Sustainable procurement decision of electric coal under fuzzy information environment

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Abstract. Green supply chain management is a crucial challenge for the sustainable development of enterprises. This study investigates the problem of supplier selection for the multi-attribute and multi-source green procurement of electric coal under fuzzy information environment. Concretely, a new index system of supplier selection is established by considering both the economic and environmental factors; then, a multi-attribute decision-making method based on 2-tuple deviation degree is presented to rank all alternative suppliers in the green procurement of electric coal. The implementation, availability, and feasibility of the green procurement decision method of electric coal are also highlighted by using an example of the multi-source procurement of electricity coal. An attempt is made to provide a theoretical basis and decision-making reference for the thermal power enterprise to implement scientific green procurement management of electric coal.

1. Introduction

Electric coal is one of the main raw materials for the thermal power generation, that is, it is a kind of coal used to generate electricity. The electric coal procurement is the basis of safe and stable generation of thermal power [1-3]. In the practical procurement of electric coal, the task of the procurement managers in thermal power enterprise is to evaluate and select the right and optimal suppliers using smart and effective procurement strategies to help enterprises enhance comprehensive competitiveness and maintain a strategically competitive position [4-7].

Many scholars studied the supplier selection problem of electric coal procurement. For example, Shiromaru et al. [8] used fuzzy satisfaction methods to deal with the fuzzy information in the process of electric coal procurement and used the genetic algorithm to select the supplier; Lai and Yang [9] presented a multi-layer optimization procurement model to evaluate and select the optimal suppliers for the power-generation enterprises; Dai et al. [10] proposed a supplier selection model based on a quantity discount contract; Yan [11] established an experimental platform of E-commerce coordinate system for selecting electric coal suppliers, etc. Based on the existing literatures on the practical electric coal procurement, the buyer considers multiple aspects when evaluating and selecting the optimal supplier, e.g., the coal mine production, the railway transportation, the highway transportation, the waterway transportation, and so on. Most of the existing methods for optimal supplier selection in electric coal procurement have only considered economic criteria, such as quality, price, delivery time, flexibility, etc., when evaluating supplier performance. Their main goal is to maximize the benefits of enterprises. However, with the development of society, the environmental problem is

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getting increasingly serious. A large quantity of waste gas, wastewater, and waste solid material was produced during the production of electric coal. Therefore, it very seriously polluted the environment [12-14]. In this sense, the buyer in a sustainable thermal power enterprise must also consider the environmental factors, in addition to the economic factors, when evaluating supplier performance in supplier selection.

In addition, the attribute values under these economic and environmental dimensions may be multiple data types, e.g., the attribute values of price, quantity, and delivery time are generally evaluated in the form of real numbers. However, due to the complexity of the decision-making environment and the ambiguity of the human mind, many attributes are difficult to quantify as an accurate real number, e.g., the supplier's reputation, supplier service level, and some environmental attributes (atmospheric pollution degree, environmental management level, etc.); thus, the values of these attributes are usually given in the form of linguistic fuzzy variables such as best, good, acceptable, poor, worst, etc. [15-31]. Thus, the decision-making on the supplier selection of electric coal procurement belongs to a kind of multi-attribute decision making under fuzzy information environment [32-46]. Further, because the supply of a single supplier in quantity and variety is limited, it is often difficult to meet the needs of the buyer within the given time. The buyer can select multiple suppliers to supply electric coal at the same time. Therefore, an optimal method is presented to solve this problem of multi-attribute and multi-source decision-making about the supplier selection of electric coal procurement.

Based on the above analysis, we focus on the following research questions in this paper:

(1) Construct the evaluation system for supplier selection by considering both the economic and environmental factors from a perspective of green supply chain management;

(b) Design an optimal decision-making method for supplier selection of electric coal based on a 2-tuple deviation degree. An attempt is made to provide a theoretical basis and decision-making reference for the thermal power enterprise to implement scientific green procurement management of electric coal under the fuzzy information environment.

