Hindawi
Mathematical Problems in Engineering
Volume 2018, Article ID 7189451, 10 pages
https://doi.org/10.1155/2018/7189451

Research Article

A Method for Multicriteria Group Decision Making with Different Evaluation Criterion Sets

Zhi-Ping Fan[1,2] **Ming-Yang Li**[3] **Yang Liu**[1] **and Tian-Hui You**[1]

[1] *Department of Information Management and Decision Sciences, School of Business Administration, Northeastern University, Shenyang 110169, China*
[2] *State Key Laboratory of Synthetical Automation for Process Industries, Northeastern University, Shenyang 110819, China*
[3] *Department of Management Science and Engineering, Business School, Liaoning University, Shenyang 110136, China*

Correspondence should be addressed to Ming-Yang Li; lmy_neu@163.com and Yang Liu; liuy@mail.neu.edu.cn

Received 27 April 2018; Revised 30 September 2018; Accepted 8 October 2018; Published 21 October 2018

Academic Editor: Rita Gamberini

Multicriteria group decision making (MCGDM) with different evaluation criterion sets is a special kind of MCGDM problem, where criterion sets considered by multiple experts may be different, while research concerning this issue is still relatively scarce. The objective of this paper is to develop a method for MCGDM with different evaluation criterion sets. In the method, according to different criterion sets, several criterion subsets are first constructed, where each criterion subset includes the criteria concerned by the same group of experts. Then, with respect to each criterion subset, a ranking of alternatives is determined by normalizing the decision matrix and calculating the ranking value of each alternative with respect to the criterion subset. Next, according to the ranking of alternatives with respect to each criterion subset, a ranking possibility matrix of alternatives with respect to the criterion subset is constructed. Further, the weight of each criterion subset is determined according to weights of the experts and weights of the criteria in the criterion subset. Moreover, an overall ranking possibility matrix is constructed by aggregating the ranking possibility matrices and weights concerning different criterion subsets, and the final ranking result of alternatives is determined by solving a linear assignment model, where the elements in the overall ranking possibility matrix are regarded as the benefits on assigning each alternative into different ranking positions. Finally, a numerical example is given to illustrate the use of the proposed method.

1. Introduction

Multicriteria group decision making (MCGDM) refers to the problem of classifying or ranking the alternatives based on the opinions provided by multiple experts concerning multiple criteria [1–3], which is a valuable research topic with extensive theoretical and practical backgrounds [4–8]. For example, to select a desirable product design scheme from several alternatives, it is necessary to make a decision according to the opinions concerning multiple criteria provided by multiple R&D experts such as financial experts and quality management experts [9]. For the recruitment of technicians, the desirable employee(s) will be selected by the human resource department and the technical department according to performances concerning multiple criteria [10–12]. For the determination of the winner in multiattribute procurement auction, the opinions of multiple financial experts and technique experts concerning the financial criteria and the technique criteria should be used [13, 14]. Therefore, how to solve the MCGDM problem is a valuable research topic.

The MCGDM problem has attracted the attention of many scholars, and many methods have been proposed [15–27]. Tavana et al. [15] presented a framework to help decision-makers develop the group decision support system combining the analytic hierarchy process and the Delphi principles. Herrrera-Viedma et al. [16] proposed a MCGDM framework with linguistic preference relations. Li [17] developed a compromise ration method for fuzzy MCGDM problem. Merigó et al. [18] introduced the uncertain generalized probabilistic weighted averaging (UGPWA) operator to solve the

MCGDM problem. Roselló et al. [19] proposed a method for MCGDM under multi-granular linguistic assessment environment. Merigó et al. [20] introduced linguistic probabilistic weighted average (LPWA) operators to develop more efficient decision-making systems, and its main advantage is to consider subjective and objective information in the same formulation. Zavadskas et al. [21] extended the application of the MULTIMOORA method for group decision making in the uncertain environment and developed the interval-valued intuitionistic fuzzy MULTIMOORA method for MCGDM. Chen et al. [22] proposed a new fuzzy MCGDM method based on intuitionistic fuzzy sets and the evidential reasoning methodology. Chu et al. [23] investigated the consistency checking process, the consensus checking process, and the selection process with respect to additive intuitionistic fuzzy preference relation. Liu et al. [24, 25] considered the problems of ranking products according to the online reviews given by a large group of consumers and proposed the methods based on the sentiment analysis technique, the intuitionistic fuzzy set theory, and interval-valued intuitionistic fuzzy TOPSIS. Zhang et al. [26] proposed a consensus improving method based on the consensus criteria and introduced the whole group decision-making process based on the aggregation operators for the probabilistic linguistic term sets. Liu et al. [27] developed a novel decision-making method to solve MCGDM problems in which the experts have different priority levels and the criteria values are in the form of Pythagorean fuzzy uncertain linguistic variables.

Prior studies have made significant contributions to MCGDM analysis. In most of the existing MCGDM studies, one criterion set is considered in group decision-making analysis. However, in reality, the criterion sets considered by multiple experts may be different since the experts are usually from different organizations or departments, and each expert may pay more attention to the criteria that relate to his/her own benefit or duty. For example, to determine the winner in multiattribute procurement auction, the opinions of multiple financial experts and technique experts should be considered, where the financial experts mainly pay attentions to the price, tax rate, and so on, while the technical experts mainly pay attentions to the technical indicators of goods from bidders. Currently, the studies on MCGDM method with different criterion sets are relatively scarce. Roy and Maji [28] presented a fuzzy soft set theoretic approach to solving the MCGDM problem. The approach involves construction of a comparison table from a fuzzy soft set in a parametric sense for decision making. Çağman and Enginoğlu [10] constructed uni-int decision-making method by using the definitions of soft sets and uni-int decision function. In the method, the evaluation information concerning different criterion sets from two decision-makers is described using soft set, and the evaluation information of two decision-makers is disposed to reduce a large alternative set into the subset of alternatives. Feng et al. [29] extended the method proposed by Çağman and Enginoğlu. They gave the definitions of satisfaction relations and developed a new algorithm to screen the desirable alternatives. Also, they pointed out that the uni-int decision making is a special case for the method proposed in their paper. Li et al. [30] proposed three rules for screening alternatives and gave the calculation process of screening alternatives based on soft sets theory. It is necessary to point out that, in the MCGDM problem with different evaluation criterion sets, a criterion may be concerned by one, two, or more experts. It is reasonable to consider different evaluation criterion sets concerned by multiple experts in group decision-making process, but different evaluation criterion sets are not considered in the existing MCGDM method. Therefore, it is necessary to develop a new decision-making method to solve MCGDM problem mentioned above. This is the research motivation of this paper.

