(s_1^3,a_1^3)=(s_2,\ 0.087),\ r_2^3=(s_2^3,a_2^3)=(s_3,\ 0.148),$$

$$r_3^3=(s_3^3,a_3^3)=(s_2,\ -0.5),\ r_4^3=(s_4^3,a_4^3)=(s_4,\ -0.14),$$

$$r_5^3=(s_5^3,a_5^3)=(s_2,\ -0.252).$$

(4) Use the *TOWA* operator given in Definition 9 to aggregate the overall evaluation value r_i^k corresponding to expert k (k=1, 2, 3). Here, the weighted vector correlating with *TOWA* is ω={0.24, 0.52, 0.24}, which is determined using the Normal distribution based method [40]. Then the collective overall evaluation value $r_i=(s_i,a_i)$ for alternative supplier C_i, (i=1, 2, 3, 4, 5) is obtained as follows.

$$r_1=(s_1,a_1)=(s_2,\ 0.137),\ r_2=(s_2,a_2)=(s_3,\ 0.148),$$

$$r_3=(s_3,a_3)=(s_2,\ -0.272), r_4=(s_4,a_4)=(s_4,\ -0.19),$$

$$r_5=(s_5,a_5)=(s_2,\ -0.376).$$

(5) Rank 5 alternative suppliers according to the value of 2-tuple $r_i=(s_i,a_i)$ (i=1, 2, 3, 4, 5), and select the best green supplier. Since $r_4>r_2>r_1>r_3>r_5$, the optimal green supplier is C_4.

4.2. *Discussion*

The evaluation result of green supplier selection in the above example is obtained under the assumption that all alternative suppliers have enough strong supply capacity. However, in the practical procurement, sometimes the firm needs to procure a huge number of goods, a single supplier only can provide a limited number of goods and not enough to satisfy all the needs for the firm within the stipulated time. Thus, the firm has to use the multi-source procurement strategy, that is, he will select multiple suppliers to supply the goods which he needs. In this case of above example, we can select multiple winners according to the evaluation result $r_4>r_2>r_1>r_3>r_5$, i.e., the supplier C_4 is the first winner and he gets the supply preferentially. If the supply is remaining, then the supplier C_2 is the second winner to supply the remaining part preferentially. Repeat this same process, until all supply of goods is fully allocated.

In addition, in order to further illustrate the feasibility and availability of our proposed decision making method in this paper, we compare our supplier selection method with the method of linguistic 2-tuple TOPSIS (LT-TOPSIS) [41]. The decision method of supplier selection based on LT-TOPSIS is described as follows.

Step 1-Step 2: See step (1) and step (2) in section 4.1. Then we can get the linguistic 2-tuple decision matrix $\widetilde{Z}_k=((s_{ji}^k,a_{ji}^k))_{15\times 5}$, k=1, 2, 3 (see Tables 9–11).

Step 3: Use the *TAA* operator in Definition 6 to aggregate all decision information given in matrixes $\widetilde{Z}_1$, $\widetilde{Z}_2$ and $\widetilde{Z}_3$ into the collective overall 2-tuple linguistic decision matrix $\widetilde{Z}=((s_{ji},a_{ji}))_{15\times 5}$ (see Table 12), where

$$(s_{ji},a_{ji})=TAA((s_{ji}^1,a_{ji}^1),(s_{ji}^2,a_{ji}^2),(s_{ji}^3,a_{ji}^3))$$
$$=\Delta\left(\frac{1}{3}\sum_{k=1}^{3}\Delta^{-1}(s_{ji}^k,a_{ji}^k)\right).$$

Step 4: Define the 2-Tuple linguistic positive ideal solution (TLPIS) and 2-Tuple linguistic negative ideal solution (TLNIS) as follows.

$$(s^+,a^+)=((s_1^+,a_1^+),(s_2^+,a_2^+),\ldots,(s_{15}^+,a_{15}^+)),$$

$$(s^-,a^-)=((s_1^-,a_1^-),(s_2^-,a_2^-),\ldots,(s_{15}^-,a_{15}^-)),$$

where

$$(s_j^+,a_j^+)=\max_i(s_{ji},a_{ji}),\ j=1,\ 2,\ \ldots,\ 15.$$

$$(s_j^-,a_j^-)=\min_i(s_{ji},a_{ji}),\ j=1,\ 2,\ \ldots,\ 15.$$

In this example, we have

$(s^+,a^+)=((s_1^+,a_1^+),(s_2^+,a_2^+),\ldots,(s_{15}^+,a_{15}^+))$ =((s_4, 0), (s_4, 0), (s_4, 0), (s_4, 0), (s_4, 0), (s_4, -0.333), (s_4, 0), (s_4, -0.333), (s_4, -0.333), (s_4, 0), (s_4, 0), (s_3, 0.333), (s_4, -0.333), (s_4, 0), (s_4, 0)),

$(s^-,a^-)=((s_1^-,a_1^-),(s_2^-,a_2^-),\ldots,(s_{15}^-,a_{15}^-))$ =((s_0, 0), (s_0, 0), (s_0, 0), (s_0, 0), (s_2, 0.333), (s_1, 0.333), (s_0, 0), (s_2, -0.333), (s_2, -0.333), (s_2, 0.333), (s_2, -0.333), (s_2, -0.333), (s_2, -0.333), (s_2, 0), (s_2, -0.333)).