Compared with the existing methods for procurement decision of electric coal, in our decision method, the supplier selection problem in the multi-source and multi-attribute green procurement of electric coal is transformed into hybrid multi-attribute decision-making problems with hybrid attribute data (the real numbers and linguistic fuzzy variables coexist). In the decision process, all hybrid data of alternative suppliers are transformed into the linguistic 2-tuples [25-28,33,47-49], and a new ranking method-2-tuple deviation degree is presented to rank all alternative suppliers and select winners. This data process can effectively prevent the loss and distortion of information in the process of information collection compared with some traditional methods. However, there are not many methods among the traditional MADM methods to deal with this kind of hybrid multi-attribute decision-making problems with hybrid attribute data. Even though there are a few, most of them transform the hybrid data into a single type data (real numbers, or interval number, or triangle fuzzy numbers); then, a comprehensive evaluation is made. This data process method is easy to cause information loss and information distortion.

The rest of this paper is organized as follows. Section 2 constructs the evaluation system for supplier selection from economic and environmental dimensions. Section 3 presents an optimal decision-making method for electric coal supplier selection based on 2-tuple deviation degree. Section 4 gives an example of the multi-source procurement of electricity coal to highlight the implementation, availability, and feasibility of the green procurement decision method. Section 5 concludes the paper.

2. The evaluation index system of selecting electric coal suppliers

In this section, a new evaluation system for supplier selection of electric coal is established. As environmental protection is critical to good green supply chain management, supplier selection requires considering the environmental and economic factors. In this paper, based on the existing related research [2,3,6-10,12-13], both the economic and environmental factors are considered as follows:

1. **Attributes under the economic dimension:**
   A_1 price represents the purchase price per ton of electric coal for a buyer (in Yuan/ton). The value of price will be directly submitted to the buyer in the form of a real number by the electric coal suppliers.

   A_2 quantity is the largest amount of electric coal that a supplier can supply for a fee at a certain time (in ton). Usually, the value of quantity will be directly submitted to the buyer in the form of a real number by the suppliers in conjunction with their production capacity and actual production.

   A_3 delivery time is the time taken by a supplier to deliver the electric coal to a buyer under contract (in day). Delivery time reflects the transport capacity of suppliers, and short delivery time represents high transportation ability. The value of delivery time will be directly submitted

to the buyer in the form of a real number by the electric coal suppliers.

A_4 quality is a core attribute in electric coal supplier evaluation. The quality level of electric coal can be characterized by the implementation level of relative quality standard system. Usually, the common quality standard is the electric coal national standard GB/T7562-2010 [50]. In this standard, some quality attributes must satisfy the basic standard; for example, the calorific value (in MJ/kg) must be greater than 12 and is generally divided into five grades:>24, 21.01∼24, 17.01 ∼ 21, 15.51∼17, >12; the volatile matter (in percentage) must be greater than 6.5 and is generally divided into five grades: 6.5 ∼ 10, 10.01 ∼ 20, 20.01 ∼ 28, >28, and >37; the ash melting point (in °C) must be greater than 1150 and is generally divided into four grades: >1150 ∼ 1250, 1260 ∼ 1350, 1360 ∼ 1450, > 1450; the ash (in %) must be less than 40, and the ash is generally divided into three grades: ≤ 20, 20 ∼ 30, 30 ∼ 40; the moisture (in %) must be greater than 8 and is generally divided into four grades: ≤ 8, 8.1∼12, 12.1∼20,> 20; the sulfur coal classification (in %) cannot be more than 2.5% and is generally divided into four grades: ≤ 0.5, 0.51∼1, 1.01∼2, 2.01∼3.

A_5 Supplier's reputation is the reputation degree, determining whether the suppliers can strictly fulfill the requirements of the procurement contract to provide high-quality electric coal for buyers within the specified time.

The attribute values of quality level of electric coal and supplier's reputation are usually given in the form of linguistic fuzzy variables, such as best, good, acceptable, poor, and worst, evaluated by the buyer.

2. **Attributes under the environmental dimension:**

A_6 carbon dioxide emission level. Its purpose is to protect the environment and slow global warming by cutting carbon dioxide emissions. The lower the level of carbon dioxide emission, the better the supplier.

A_7 wastewater discharge level refers to the density level of the indices such as physical water pollution, chemical water pollution, and biological water pollution.