The objective of this paper is to develop a method for MCGDM with different evaluation criterion sets. In the method, according to the criterion sets considered by multiple experts, several criterion subsets are first constructed, where each criterion subset includes the criteria concerned by the same group of experts. Then, with respect to each criterion subset, a ranking of alternatives is determined by normalizing the decision matrix and calculating the ranking value of each alternative with respect to the criterion subset. According to the ranking of alternatives with respect to each criterion subset, a ranking possibility matrix of alternatives with respect to the criterion subset is constructed. Further, the weight of each criterion subset is determined according to the weights of experts and the weights of criteria in the criterion subset. Moreover, an overall ranking possibility matrix is constructed by aggregating the ranking possibility matrices and weights concerning different criterion subsets, and the final ranking result of alternatives is determined by solving a linear assignment model, where the elements in the overall ranking possibility matrix are regarded as the benefits on assigning each alternative into different ranking positions.

The rest of this paper is arranged as follows. Section 2 describes the MCGDM problem with different evaluation criterion sets. Section 3 presents a decision-making method for solving the MCGDM problem. In Section 4, a numerical example is used to illustrate the applicability of the proposed method. Finally, we summarize and highlight main features of the proposed method in Section 5.

2. Problem Description

The following notations are used to denote the sets and variables in the MCGDM problem with different evaluation criterion sets, which are used throughout this paper.

(i) $A = \{A_1, A_2, \cdots, A_m\}$: the set of m alternatives, where A_i denotes the ith alternative, $i = 1, 2, \cdots, m$.

(ii) $E = \{E_1, E_2, \cdots, E_q\}$: the set of q experts, where E_k denotes the kth expert, $k = 1, 2, \cdots, q$.

(iii) $\boldsymbol{b} = (b_1, b_2, \cdots, b_q)$: the weight vector of experts, where b_k denotes the weight or importance degree of expert E_k, $k = 1, 2, \cdots, q$.

(iv) $C = \{C_1, C_2, \cdots, C_n\}$: the set of all criteria considered by the experts, where C_j denotes the jth criterion, $j = 1, 2, \cdots, n$.

(v) C^k: the set of criteria concerned by the expert E_k, $k = 1, 2, \cdots, q$, $C^k \subset C$, $C^1 \cup C^2 \cup \cdots \cup C^q = C$. If $C^k = \varnothing$, then it means that E_k does not concern any criteria and it is

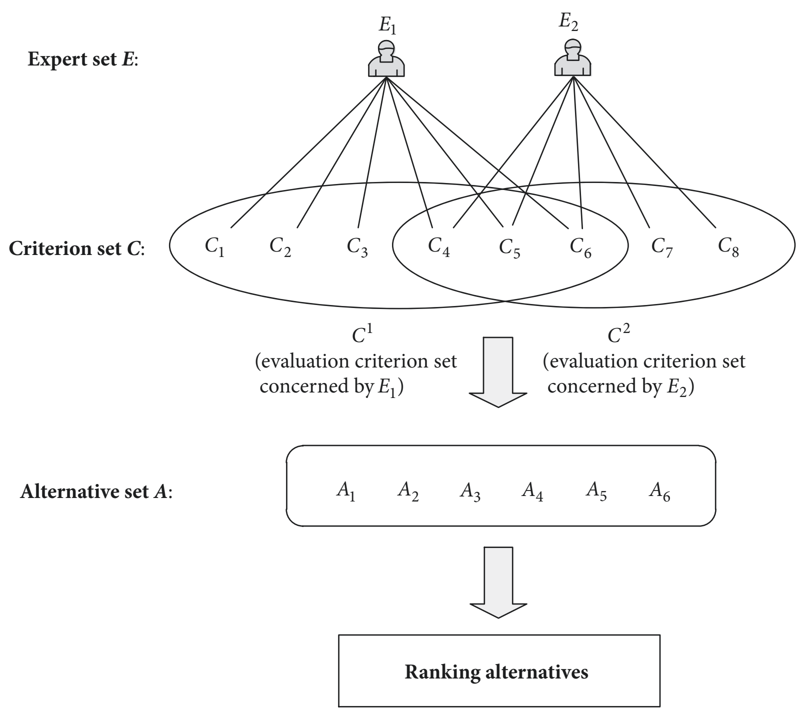

Figure 1: The MCGDM problem with two different evaluation criterion sets.

not necessary for E_k to participate the decision analysis as an expert. Thus, we assume $C^k \neq \varnothing$ in this paper.

(vi) $w_k = (w_1^k, w_2^k, \cdots, w_n^k)$: the weight vector of criteria provided by E_k, where w_j^k denotes the weight or importance degree of evaluation criterion C_j. If $C_j \notin C^k$, i.e., E_k does not concern criterion C_j, then $w_j^k = 0$; if $C_j \in C^k$, then $0 < w_j^k \leq 1$. According to the above description, we know that $b_1, b_2, \cdots, b_q$ have been used to represent the differences among the weights. Thus, $w_1^k, w_2^k, \cdots, w_n^k$ are only used to reflect the differences among the weights of different criteria in E_k's mind, $k = 1, 2, \cdots, q$. For this, the sum of $w_1^k, w_2^k, \cdots, w_n^k$ should be unified, i.e., $\sum_{j=1}^{n} w_j^k = 1$, $k = 1, 2, \cdots, q$. The $w_1^k, w_2^k, \cdots, w_n^k$ can be obtained either directly from the expert or indirectly using the existing procedures such as AHP [31, 32].

(vii) $\boldsymbol{V} = [v_{ij}]_{m\times n}$: the decision matrix, where v_{ij} denotes the value of alternative A_i with respect to criterion C_j, $i = 1, 2, \cdots, m$, $j = 1, 2, \cdots, n$.

Without loss of generality, the criteria can be classed into two types: the benefit criterion and the cost criterion [33–35]. The benefit criterion means that the larger the value of an alternative with respect to the criterion is, the better the alternative will be; and the cost criterion means that the smaller the value of an alternative with respect to the criterion is, the better the alternative will be. Let C^B and C^C be the sets of benefit and cost criteria, respectively, $C^B \cap C^C = \varnothing$, $C^B \cup C^C = C$.