Step 5: Calculate the distance of each alternative supplier from TLPIS and TLNIS using the following equation, respectively, i.e.,

$$(\eta_i^+,\zeta_i^+)=\Delta\left(\sum_{j=1}^{15}w_j\left|\Delta^{-1}(s_{ji},a_{ji})-\Delta^{-1}(s_j^+,a_j^+)\right|\right),$$

$$(\eta_i^-,\zeta_i^-)=\Delta\left(\sum_{j=1}^{15} w_j\left|\Delta^{-1}(s_{ji},a_{ji})-\Delta^{-1}(s_j^-,a_j^-)\right|\right),$$

i=1, 2, 3, 4, 5.

So we have

(η_1^+,ζ_1^+)=(s_1, -0.237), (η_2^+,ζ_2^+)=(s_1, -0.248),

(η_3^+,ζ_3^+)=(s_2, 0.2), (η_4^+,ζ_4^+)=(s_0, 0.09),

(η_5^+,ζ_5^+)=(s_2, 0.285).

(η_1^-,ζ_1^-)=(s_1, 0.137), (η_2^-,ζ_2^-)=(s_2, 0.148),

(η_3^-,ζ_3^-)=(s_1, -0.3), (η_4^-,ζ_4^-)=(s_3, -0.19),

(η_5^-,ζ_5^-)=(s_1, -0.385).

Step 6: Calculate the relative closeness degree of each alternative supplier from TLPIS using the following equation.

$$(\eta_i,\zeta_i)=\Delta\left(\frac{\Delta^{-1}(\eta_1^-,\zeta_1^-)}{\Delta^{-1}(\eta_1^+,\zeta_1^+)+\Delta^{-1}(\eta_1^-,\zeta_1^-)}\right),\ i=1,\ 2,\ 3,\ 4,\ 5.$$

Then we obtain

(η_1,ζ_1)=(s_2, -0.431), (η_2,ζ_2)=(s_3, -0.038),

(η_3,ζ_3)=(s_1, -0.034), (η_4,ζ_4)=(s_4, -0.125),

(η_5,ζ_5)=(s_1, -0.152).

Step 7: Rank all alternative suppliers according to the value of (η_i,ζ_i), i=1, 2, 3, 4, 5. The greater the value of (η_i,ζ_i), the better is alternative supplier C_i.

By step 6, we obtain

$$(\eta_4,\zeta_4)>(\eta_2,\zeta_2)>(\eta_1,\zeta_1)>(\eta_3,\zeta_3)>(\eta_5,\zeta_5),$$

thus we have

$$C_4 \succ C_2 \succ C_1 \succ C_3 \succ C_5.$$

Table 12: The collective overall 2-tuple linguistic decision matrix $\widetilde{Z}$.

Attribute	C_1	C_2	C_3	C_4	C_5
A_1	(s_4, 0)	(s_2, 0.286)	(s_0, 0)	(s_3, 0.429)	(s_1, -0.429)
A_2	(s_0, 0)	(s_3, -0.333)	(s_2, 0)	(s_4, 0)	(s_1, -0.333)
A_3	(s_2, -0.333)	(s_4, 0)	(s_0, 0)	(s_3, 0.333)	(s_3, -0.333)
A_4	(s_3, 0.077)	(s_3, 0.385)	(s_0, 0)	(s_4, 0)	(s_2, 0.154)
A_5	(s_2, 0.333)	(s_3, -0.333)	(s_2, 0.333)	(s_4, 0)	(s_3, -0.333)
A_6	(s_3, -0.333)	(s_4, -0.333)	(s_3, -0.333)	(s_4, -0.333)	(s_1, 0.333)
A_7	(s_2, -0.5)	(s_3, 0)	(s_2, -0.5)	(s_4, 0)	(s_0, 0)
A_8	(s_3, -0.333)	(s_4, -0.333)	(s_2, -0.333)	(s_4, -0.333)	(s_2, 0)
A_9	(s_2, 0.333)	(s_4, -0.333)	(s_3, 0.333)	(s_4, -0.333)	(s_2, -0.333)
A_{10}	(s_3, -0.333)	(s_3, 0)	(s_3, 0.333)	(s_4, 0)	(s_2, 0.333)
A_{11}	(s_2, 0.333)	(s_3, 0.333)	(s_2, -0.333)	(s_4, 0)	(s_2, 0.333)
A_{12}	(s_3, -0.333)	(s_3, 0.333)	(s_2, -0.333)	(s_3, 0.333)	(s_2, 0.333)
A_{13}	(s_2, 0.333)	(s_2, 0.333)	(s_2, -0.333)	(s_4, -0.333)	(s_3, -0.333)
A_{14}	(s_3, -0.333)	(s_4, 0)	(s_2, 0)	(s_4, 0)	(s_3, -0.333)
A_{15}	(s_2, -0.333)	(s_3, 0.333)	(s_3, -0.333)	(s_4, 0)	(s_2, -0.333)