A_8 Solid waste generation level mainly refers to the control degree of the remaining sludge and industrial waste from metal processing, smelting, casting, power production of raw materials, and water treatment.

The reduction rate of wastewater, waste gas, and solid waste reflects the degree of waste reduction. Ecotype enterprises slash the emission

of waste water, waste gas, and solid waste in the process of construction. The recommended values are as follows. The reduction rate of wastewater emission should be greater than 40%, the reduction rate of waste gas emission should be greater than 20%, and the reduction rate of solid waste emission should be greater than 30%.

A_9 recycling utilization rate of waste materials refers to the percentage of recycling utilization amount of waste material to the total generation amount of waste material. Generally, in order to realize the material integration, energy integration, and water resources integration, the recycling utilization rate of waste material should not be less than 80%.

A_{10} investment rate of environmental protection refers to the percentage of the total investment of environmental protection to the total investment of the enterprise within a certain period of time. Generally, the green supply chain requires that an enterprise's investment rate of environmental protection be more than 3.0%.

A_{11} Environmental management level is mainly measured by the development and implementation of environmental management systems and related regulations as well as the level of environmental information management.

The values of attributes A_6, A_7, A_8, A_9, A_{10}, and A_{11} under the environmental dimension are usually given in the form of linguistic fuzzy variables, such as best, good, acceptable, poor, and worst, evaluated by the buyer.

For the above 11 attributes, the values of A_1 price and A_3 delivery time are given in the form of real numbers and are cost type attributes; the values of A_2 quantity are also given in the form of real numbers; however, A_2 is a benefit type attribute. The other 8 attributes are given in the form of linguistic fuzzy variables and are all transformed as benefit type attributes.

Now, it is supposed that a buyer in a power-generation enterprise wants to procure Q_0 tons of electric coal. m ($m \geq 2$) suppliers take part in the supply competition. The above 11 attributes are used to evaluate m suppliers' performance. The values of these 11 attributes for m suppliers form the original decision-making matrix:

$$X = (x_{ij})_{m \times 11}, \quad i = 1, 2, \cdots, m,$$

where x_{ij} is the attribute value of supplier i under attribute j, $j = 1, 2, \cdots, 11$. In addition, we suppose that the weight set of above 11 attributes is $W = (w_1, w_2, \cdots, w_{11})$, such that $0 \leq w_j \leq 1$ and $\sum_{j=1}^{11} w_j = 1$. We can determine the values of attribute weights by the method of analytic hier-

archy process or the Delphi method in the practical decision-making procurement of electricity coal.

3. Supplier selection method based on 2-tuple deviation degree

Based on the data information in the original decision-making matrix $X = (x_{ij})_{m \times 11}$, our decision goal is to select the optimal suppliers to supply Q_0 units of electric coal to the buyer. Now, in this section, we will present an optimal decision-making method of electric coal supplier selection based on 2-tuple deviation degree.

3.1. Preliminaries

The 2-tuple [47-49] was first presented by professor Herrera of Spain in 2000; he used a dual combination (s_k, a_k) to express the evaluation result of an evaluation objective, where s_k is the kth element in a predefined linguistic term set S, $S = \{s_0, s_1, \cdots, s_h\}$, where $s_0, s_1, \cdots, s_h$ are $h + 1$ linguistic fuzzy variables. Also, a_k is a numerical value that represents the value of the symbolic translation, such that $a_k \in [-0.5, 0.5)$, implying the deviation between the evaluation result and s_k. The dual combination (s_k, a_k) is called a 2-tuple.

For a predefined linguistic term set, $S = \{s_0, s_1, \cdots, s_h\}$, the following properties are satisfied, i.e.:

(i) If $k \geq l$, then $s_k \geq s_l$;

(ii) There exists a negation operator $\text{Neg}(s_k) = s_l$, where $l = h - k$;

(iii) If $s_k \geq s_l$, then $\max(s_k, s_l) = s_k$ and $\min(s_k, s_l) = s_l$.

Now, some definitions are presented [47,48] on 2-tuple.