The problem addressed in this paper is how to rank alternatives or select the most desirable alternative(s) among the set A using weight vector $\boldsymbol{b}$, weight vector w_k, and decision matrix $\boldsymbol{V}$.

To illustrate the MCGDM problem with different evaluation criterion sets more clearly, Figure 1 is given as an example, where two experts E_1 and E_2 are considered. In Figure 1, the criterion sets concerned by E_1 and E_2 are different, i.e., the criterion set concerned by E_1 is $\{C_1, C_2, C_3, C_4, C_5, C_6\}$ and the criterion set concerned by E_2 is $\{C_4, C_5, C_6, C_7, C_8\}$. According to different criterion sets concerned by the two experts, three criterion subsets can be constructed, i.e., the criterion subset $\{C_1, C_2, C_3\}$ concerned by E_1, the criterion subset $\{C_7, C_8\}$ concerned by E_2, and the criterion subset $\{C_4, C_5, C_6\}$ concerned by both E_1 and E_2. To determine the ranking of alternatives, it is necessary to consider the performance of each alternative with respect to the above three criterion subsets.

3. The Method

To solve the above MCGDM problem with different evaluation criterion sets, a method is proposed in this section. The resolution procedure of the method is shown in Figure 2. In the method, according to the criterion sets concerned by different experts, several criterion subsets are first constructed, where each criterion subset includes the criteria concerned by the same group of experts. Then, with respect to each criterion subset, a ranking of alternatives is determined by normalizing the decision matrix and calculating the ranking value of each alternative with respect to the criterion subset. According to the ranking of alternatives with respect to each criterion subset, a ranking possibility matrix of alternatives is

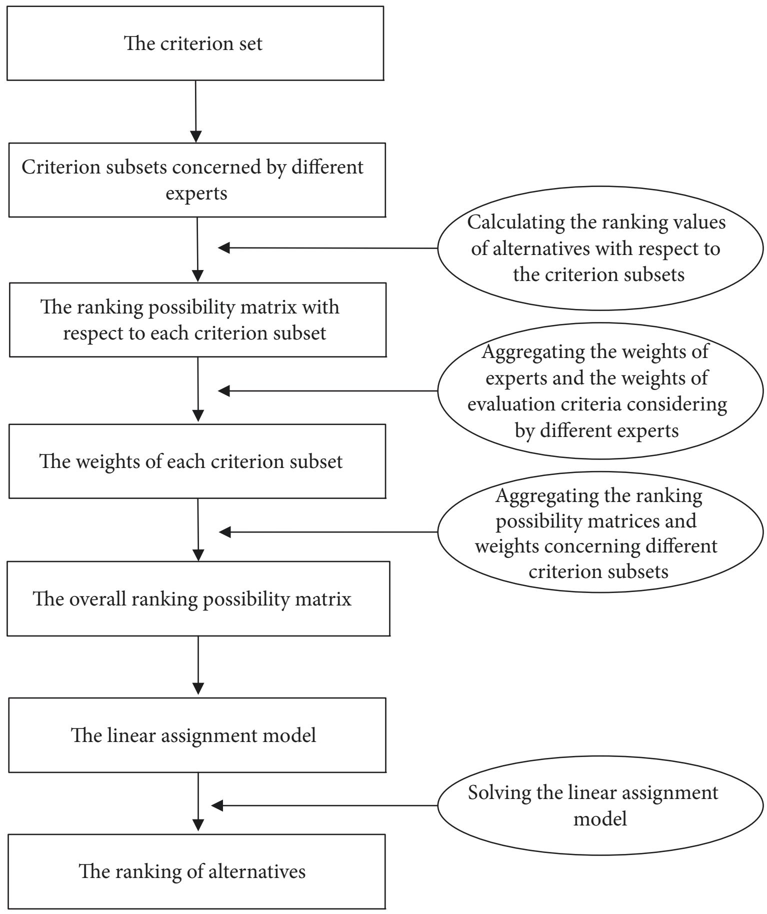

FIGURE 2: The resolution procedure for solving the MCGDM problem with different evaluation criterion sets.

constructed with respect to the criterion subset. Further, the weight of each criterion subset is determined according to the weights of experts and the weights of criteria in the criterion subset. Moreover, an overall ranking possibility matrix is constructed by aggregating the ranking possibility matrices and the weights concerning different criterion subsets, and the final ranking results of alternatives is determined by solving a linear assignment model, where the elements in the overall ranking possibility matrix are regarded as the benefits on assigning each alternative into different ranking positions.

3.1. Constructing Criterion Subsets Concerned by Different Groups of Experts. According to the resolution procedure shown in Figure 2, several criterion subsets are first constructed, where each criterion subset includes the criteria concerned by the same group of experts.

Let $P(E)$ be the power set of E, i.e., $P(E) = \{\varnothing, \{E_1\}, \{E_2\}, \cdots, \{E_q\}, \{E_1, E_2\}, \cdots, \{E_1, E_2, \cdots, E_q\}\}$; let $\widetilde{P}(E) = P(E) \setminus \varnothing$; i.e., $\widetilde{P}(E)$ is the subset of $P(E)$ by deleting $\varnothing$ from $P(E)$. Let E' denote a subset of experts (i.e., $E' \in \widetilde{P}(E)$); let $C(E')$ denote the criterion subset concerned by the experts in E'. For example, if $E' = \{E_1\}$, then $C(E') = C(\{E_1\})$, and $C(E')$ denotes the criterion set, in which the criteria are only concerned by E_1. If $E' = \{E_1, E_2\}$, then $C(E') = C(\{E_1, E_2\})$, and $C(E')$ denotes the criterion set, in which the criteria are concerned by E_1 and E_2. If $E' = \{E_1, E_2, \cdots, E_q\}$, then $C(E') = C(\{E_1, E_2, \cdots, E_q\})$, and $C(E')$ denotes the criterion set, in which the criteria are concerned by all the experts. To determine $C(E')$ concerning each E' ($E' \in \widetilde{P}(E)$), the process for constructing criterion subsets considered by different groups of experts is given below.