By above decision process, we can see that the ranking result obtained by using LT-TOPSIS is the same with the result in this paper. Thus, these two methods demonstrate the validity and reasonability of the decision-making results with each other. But there are differences between them as follows.

(i) In our decision method with 2-tuple linguistic assessments, we use the *TWA* operator and *TOWA* operator to aggregate all the individual values into the collective ones. In the whole process, all linguistic 2-tuples always express the evaluation values of alternative suppliers, which can effectively avoid the loss and distortion of information in the process of information gathering. So it makes the evaluation results have definite and specific meanings. For example, the collective overall evaluation values of five alternative suppliers are $r_1=(s_1,a_1)=$ (s_2, 0.137), $r_2=(s_2,a_2)=$ (s_3, 0.148), $r_3=(s_3,a_3)=$ (s_2, -0.272), $r_4=(s_4,a_4)=$ (s_4, -0.19), and $r_5=(s_5,a_5)=$ (s_2, -0.376) respectively, which means that the comprehensive evaluation level of supplier C_1 is superior to the rating "Acceptable" but inferior to "Good", the comprehensive evaluation level of supplier C_2 is superior to "Good" but inferior to "Best", the comprehensive evaluation level of supplier C_3 is superior to "Poor" but inferior to "Acceptable", the comprehensive evaluation level of supplier C_4 is superior to "good" but inferior to "Best", and the comprehensive evaluation level of supplier C_5 is superior to "Poor" but inferior to "Acceptable". Although supplier C_4 and supplier C_2 belong to the same rating, the values -0.19 and 0.148 can reflect the deviation degree. In this sense, our method can not only rank the order but also give the specific comprehensive evaluation ratings for the five alternative suppliers. In LT-TOPSIS, all original decision data are also expressed by linguistic 2-tuples, but in step 4 (calculate the distance of each alternative supplier from TLPIS and TLNIS) and step 5 (calculate the relative closeness degree of each alternative supplier from TLPIS), the linguistic 2-tuples express the distances and relative closeness degree respectively. This leads the final evaluation result (η_i, ζ_i) can only show relative ranking order of alternative suppliers, but have no definite and specific meanings on the evaluation rating.

(ii) In the practical group decision making, there are maybe some experts assign unduly high or unduly low uncertain preference values to their preferred or repugnant objects [42]. To relieve the influence of these unfair arguments on the decision results and reflect the importance of all the experts, we use the *TOWA* operator to aggregate all the individual weighted overall preference values of each alternative into the collective ones of alternatives. That is, *TOWA* operator may well weaken the adverse effects of emotional factors in the decision-making process, and can make the decision results more fair and reasonable through assigning low weights to those ‘‘false’’ or ‘‘biased’’ arguments. But these advantages can not be reflected in the method of LT-TOPSIS.

5. Conclusions

This paper proposes a new evaluation system for green supplier selection by considering the attributes under the commercial criterion and the environmental criterion, and presents a multi-attribute group decision making method with 2-tuple linguistic assessments for green supplier selection under a fuzzy uncertain information environment. In order to demonstrate the practicality and effectiveness of our decision method, we also give an application decision making example of green supplier selection and compare our method with the method of LT-TOPSIS. The comparison results show that our method has some advantages, i.e., our method can not only rank the order but also give the specific comprehensive evaluation ratings for all alternative suppliers, our method can well weaken the adverse effects of irrationality in the decision-making process and can make the decision results fairer and more reasonable by assigning low weights to those untrue or biased arguments, our method can effectively avoid the loss and distortion of information in the process of information gathering, and so on. Our future research is to present some new aggregation operators with linguistic 2-tuple assessment information just like *TOWA* to solve the problems of green supplier selection under multiple uncertain (e.g. fuzzy and grey) information environments.

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