Definition 1. Let $s_k \in S$ be a linguistic fuzzy variable; then, the corresponding linguistic 2-tuple can be obtained by the following function, θ:

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

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

Definition 2. Let $S = \{s_0, s_1, \cdots, s_h\}$ be a linguistic term set and $\beta \in [0, 1)$ be a value supporting the result of a symbolic aggregation operation. Then, the 2-tuple that expresses the equivalent information is obtained with the following function:

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

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

where:

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

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

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

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

Definition 3. Let $S = \{s_0, s_1, \cdots, s_h\}$ be a linguistic term set and $\beta \in [1, h]$ be a value supporting the result of a symbolic aggregation operation. Then, the 2-tuple that expresses the equivalent information is obtained with the following function:

$$\Delta : [1, h] \rightarrow S \times [-0.5, 0.5),$$

$$\Delta(\beta) = \begin{cases} s_k, & k = \text{round}(\beta) \\ a_k = \beta - k, & a_k \in [-0.5, 0.5) \end{cases}$$

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

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

Definition 4. For any two linguistic 2-tuples (s_k, a_k) and (s_l, a_l), their compared operations are defined as follows:

1. If $k > l$, then $(s_k, a_k) > (s_l, a_l)$,
2. If $k = l$, then:
   (i) $a_k = a_l$, then $(s_k, a_k) = (s_l, a_l)$;
   (ii) $a_k > a_l$, then $(s_k, a_k) > (s_l, a_l)$;
   (iii) $a_k < a_l$, then $(s_k, a_k) < (s_l, a_l)$.
3. If $(s_k, a_k) \geq (s_l, a_l)$, then:

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

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

Definition 5. For any two 2-tuples, $A : (s_k, a_k)$ and $B : (s_l, a_l)$, the distance between A and B is defined as follows:

$$D(A, B) = \frac{|(k + a_k) - (l + a_l)|}{2}. \tag{1}$$

Based on the definition of distance given by Eq. (1), the definition of the deviation degree between two 2-tuple sequences is given as follows.

Definition 6. Let f_k and f_l be two 2-tuple sequences, where:

$$f_k = (f_k(1), f_k(2), \cdots, f_k(n))$$

$$= (s_{k1}, a_{k1}), (s_{k2}, a_{k2}), \cdots, (s_{kn}, a_{kn})),$$

$$f_l = (f_l(1), f_l(2), \cdots, f_l(n))$$

$$= (s_{l1}, a_{l1}), (s_{l2}, a_{l2}), \cdots, (s_{\ln}, a_{\ln})),$$

w_j is the weight of the jth 2-tuple, $j = 1, 2, \cdots, n$; thus, we set:

$$\delta(f_k, f_l) = w_1 D(f_k(1), f_l(1)) + w_2 D(f_k(2), f_l(2))$$

$$+ \cdots + w_n D(f_k(n), f_l(n)),$$

where:

$$D(f_k(j), f_l(j)) = \frac{|(kj + a_{kj}) - (lj + a_{lj})|}{2}.$$

Then, $\delta(f_k, f_l)$ is called a 2-tuple deviation degree between 2-tuple sequences, f_k and f_l.

3.2. A ranking method based on the 2-tuple deviation degree

In this section, a ranking method based on a 2-tuple deviation degree is presented to evaluate and rank all alternative electric coal suppliers. Now, the detailed decision steps are given.

Step 1. For cost type attributes of A_1 price and A_3 delivery time, the following Eq. (2) is used to normalize their attribute values. For the benefit-type attribute A_2 quantity, the following Eq. (3) is used to normalize its attribute value. Then, the original decision-making matrix, $X = (x_{ij})_{m \times 11}$, becomes a new decision-making matrix, $Y = (y_{ij})_{m \times 11}$.

$$y_{ij} = \frac{\max_i x_{ij}}{x_{ij}}, \qquad i = 1, 2, \cdots, m, \qquad j = 1, 3, \quad (2)$$

$$y_{ij} = \frac{x_{ij}}{\max_i x_{ij}}, \qquad i = 1, 2, \cdots, m, \qquad j = 2. \quad (3)$$