Firstly, an indicator matrix $\boldsymbol{T} = [t_{kj}]_{q\times n}$ is constructed, t_{kj} =0 or 1, where $t_{kj} = 1$ if the criterion C_j is concerned by E_k (i.e., $C_j \in C^k$); otherwise $t_{kj} = 0$, $k = 1, 2, \cdots, q, j = 1, 2, \cdots, n$. An example on the construction of indicator matrix $\boldsymbol{T} = [t_{kj}]_{q\times n}$ is given below.

Example 1. Consider a MCGDM problem with three experts (E_1, E_2, E_3), and there are eight criteria concerned by the experts, i.e., $C = \{C_1, C_2, \cdots, C_8\}$. The criteria concerned by E_1, E_2, and E_3 are $C^1 = \{C_1, C_2, C_5, C_7, C_8\}$, $C^2 = \{C_2, C_3, C_4, C_6, C_7, C_8\}$, and $C^3 = \{C_2, C_3, C_6, C_7\}$, respectively. Thus, indicator matrix $\boldsymbol{T} = [t_{kj}]_{3\times 8}$ can be constructed, as shown in Table 1.

Then, according to the constructed indicator matrix $\boldsymbol{T} = [t_{kj}]_{q\times n}$, an indicator vector $\boldsymbol{t}_j = [t_{1j}, t_{2j}, \ldots, t_{qj}]^T$

TABLE 1: The indicator matrix $\boldsymbol{T} = [t_{kj}]_{3\times 8}$.

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8
E_1	1	1	0	0	1	0	1	1
E_2	0	1	1	1	0	1	1	1
E_3	0	1	1	0	0	1	1	0

concerning criterion C_j can be determined, $j = 1, 2, \cdots, n$. Thus, $\boldsymbol{T} = [t_{kj}]_{q\times n}$ can be further represented by $\boldsymbol{T} = [t_{kj}]_{q\times n} = [\boldsymbol{t}_1, \boldsymbol{t}_2, \cdots, \boldsymbol{t}_n]$, where vector $\boldsymbol{t}_j$ is the indicator vector concerning criterion C_j, $j = 1, 2, \cdots, n$.

Further, let $e(E') = [e_1, e_2, \ldots, e_q]^T$ denote the indicator vector corresponding to set $C(E')$, $e_k = 0$ or 1, where $e_k = 1$ denotes that expert E_k belongs to the set E'; otherwise $e_k = 0$, $k = 1, 2, \cdots, q$.

The following Example 2 is given to illustrate the construction of indicator vector $e(E') = [e_1, e_2, \ldots, e_q]^T$.

Example 2. Consider the MCGDM problem shown in Example 1. The subset of experts is $\widetilde{P}(E) = \{\{E_1\}, \{E_2\}, \{E_3\}, \{E_1, E_2\}, \{E_1, E_3\}, \{E_2, E_3\}, \{E_1, E_2, E_3\}\}$. Obviously, there are seven indicator vectors $e(E') = [e_1, e_2, \ldots, e_q]^T$, i.e.,

$$e(\{E_1\}) = \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix},$$

$$e(\{E_2\}) = \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix},$$

$$e(\{E_3\}) = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix},$$

$$e(\{E_1, E_2\}) = \begin{bmatrix} 1 \\ 1 \\ 0 \end{bmatrix}, \tag{1}$$

$$e(\{E_1, E_3\}) = \begin{bmatrix} 1 \\ 0 \\ 1 \end{bmatrix},$$

$$e(\{E_2, E_3\}) = \begin{bmatrix} 0 \\ 1 \\ 1 \end{bmatrix},$$

$$e(\{E_1, E_2, E_3\}) = \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix}.$$

Property 1. In a MCGDM problem with q experts, there are $2^q - 1$ indicator vectors $e(E') = [e_1, e_2, \ldots, e_q]^T$.

Proof. Since there are two possible values of e_k, $e_k = 0$ or 1, there are 2^q possible combinations of the q binary variables. Since $e(\{\varnothing\}) = (0, 0, \ldots, 0)$ is not considered, there are $2^q - 1$ possible indicator vectors $e(E') = [e_1, e_2, \ldots, e_q]^T$.

Next, according to the indicator vector $\boldsymbol{t}_j = [t_{1j}, t_{2j}, \cdots, t_{qj}]^T$ and $e(E') = [e_1, e_2, \ldots, e_q]^T$, the distance between $\boldsymbol{t}_j$ and $e(E')$ can be calculated using (2), i.e.,

$$d(\boldsymbol{t}_j, e(E')) = \sqrt{\sum_{k=1}^{q} (t_{kj} - e_k)^2}, \quad j = 1, 2, \cdots, n, \ E' \in \widetilde{P}(E) \tag{2}$$

It can be seen from (2) that $C_j \in C(E')$ if $d(\boldsymbol{t}_j, e(E')) = 0$; otherwise $C_j \notin C(E')$. □

3.2. Ranking Alternatives with respect to Each Criterion Subset. First, according to the decision matrix $\boldsymbol{V} = [v_{ij}]_{m\times n}$, the normalized decision matrix $\overline{\boldsymbol{V}} = [\overline{v}_{ij}]_{m\times n}$ can be constructed, where $\overline{v}_{ij}$ denotes the normalized value of v_{ij}. It can be calculated by the following (3), i.e.,

$$\overline{v}_{ij} = \begin{cases} \dfrac{(v_{ij} - v_j^{\min})}{(v_j^{\max} - v_j^{\min})}, & i = 1, 2, \cdots, m; \ j \in C^B \\ \dfrac{(v_j^{\max} - v_{ij})}{(v_j^{\max} - v_j^{\min})}, & i = 1, 2, \cdots, m; \ j \in C^C \end{cases} \tag{3}$$

where $v_j^{\min} = \min\{v_{ij} \mid i = 1, 2, \cdots, m\}$ and $v_j^{\max} = \max\{v_{ij} \mid i = 1, 2, \cdots, m\}$, $j = 1, 2, \cdots, n$.

Then, the ranking value of alternative A_i with respect to the criterion subset $C(E')$ can be calculated, i.e.,

$$V_{E'}(A_i) = \sum_{\substack{C_j \in C(E') \\ E_k \in E'}} b_k w_j^k \overline{v}_{ij}, \quad i = 1, 2, \cdots, m \tag{4}$$

According to the ranking values, $V_{E'}(A_1)$, $V_{E'}(A_2)$, $\ldots, V_{E'}(A_m)$, the ranking order of alternatives $(A_1, A_2, \cdots, A_m)$ with respect to the criterion subset $C(E')$ can be determined. Let $\boldsymbol{r}^{E'} = [r_{is}^{E'}]_{m\times m}$ denote the ranking possibility matrix concerning the criterion subset $C(E')$, where $r_{is}^{E'}$ denotes the possibility that alternative A_i is ranked at the sth position with respect to the criterion subset $C(E')$, $i, s = 1, 2, \cdots, m$. As for the determination of the value of $r_{is}^{E'}$, the following two possible cases are considered.