Step 2. For the attributes $A_4, A_5, \cdots, A_{11}$, their attributes such as best, good, acceptable, poor, and worst form a linguistic term set, $S = \{s_0, s_1, \cdots, s_4\}$, where:

$$s_0 = \text{worst}, \qquad s_1 = \text{poor}, \qquad s_2 = \text{acceptable},$$

$$s_3 = \text{good}, \qquad s_4 = \text{best}.$$

Then, the method given by Definition 1 is used to transform all linguistic fuzzy variables in decision-making matrix, $Y = (y_{ij})_{m \times 11}$, into the 2-tuples;

the method given by Definitions 2 and 3 is used to transform all real numbers in decision-making matrix, $Y = (y_{ij})_{m \times 11}$, into the 2-tuples; then, a new normative 2-tuple matrix, $Z = [(s_{ij}, a_{ij})]_{m \times 11}$, is found;

Step 3. Define the positive ideal solution and the negative ideal solution from the 2-tuple matrix, $Z = [(s_{ij}, a_{ij})]_{m \times 11}$. The positive ideal solution, f^+, and the negative ideal solution, f^-, are determined as follows:

$$f^+ = (f^+(1), f^+(2), \cdots, f^+(11)) = (\max_i(s_{i1}, a_{i1}),$$

$$\max_i(s_{i2}, a_{i2}), \cdots, \max_i(s_{i11}, a_{i11})), \quad (4)$$

$$f^- = (f^-(1), f^-(2), \cdots, f^-(11)) = (\min_i(s_{i1}, a_{i1}),$$

$$\min_i(s_{i2}, a_{i2}), \cdots, \min_i(s_{i11}, a_{i11})), \quad (5)$$

where the compared operation "max" and "min" of any two 2-tuples are given in Definition 4;

Step 4. Calculate the deviation degree between each alternative and positive ideal solution f^+ and calculate the deviation degree between each alternative and negative ideal solution f^-. The alternative i is formed by 11 elements of each row in 2-tuple matrix $Z = [(s_{ij}, a_{ij})]_{m \times 11}$, i.e.:

$$f_i = (f_i(1), f_i(2), \cdots, f_i(11))$$

$$= ((s_{i1}, a_{i1}), (s_{i2}, a_{i2}), \cdots, (s_{i11}, a_{i11}))$$

$$i = 1, 2, \cdots, m, \quad (6)$$

and the calculation formulas of deviation degree are presented as follows:

$$\delta(f^+, f_i) = w_1 D(f^+(1), f_i(1)) + w_2 D(f^+(2), f_i(2))$$

$$+ \cdots + w_{11} D(f^+(11), f_i(11)), \quad (7)$$

$$\delta(f^-, f_i) = w_1 D(f^-(1), f_i(1)) + w_2 D(f^-(2), f_i(2))$$

$$+ \cdots + w_{11} D(f^-(11), f_i(11)), \quad (8)$$

where w_j is the weight of the jth attribute, $j = 1, 2, \cdots, 11$, $D(f^+(j), f_i(j))$ is the distance between $f^+(j)$ and $f_i(j)$, and $D(f^-(j), f_i(j))$ is the distance between $f^-(j)$ and $f_i(j)$ (see Definition 5). The smaller the value of $\delta(f^+, f_i)$, the better the alternative i; the greater the value of $\delta(f^-, f_i)$, the better the alternative i;

Step 5. Calculate the relative closeness degree for each alternative and positive ideal solution, f^+. The

calculation formulas of relative closeness degree are as follows:

$$r_i = \frac{\delta(f^-, f_i)}{\delta(f^+, f_i) + \delta(f^-, f_i)}, \qquad i = 1, 2, \cdots, m. \quad (9)$$

Step 6. Rank all the alternative electric coal suppliers in accordance with the value of relative closeness degree, r_i, $i = 1, 2, \cdots, m$. The greater the value of r_i, the better the alter-native supplier i;

Step 7. Determine the final winners.