① If and only if A_i itself with respect to criterion subset $C(E')$ is ranked at the kth position, then $r_{is}^{E'}$ can be determined by

$$r_{is}^{E'} = \begin{cases} 1, & s = k \\ 0, & s \neq k \end{cases}, \quad i = 1, 2, \cdots, m \tag{5}$$

② If g alternatives including A_i are ranked at the kth position, then $r_{is}^{E'}$ can be given by

$$r_{is}^{E'} = \begin{cases} \dfrac{1}{g}, & s = k, k+1, \cdots, k+g-1 \\ 0, & otherwise \end{cases}, \quad i = 1, 2, \cdots, m \tag{6}$$

To illustrate the determination of $\boldsymbol{r}^{E'} = [r_{is}^{E'}]_{m\times m}$, the following Example 2 is given.

Example 2. There are 5 alternatives $(A_1, A_2, A_3, A_4, A_5)$ in a MCGDM problem, and the ranking order of alternatives with respect to the evaluation criteria set $C(E')$ is $A_2 \succ A_3 \succ A_1 \succ A_5 \succ A_4$. The ranking possibility matrix can be constructed as

$$\boldsymbol{r}^{E'} = \left[r_{is}^{E'}\right]_{5\times 5} = \begin{array}{c} \\ A_1 \\ A_2 \\ A_3 \\ A_4 \\ A_5 \end{array} \begin{array}{c} \begin{array}{ccccc} \text{1st} & \text{2nd} & \text{3rd} & \text{4th} & \text{5th} \end{array} \\ \begin{bmatrix} 0 & 0.5 & 0.5 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \\ 0 & 0.5 & 0.5 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 1 & 0 \end{bmatrix} \end{array} \tag{7}$$

3.3. Determining the Weight of Ranking Result Concerning Each Criterion Subset. To determine the final ranking result of alternatives by aggregating the ranking possibility matrices concerning different criterion subsets, it is necessary to determine the weight of ranking result concerning each criterion subset. Since each criterion subset includes the criteria concerned by a group of experts, it is reasonable that the weight of ranking result concerning each criterion subset is calculated by both the weights of experts and the weights of evaluation criteria concerned by different experts. The weight of criterion subset $C(E')$ can be obtained by

$$w_{E'} = \sum_{\substack{C_j \in C(E') \\ E_k \in E'}} b_k w_j^k, \quad E' \in \widetilde{P}(E) \tag{8}$$

3.4. Determining the Final Ranking Result of Alternatives. Based on the ranking possibility matrix $\boldsymbol{r}^{E'} = [r_{is}^{E'}]_{m\times m}$ and weight $w_{E'}$ concerning criterion subset $C(E')$, the overall ranking possibility matrix $\boldsymbol{P} = [p_{is}]_{m\times m}$ can be constructed, where p_{is} denotes the overall possibility that alternative A_i is ranked at the sth position, and p_{is} can be calculated by

$$p_{is} = \sum_{E' \in \widetilde{P}(E)} w_{E'} \cdot r_{is}^{E'} \tag{9}$$

Based on the overall ranking possibility matrix $\boldsymbol{P} = [p_{is}]_{m\times m}$, the final ranking result of alternatives can be determined. In this paper, we want to obtain a clear alternative ranking results, i.e., each alternative is only ranked at one position, and each position only contains one alternative. Thus, a linear assignment model is constructed as follows:

$$\max \quad Z = \sum_{i=1}^{m}\sum_{s=1}^{m} p_{is} x_{is} \tag{10a}$$

$$\text{s.t.} \quad \sum_{i=1}^{m} x_{is} = 1, \quad s = 1, 2, \cdots, m \tag{10b}$$

$$\sum_{s=1}^{m} x_{is} = 1, \quad i = 1, 2, \cdots, m \tag{10c}$$

$$x = 0 \text{ or } 1, \ i = 1, 2, \cdots, m, \ s = 1, 2, \cdots, m \tag{10d}$$

In the model ((10a)–(10d)), (10a) is to maximize the sum of ranking possibilities. Equations (10b) and (10c) are equation constrains, i.e., (10b) is to guarantee that each position only contains one alternative, and (10c) is to guarantee that each alternative is ranked at one position. If $x_{is} = 1$, then the alternative A_i is ranked at the sth position. Obviously, model ((10a)–(10d)) is an assignment model. It can be converted into a classical assignment model and be solved by Kuhn-Munkres algorithm [36] or Bertsekas algorithm [37]. According to the solution to model ((10a)–(10d)), the final ranking results of alternatives can be determined.

In summary, the procedure for solving the MCGDM problem with different evaluation criterion sets is given as follows.

Step 1. Construct the nonempty power set $\widetilde{P}(E)$ based on the expert set E, and determine criterion subset $C(E')$ concerning each E' $(E' \in \widetilde{P}(E))$.

Step 2. Construct the indicator matrix $\boldsymbol{T} = [t_{kj}]_{q\times n}$, and determine the indicator vector $\boldsymbol{t}_j$ concerning criterion C_j.

Step 3. Construct the indicator vector $e(E')$ corresponding to set $C(E')$.

Step 4. Calculate the distance between $\boldsymbol{t}_j$ and $e(E')$ using (2), and determine whether the criterion C_j belongs to the criterion subset $C(E')$.

Step 5. Construct the ranking possibility matrix $\boldsymbol{r}^{E'}$ concerning the criterion subset $C(E')$ using (3)–(6).

Step 6. Calculate the weight $w_{E'}$ of criterion subset $C(E')$ using (8).

Table 2: The decision matrix $\boldsymbol{V} = [v_{ij}]_{6\times8}$ for bidding products.

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_7
A_1	0.005	500	850	8.6	30500	1.5	530000	50
A_2	0.01	550	925	8.2	26500	2	420000	40
A_3	0.008	600	960	9.0	28500	3	450000	35
A_4	0.008	450	720	9.2	25800	2	480000	40
A_5	0.015	400	650	8.0	24000	1.5	380000	30
A_6	0.012	480	710	8.4	23500	1	40000	60

Table 3: The normalized decision matrix $\overline{\boldsymbol{V}} = [\overline{v}_{ij}]_{6\times8}$ for bidding products.

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_7
A_1	1	0.5	0.6452	0.5	1	0.75	0	0.3333
A_2	0.5	0.75	0.8871	0.1667	0.4286	0.5	0.7333	0.6667
A_3	0.7	1	1	0.8333	0.7143	0	0.5333	0.8333
A_4	0.7	0.25	0.2258	1	0.3286	0.5	0.3333	0.6667
A_5	0	0	0	0	0.0714	0.75	1	1
A_6	0.3	0.4	0.1935	0.3333	0	1	0.8667	0

Step 7. Construct the overall ranking possibility matrix $\boldsymbol{P}$ using (9).

Step 8. Construct the linear assignment model ((10a)–(10d)) based on the overall ranking possibility matrix $\boldsymbol{P}$.

Step 9. Determine the final ranking result by solving the model ((10a)–(10d)).

4. Illustrative Example

In this section, an example is used to illustrate the use of the proposed method. Company BS is a food machinery manufacturing enterprise. To meet the increasing personalized demands of customers, Company BS decides to purchase a three axis vertical integrated cutting CNC machine. In order to improve the purchasing efficiency and save the purchasing cost, Company BS purchases the machine by the way of online reverse auction. The manufacture department (E_1) and the financial department (E_2) are responsible for the purchasing task. The criteria concerned by the manufacture department (E_1) include C_1: positioning accuracy (mm), C_2: maximum load (kg), C_3: mean time to failure (h), C_4: degree of standardization of parts (0-10, the greater criterion value, the degree of standardization is greater), and C_5: reliable service life (h), and C_6: delivery time (month). The criteria concerned by the financial department (E_2) include C_5: reliable service life (h), C_6: delivery time (month), C_7: price (\$), and C_8:down payment ratio (percent). The importance degrees of the manufacture department (E_1) and the financial department (E_2) are same in the decision making of reverse auction, i.e., $\boldsymbol{b} = (b_1, b_2) = (0.5, 0.5)$. The weight vector of criterion set concerned by the manufacture department (E_1) is $w_1 = (0.3, 0.2, 0.1, 0.05, 0.2, 0.15, 0, 0)$, and the weight vector of criterion set concerned by the financial department (E_2) is $w_2 = (0, 0, 0, 0, 0.25, 0.15, 0.45, 0.15)$.

There are six CNC machine manufacturers bidding online; the bidding products are denoted as $A_1, A_2, A_3, A_4, A_5, A_6$. Based on the actual situation of manufacturers and the performance of bidding products, the decision matrix for bidding products is shown as Table 2.

To determine the best bidding products, the method proposed in this paper is used. Some computation processes and results are presented below.

Firstly, $E = \{E_1, E_2\}$, so the nonempty power set $\widetilde{P}(E)$ are constructed, i.e., $\widetilde{P}(E) = \{\{E_1\}, \{E_2\}, \{E_1, E_2\}\}$, the criterion subset concerning $\{E_1\}$ is $C(\{E_1\}) = \{C_1, C_2, C_3, C_4\}$, the criterion subset concerning $\{E_2\}$ is $C(\{E_2\}) = \{C_7, C_8\}$, and the criterion subset concerning $\{E_1, E_2\}$ is $C(\{E_1, E_2\}) = \{C_5, C_6\}$.

Then, using (3), the normalized decision matrix $\overline{\boldsymbol{V}} = [\overline{v}_{ij}]_{6\times8}$ for bidding products is constructed, as shown in Table 3.

Using (4), the ranking value of each alternative with respect to the criterion subsets $C(\{E_1\})$, $C(\{E_2\})$, $C(\{E_1, E_2\})$ is calculated, and the ranking orders of alternatives $A_1, A_2, \cdots, A_6$ with respect to the criterion subsets $C(\{E_1\})$, $C(\{E_2\})$, $C(\{E_1, E_2\})$ can be determined as follows.

For the criterion subset $C(\{E_1\}) = \{C_1, C_2, C_3, C_4\}$, $V_{\{E_1\}}(A_1) = 0.2448$, $V_{\{E_1\}}(A_2) = 0.1985$, $V_{\{E_1\}}(A_3) = 0.2758$, $V_{\{E_1\}}(A_4) = 0.1663$, $V_{\{E_1\}}(A_5) = 0$, and $V_{\{E_1\}}(A_6) = 0.1030$. We can obtain that the ranking order is $A_3 \succ A_1 \succ A_2 \succ A_4 \succ A_6 \succ A_5$.

For the criterion subset $C(\{E_2\}) = \{C_7, C_8\}$, $V_{\{E_2\}}(A_1) = 0.0250$, $V_{\{E_2\}}(A_2) = 0.2150$, $V_{\{E_2\}}(A_3) = 0.1825$, $V_{\{E_2\}}(A_4) = 0.1250$, $V_{\{E_2\}}(A_5) = 0.3$, and $V_{\{E_2\}}(A_6) = 0.1950$. We can obtain that the ranking order is $A_5 \succ A_2 \succ A_6 \succ A_3 \succ A_4 \succ A_1$.

For the criterion subset $C(\{E_1, E_2\}) = \{C_5, C_6\}$, $V_{\{E_1,E_2\}}(A_1) = 0.3375$, $V_{\{E_1,E_2\}}(A_2) = 0.1714$, $V_{\{E_1,E_2\}}(A_3) = 0.1607$, $V_{\{E_1,E_2\}}(A_4) = 0.1489$, $V_{\{E_1,E_2\}}(A_5) = 0.1286$, and

$V_{\{E_1,E_2\}}(A_6) = 0.15$. We can obtain that the ranking order is $A_1 \succ A_2 \succ A_3 \succ A_6 \succ A_4 \succ A_5$.

Using (8), the weights of criterion subsets $C(\{E_1\})$, $C(\{E_2\})$, $C(\{E_1, E_2\})$ can be obtained, i.e., $w_{\{E_1\}} = 0.325$, $w_{\{E_2\}} = 0.3$, and $w_{\{E_1,E_2\}} = 0.375$.