Suppose that the ranking order of the value of relative closeness degree r_i is $r_1 \geq r_2 \geq \cdots \geq r_m$, and the corresponding maximum supply quantities of the suppliers to the buyer are $x_{12}, x_{22}, \cdots, x_{m2}$. The rule of determining the final winners is that the buyer gives priority to allocating the electric coal to the supplier with a greater value of r_i. Firstly, the buyer will allocate the total amount, Q_0, of electric coal to the supplier with the greatest r_1, and Supplier 1 obtains the allowed supply quantity $q_1^* = x_{12}$. Secondly, the buyer will allocate the remaining amount $Q_0 - x_{12}$ to the supplier with the second greatest r_2. If the condition $x_{22} \geq Q_0 - x_{12}$ is satisfied, then Supplier 2 gets the allowed supply quantity $q_2^* = Q_0 - x_{12}$ and $q_3^* = q_4^* = \cdots = q_m^* = 0$, meaning that the allocation is over, and the suppliers with the value of r_i in the top 2 are the winners. If $x_{22} < Q_0 - x_{12}$, then $q_2^* = x_{22}$, and the residual amount, $Q_0 - x_{12} - x_{22}$, will be allocated to the rest of suppliers sequentially by the similar method. Repeat the similar process until the total amount, Q_0, is fully allocated.

4. A decision-making example of supplier selection in electric coal procurement

In this section, a decision-making example of supplier selection in electric coal procurement is presented to show how to implement our optimal decision-making method for selecting green suppliers and to demonstrate the effectiveness of this method.

It is supposed that a buyer wants to procure 1100 tons of electric coal. Five risk neutral suppliers are allowed to participate in the supply competition, i.e., $M = \{1, 2, \cdots, 5\}$. The buyer will measure and evaluate all electric coal suppliers' performance and select optimal suppliers from economic and environmental dimensions. The detailed evaluation attributes are given in Section 2, i.e., A_1 price (Yuan/ton), A_2 quantity (tons), A_3 delivery time (days), A_4 quality, A_5 supplier's reputation, A_6 carbon dioxide emission level, A_7 wastewater discharge level, A_8 solid waste generation level, A_9 recycling utilization rate of waste material, A_{10} investment rate of environmental protection, and A_{11} environmental management level. Let the weight set of the 11 attributes be $W = (w_1, w_2, \cdots, w_{11}) = (0.15, 0.05, 0.15, 0.15, 0.1, 0.1, 0.05, 0.05, 0.05, 0.1, 0.05)$.

After evaluating 11 attributes for all 5 alternative electric coal suppliers, it is supposed that the buyer gives the original decision-making matrix, $X = (x_{ji})_{11 \times 5}$, $i = 1, 2, \cdots, 5$, $j = 1, 2, \cdots, 11$. All data are listed in Table 1.

In Table 1, s_0 = worst, s_1 = poor, s_2 = acceptable, s_3 = good, and s_4 = best. The detailed decision process is as follows:

1. Use Eqs. (1), (2), and (3) to process the values of attributes A_1, A_2, and A_3 in matrix $X = (x_{ji})_{11 \times 5}$; then, we obtain the normalized decision-making matrix, $Y = (y_{ji})_{11 \times 5}$, as follows:

$$Y = \begin{pmatrix} 1.272 & 1.077 & 1.120 & 1 & 1.167 \\ 0.833 & 0.729 & 0.625 & 0.833 & 1 \\ 1.25 & 1.136 & 1 & 1.389 & 1.250 \\ s_3 & s_3 & s_4 & s_3 & s_4 \\ s_4 & s_2 & s_3 & s_4 & s_4 \\ s_3 & s_4 & s_2 & s_2 & s_3 \\ s_3 & s_3 & s_2 & s_2 & s_4 \\ s_3 & s_2 & s_3 & s_3 & s_4 \\ s_4 & s_2 & s_4 & s_3 & s_3 \\ s_4 & s_3 & s_4 & s_2 & s_4 \\ s_3 & s_2 & s_3 & s_3 & s_4 \end{pmatrix}.$$

Table 1. Original decision-making matrix.