Further, using (9), the overall ranking possibility matrix $\boldsymbol{P} = [p_{is}]_{6\times6}$ is constructed, i.e.,

$$\boldsymbol{P} = \begin{bmatrix} 0.375 & 0.325 & 0 & 0 & 0 & 0.3 \\ 0 & 0.678 & 0.325 & 0 & 0 & 0 \\ 0.325 & 0 & 0.375 & 0.3 & 0 & 0 \\ 0 & 0 & 0 & 0.325 & 0.675 & 0 \\ 0.3 & 0 & 0 & 0 & 0 & 0.7 \\ 0 & 0 & 0.3 & 0.375 & 0.325 & 0 \end{bmatrix} \quad (11)$$

Based on matrix $\boldsymbol{P}$, a linear assignment model is built as follows:

$$\begin{aligned} \max \quad & Z = \sum_{i=1}^{6}\sum_{s=1}^{6} p_{is} x_{is} \\ \text{s.t.} \quad & \sum_{i=1}^{m} x_{is} = 1, \quad s = 1, 2, \cdots, 6 \\ & \sum_{s=1}^{m} x_{is} = 1, \quad i = 1, 2, \cdots, 6 \\ & x = 0 \text{ or } 1, \; i = 1, 2, \cdots, 6, \; s = 1, 2, \cdots, 6 \end{aligned} \quad (12)$$

By solving the above model, the optimal solution can be obtained, i.e.,

$$\boldsymbol{X} = [x_{is}]_{6\times6} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 1 & 0 & 0 \end{bmatrix} \quad (13)$$

Therefore, the final ranking result of alternatives is $A_1 \succ A_2 \succ A_3 \succ A_6 \succ A_4 \succ A_5$. Obviously, A_1 is the best bidding product.

5. Conclusions

This paper presents a novel method for solving the MCGDM problem in which evaluation criterion sets concerned by multiple experts are different. In the method, an approach is first given to construct criterion subsets based on the criterion sets considered by different experts. Then, the ranking possibility matrix with respect to each criterion subset is built, and the weight of each criterion subset is measured according to the weights of experts and the weights of criteria in the criterion subset. Further, by aggregating the ranking possibility matrices and the weights concerning different criterion subsets, the overall ranking possibility matrix is built and the final ranking result of alternatives is determined by a linear assignment model. The major contributions of this paper are discussed as follows.

First, this paper focuses on the MCGDM problem with different evaluation criterion sets, which is a new research topic with a lot of practical backgrounds. In the problem, multiple experts from different organizations or departments take part in the decision-making process and each expert can pay more attention to the criteria that relate to his/her own benefit or duty.

Second, this paper presents a method for solving the MCGDM problem with different evaluation criterion sets. The method includes four aspects: (1) constructing criterion subsets concerned by different groups of experts; (2) ranking alternatives with respect to each criterion subset; (3) determining the weight of ranking result concerning each criterion subset; (4) determining the final ranking result of alternatives. It is a new idea for aggregating individual preferences or opinions in group decision-making analysis and lays a good foundation for studying on MCGDM problems with different evaluation criterion sets.

It is important to highlight that, since the proposed method is new and different from the existing methods, it can give the decision-maker one more choice for identifying the appropriate method for solving the MCGDM problem with different evaluation criterion sets. In addition to supplementing the existing methods, the proposed method is also important for developing and enriching theories and methods of MCGDM.

The study also has some limitations, which may serve as avenues for future research. First, in this study, we only consider the situation that the values of alternatives with respect to criteria are in the form of crisp numbers. But, in reality, the values of alternatives with respect to criteria may be different forms, such as interval number, fuzzy number, or stochastic variable. Thus, it is necessary to develop some new methods for solving MCGDM problems in which the criterion sets considered by different experts are different and the criterion values are in different formats. Besides, to support DMs to facilitate the use of the method proposed in this paper, the decision support system needs to be developed.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

This work was partly supported by the National Natural Science Foundation of China (Projects nos. 71571039, 71471032, and 71771043), the 111 Project (B16009), the Fundamental Research Funds for the Central Universities, China (Project no. N170605001), the Economic and Social Development Foundation of Liaoning Province (2019lslktyb-034), and the Key Technology R&D Program of Shenyang (17-192-9-00).

References

[1] C. L. Hwang and M. J. Lin, *Group decision making under multiple criteria: methods and applications*, Springer-Verlag, Berlin, Germany, 1987.

[2] R. R. Yager, "Non-numeric multi-criteria multi-person decision making," *Group Decision and Negotiation*, vol. 2, no. 1, pp. 81–93, 1993.

[3] W. Liu, Y. Dong, F. Chiclana, F. J. Cabrerizo, and E. Herrera-Viedma, "Group decision-making based on heterogeneous preference relations with self-confidence," *Fuzzy Optimization and Decision Making. A Journal of Modeling and Computation Under Uncertainty*, vol. 16, no. 4, pp. 429–447, 2017.

[4] B. Roy, "Comparing Actions and Developing Criteria," in *Multicriteria Methodology for Decision Aiding*, vol. 12 of *Nonconvex Optimization and Its Applications*, pp. 163–210, Springer US, Boston, MA, 1996.

[5] B. F. Hobbs and P. Meier, *Energy decisions and the environment: a guide to the use of multicriteria methods*, Kluwer Academic Publishers, 2000.

[6] Y. Chen, D. M. Kilgour, and K. W. Hipel, "Screening in multiple criteria decision analysis," *Decision Support Systems*, vol. 45, no. 2, pp. 278–290, 2008.

[7] J. A. Morente-Molinera, G. Kou, R. González-Crespo, J. M. Corchado, and E. Herrera-Viedma, "Solving multi-criteria group decision making problems under environments with a high number of alternatives using fuzzy ontologies and multi-granular linguistic modelling methods," *Knowledge-Based Systems*, vol. 137, pp. 54–64, 2017.

[8] C.-C. Li, Y. Dong, F. Herrera, E. Herrera-Viedma, and L. Martínez, "Personalized individual semantics in computing with words for supporting linguistic group decision making. An application on consensus reaching," *Information Fusion*, vol. 33, pp. 29–40, 2017.

[9] C.-C. Lo, P. Wang, and K.-M. Chao, "A fuzzy group-preferences analysis method for new-product development," *Expert Systems with Applications*, vol. 31, no. 4, pp. 826–834, 2006.