Attribute	Supplier 1	Supplier 2	Supplier 3	Supplier 4	Supplier 5
A_1	220	260	250	280	240
A_2	400	350	300	400	480
A_3	20	22	25	18	20
A_4	s_3	s_3	s_4	s_3	s_4
A_5	s_4	s_2	s_3	s_4	s_4
A_6	s_3	s_4	s_2	s_2	s_3
A_7	s_3	s_3	s_2	s_2	s_4
A_8	s_3	s_2	s_3	s_3	s_4
A_9	s_4	s_2	s_4	s_3	s_3
A_{10}	s_4	s_3	s_4	s_2	s_4
A_{11}	s_3	s_2	s_3	s_3	s_4

$$R = \begin{pmatrix} (s_1, 0.272) & (s_1, 0.077) & (s_1, 0.120) & (s_1, 0) & (s_1, 0.167) \\ (s_3, 0.332) & (s_3, -0.084) & (s_3, -0.5) & (s_3, 0.332) & (s_4, 0) \\ (s_1, 0.25) & (s_1, 0.136) & (s_1, 0) & (s_1, 0.389) & (s_1, 0.250) \\ (s_3, 0) & (s_3, 0) & (s_4, 0) & (s_3, 0) & (s_4, 0) \\ (s_4, 0) & (s_2, 0) & (s_3, 0) & (s_4, 0) & (s_4, 0) \\ (s_3, 0) & (s_4, 0) & (s_2, 0) & (s_2, 0) & (s_3, 0) \\ (s_3, 0) & (s_3, 0) & (s_2, 0) & (s_2, 0) & (s_4, 0) \\ (s_3, 0) & (s_2, 0) & (s_3, 0) & (s_3, 0) & (s_4, 0) \\ (s_4, 0) & (s_2, 0) & (s_4, 0) & (s_3, 0) & (s_3, 0) \\ (s_4, 0) & (s_3, 0) & (s_4, 0) & (s_2, 0) & (s_4, 0) \\ (s_3, 0) & (s_2, 0) & (s_3, 0) & (s_3, 0) & (s_4, 0) \end{pmatrix} .$$

<div align="center">Box I</div>

2. Use the transformation methods in Definition 1, Definition 2, and Definition 3 to transform all attribute values in $Y = (y_{ji})_{11 \times 5}$ into 2-tuples; then, the normative 2-tuple matrix $R = [(s_{ji}, a_{ji})]_{11 \times 5}$ is obtained as shown in Box I.

3. Use Eqs. (4), (5), and (6) to determine compared sequences, $f_1, f_2, \cdots, f_5$, the positive ideal solution, f^+, and the negative ideal solution, f^-, in the normative 2-tuple matrix, $R = [(s_{ji}, a_{ji})]_{11 \times 5}$:

$$f_1 = ((s_1, 0.272), (s_3, 0.332), (s_1, 0.25), (s_3, 0),$$
$$(s_4, 0), (s_3, 0), (s_3, 0), (s_3, 0),$$
$$(s_4, 0), (s_4, 0), (s_3, 0)),$$

$$f_2 = ((s_1, 0.077), (s_3, -0.084), (s_1, 0.136),$$
$$(s_3, 0), (s_2, 0), (s_4, 0), (s_3, 0), (s_2, 0),$$
$$(s_2, 0), (s_3, 0), (s_2, 0)),$$

$$f_3 = ((s_1, 0.120), (s_3, -0.5), (s_1, 0), (s_4, 0),$$
$$(s_3, 0), (s_2, 0), (s_2, 0), (s_3, 0), (s_4, 0),$$
$$(s_4, 0), (s_3, 0)),$$

$$f_4 = ((s_1, 0), (s_3, 0.332), (s_1, 0.389), (s_3, 0),$$
$$(s_4, 0), (s_2, 0), (s_2, 0), (s_3, 0), (s_3, 0),$$
$$(s_2, 0), (s_3, 0)),$$

$$f_5 = ((s_1, 0.167), (s_4, 0), (s_1, 0.25), (s_4, 0),$$
$$(s_4, 0), (s_3, 0), (s_4, 0), (s_4, 0), (s_3, 0),$$
$$(s_4, 0), (s_4, 0)),$$

$$f^+ = ((s_1, 0.272), (s_4, 0), (s_1, 0.389), (s_4, 0),$$
$$(s_4, 0), (s_4, 0), (s_4, 0), (s_4, 0), (s_4, 0),$$
$$(s_4, 0), (s_4, 0)),$$

$$f^- = ((s_1, 0), (s_3, -0.5), (s_1, 0), (s_3, 0), (s_2, 0),$$
$$(s_2, 0), (s_2, 0), (s_2, 0), (s_2, 0), (s_2, 0),$$
$$(s_2, 0).$$