[10] N. Çağman and S. Enginoğlu, "Soft set theory and *uni-int* decision making," *European Journal of Operational Research*, vol. 207, no. 2, pp. 848–855, 2010.

[11] D. S. Chapman and J. Webster, "The use of technologies in the recruiting, screening, and selection processes for job candidates," *International Journal of Selection and Assessment*, vol. 11, no. 2-3, pp. 113–120, 2003.

[12] P. H. Raymark, M. J. Schmit, and R. M. Guion, "Identifying potentially useful personality constructs for employee selection," *Personnel Psychology*, vol. 50, no. 3, pp. 723–736, 1997.

[13] C. A. Bana e Costa, É. C. Corrêa, J.-M. De Corte, and J.-C. Vansnick, "Facilitating bid evaluation in public call for tenders: a socio-technical approach," *Omega* , vol. 30, no. 3, pp. 227–242, 2002.

[14] H.-Y. Yan, "The construction project bid evaluation based on gray relational model," in *Proceedings of the 2011 International Conference on Advanced in Control Engineering and Information Science, CEIS 2011*, pp. 4553–4557, China, August 2011.

[15] M. Tavana, D. T. Kennedy, and P. Joglekar, "A group decision support framework for consensus ranking of technical manager candidates," *Omega* , vol. 24, no. 5, pp. 523–538, 1996.

[16] E. Herrera-Viedma, L. Martínez, F. Mata, and F. Chiclana, "A consensus support system model for group decision-making problems with multigranular linguistic preference relations," *IEEE Transactions on Fuzzy Systems*, vol. 13, no. 5, pp. 644–658, 2005.

[17] D.-F. Li, "Compromise ratio method for fuzzy multi-attribute group decision making," *Applied Soft Computing*, vol. 7, no. 3, pp. 807–817, 2007.

[18] J. M. Merig, M. Casanovas, and J.-B. Yang, "Group decision making with expertons and uncertain generalized probabilistic weighted aggregation operators," *European Journal of Operational Research*, vol. 235, no. 1, pp. 215–224, 2014.

[19] L. Roselló, M. Sánchez, N. Agell, F. Prats, and F. A. Mazaira, "Using consensus and distances between generalized multi-attribute linguistic assessments for group decision-making," *Information Fusion*, vol. 17, no. 1, pp. 83–92, 2014.

[20] J. M. Merigó, D. Palacios-Marqués, and S. Zeng, "Subjective and objective information in linguistic multi-criteria group decision making," *European Journal of Operational Research*, vol. 248, no. 2, pp. 522–531, 2016.

[21] E. K. Zavadskas, J. Antucheviciene, S. H. R. Hajiagha, and S. S. Hashemi, "The interval-valued intuitionistic fuzzy MULTIMOORA method for group decision making in engineering," *Mathematical Problems in Engineering*, vol. 2015, Article ID 560690, 13 pages, 2015.

[22] S.-M. Chen, S.-H. Cheng, and C.-H. Chiou, "Fuzzy multiattribute group decision making based on intuitionistic fuzzy sets and evidential reasoning methodology," *Information Fusion*, vol. 27, pp. 215–227, 2016.

[23] J. Chu, X. Liu, Y. Wang, and K.-S. Chin, "A group decision making model considering both the additive consistency and group consensus of intuitionistic fuzzy preference relations," *Computers & Industrial Engineering*, vol. 101, pp. 227–242, 2016.

[24] Y. Liu, J.-W. Bi, and Z.-P. Fan, "Ranking products through online reviews: A method based on sentiment analysis technique and intuitionistic fuzzy set theory," *Information Fusion*, vol. 36, pp. 149–161, 2017.

[25] Y. Liu, J.-W. Bi, and Z.-P. Fan, "A method for ranking products through online reviews based on sentiment classification and interval-valued intuitionistic fuzzy topsis," *International Journal of Information Technology & Decision Making*, vol. 16, no. 6, pp. 1497–1522, 2017.

[26] Y. Zhang, Z. Xu, and H. Liao, "A consensus process for group decision making with probabilistic linguistic preference relations," *Information Sciences*, vol. 414, pp. 260–275, 2017.

[27] C. Liu, G. Tang, and P. Liu, "An approach to multicriteria group decision-making with unknown weight information based on pythagorean fuzzy uncertain linguistic aggregation operators," *Mathematical Problems in Engineering*, vol. 2017, Article ID 6414020, 18 pages, 2017.

[28] A. R. Roy and P. K. Maji, "A fuzzy soft set theoretic approach to decision making problems," *Journal of Computational and Applied Mathematics*, vol. 203, no. 2, pp. 412–418, 2007.

[29] F. Feng, Y. Li, and N. Çağman, "Generalized *uni-int* decision making schemes based on choice value soft sets," *European Journal of Operational Research*, vol. 220, no. 1, pp. 162–170, 2012.

[30] M.-Y. Li, Z.-P. Fan, and T.-H. You, "Screening alternatives considering different evaluation index sets: A method based on soft set theory," *Applied Soft Computing*, vol. 64, pp. 614–626, 2018.

[31] T. L. Saaty, *The Analytic Hierarchy Process*, McGraw-Hill, New York, NY, USA, 1980.

[32] Y. Liu, Z.-P. Fan, and X. Zhang, "A method for large group decision-making based on evaluation information provided by participators from multiple groups," *Information Fusion*, vol. 29, pp. 132–141, 2016.

[33] J.-Q. Wang, Z.-Q. Han, and H.-Y. Zhang, "Multi-criteria group decision-making method based on intuitionistic interval fuzzy information," *Group Decision and Negotiation*, vol. 23, no. 4, pp. 715–733, 2014.

[34] B. Oztaysi, "A decision model for information technology selection using AHP integrated TOPSIS-Grey: the case of content management systems," *Knowledge-Based Systems*, vol. 70, pp. 44–54, 2014.

[35] J. Qin, X. Liu, and W. Pedrycz, "An extended TODIM multi-criteria group decision making method for green supplier selection in interval type-2 fuzzy environment," *European Journal of Operational Research*, vol. 258, no. 2, pp. 626–638, 2017.

[36] J. Munkres, "Algorithms for the assignment and transportation problems," *Journal of the Society for Industrial & Applied Mathematics*, vol. 5, no. 1, pp. 32–38, 1957.

[37] D. P. Bertsekas, "A new algorithm for the assignment problem," *Mathematical Programming*, vol. 21, no. 2, pp. 152–171, 1981.