4. Use Eqs. (7) and (8) to calculate the deviation degrees $\delta(f^+, f_i)$ and $\delta(f^-, f_i)$, and the results are as follows:

$$\delta(f^+, f_1) = 0.227, \qquad \delta(f^+, f_2) = 0.458,$$
$$\delta(f^+, f_3) = 0.328, \qquad \delta(f^+, f_4) = 0.437,$$
$$\delta(f^+, f_5) = 0.093, \qquad \delta(f^-, f_1) = 0.435,$$
$$\delta(f^-, f_2) = 0.204, \qquad \delta(f^-, f_3) = 0.334,$$
$$\delta(f^-, f_4) = 0.225, \qquad \delta(f^-, f_5) = 0.569.$$

5. Use Eqs. (9) to calculate the relative closeness degree r_i, $i = 1, 2, \cdots, 5$.

$$r_1 = 0.657, \qquad r_2 = 0.309, \qquad r_3 = 0.504,$$
$$r_4 = 0.340, \qquad r_5 = 0.859.$$

6. Rank all 5 alternative electric coal suppliers in accordance with r_i, $i = 1, 2, \cdots, 5$. Since:

$$r_5 > r_1 > r_3 > r_4 > r_2,$$

the five alternative suppliers are ranked as Supplier 5 $\succ$ Supplier 1 $\succ$ Supplier 3 $\succ$ Supplier 4 $\succ$ Supplier 2.

7. Use the method for determining winners given in Section 3.2 to determine the final winners.

First, the buyer allocates the total amount $Q_0 = 1100$ tons of electric coal to Supplier 5 with the greatest relative closeness degree, r_5, and Supplier 5 gets the allowable supply quantity, $q_5^* = x_{25} = 480$ tons. Second, the buyer allocates the remaining amount of $Q_0 - q_5^* = 1100 - 480 = 620$ tons to Supplier 1. Since the maximum supply quantity of Supplier 1 is $x_{21} = 400$ tons and $x_{21} = 400 < 620$, Supplier 1 gets the allowable supply quantity of $q_1^* = 400$ tons. Third, the buyer allocates the remaining amount of $Q_0 - q_5^* - q_1^* = 1100 - 480 - 400$ tons to Supplier 3. Since $c_{23} = 300 > 220$, Supplier 3 can only get the allowable supply quantity of 220 tons. Now, the allocation is over, and Supplier 5, Supplier 1, and Supplier 3 are the final three winners.

In the final contract, Supplier 5 will supply 480 tons of goods to the buyer at a transaction price of 240 Yuan/ton. Supplier 1 will supply 400 tons of goods at 220 Yuan/ton. Supplier 3 will supply 220 tons goods at 250 Yuan/ton.

5. Conclusion

This study focused on the problem of selecting green supplies in the multi-attribute and multi-source procurement of electric coal. Then, it presented a new index system of supplier selection by considering both the economic and environmental factors. This new evaluation system effectively improved the traditional evaluation system, which only considered economic factors such as price, quality, delivery time, flexibility, and so on. We also considered the green supplier selection under fuzzy information environment and presented a multi-attribute decision-making method based on linguistic 2-tuple to rank all alternative suppliers. This method may well improve the procurement efficiency of electric coal and can effectively prevent the information loss in the decision-making process; in addition, it also provides a feasible winner selection method for a kind of hybrid multi-attribute decision-making problems with hybrid attribute data. In the future, we will further study the sustainable procurement decision of electric coal under a more complex information environment, e.g., the supplier selection with hybrid attribute data (precise values, interval numbers, and the linguistic fuzzy variable coexist).

Acknowledgments

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