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SOLVING CONSTRUCTION PROJECT SELECTION PROBLEM BY A NEW UNCERTAIN WEIGHTING AND RANKING BASED ON COMPROMISE SOLUTION WITH LINEAR ASSIGNMENT APPROACH

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Abstract. Selecting a suitable construction project is a significant issue for contractors to decrease their costs. In real cases, the imprecise and uncertain information lead to decisions made based on vagueness. Fuzzy sets theory could help decision makers (DMs) to address incomplete information. However, this article develops a new integrated multi-criteria group decision-making model based on compromise solution and linear assignment approaches with interval-valued intuitionistic fuzzy sets (IVIFSs). IVIFSs by presenting a membership and non-membership degree for each candidate based on appraisement criteria could decrease the vagueness of selection decisions. The proposed algorithm involves a new decision process under uncertain conditions to determine the importance of criteria and DMs, separately. In this regard, no subjective or additional information is needed for this process; only the input information required is an alternative assessment matrix. In this approach, weights of criteria and DMs are specified based on novel indexes to increase the reliability of obtained results. In this respect, the criteria' weights are computed regarding entropy concepts. The basis for calculating the weight of each DM is the distance between each DM and an average of the DMs' community. Furthermore, the linear assignment model is extended to rank the candidates. A case study about the construction project selection problem (CPSP) is illustrated to indicate the application of proposed model.

Keywords: construction project selection problem, experts' weights, interval-valued intuitionistic fuzzy sets, compromise solution, incomplete information, linear assignment.

Introduction

The fuzzy sets theory was first introduced by Zadeh (1965); this theory and its developments have been widely considered for extending the decision-making techniques to solve the selection problems based on uncertain input parameters. Moreover, these fuzzy sets theories are provided in some fields, such as artificial intelligence (Greco, Matarazzo, & Giove, 2011; Keramitsoglou et al., 2013), pattern recognition (Melin & Castillo, 2013, 2014), management (Doria, 2012; Paksoy, Pehlivan, & Kahraman, 2012), and decision making (Moradi, Mousavi, & Vahdani, 2017, 2018; Qin & Liu, 2013). Hence, decision making is a process that helps the specialists for taking account of an appropriate candidate via assessment factors (L. Wang, Zhang, J. Q. Wang, & Li, 2018; Shao, Ma, Sheu, & Gao, 2018; Foroozesh, Gitinavard, Mousavi, & Vahdani, 2017).

Multi-criteria decision making (MCDM) is an efficient approach for appraising problems that have been judged by experts (N. Prascevic & Z. Prascevic, 2017; Kaya & Kahraman, 2014; Polat, Eray, & Bingol, 2017; Dorfeshan, Mousavi, Mohagheghi, & Vahdani, 2018; Dorfeshan & Mousavi, 2019). In classical MCDM approaches, the assessment of decision-making problems is judged via crisp values; but in hesitant situations the group decision-making (GDM) problems should be appraise via linguistic terms. Therefore, the fuzzy MCDM (FMCDM) approaches are obtained to assess the candidates in an uncertain environment (Giti-

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navard, Makui, & Jabbarzadeh, 2016; Gitinavard, Mousavi, & Vahdani, 2016; Gitinavard, & Zarandi, 2016). Furthermore, establishing a group of specialists for appraising the problem under imprecise information is lead the FMCDM approaches to fuzzy multi-criteria group decision-making (FMCGDM) approaches (e.g., Mohagheghi, Mousavi, Aghamohagheghi, & Vahdani, 2017; Mohagheghi, Mousavi, Vahdani, & Siadat, 2017; Mohagheghi, Mousavi, & Vahdani, 2017a, 2017b; Zolfaghari & Mousavi, 2018).

Some authors focused on decision-making tools to solve the project evaluation and selection problem. Thereby, Chang and Lee (2012) elaborated a possibilistic mathematical programming approach based on knapsack formulation and data envelopment analysis (DEA) to solve the project selection problem. Wang, Lee, Peng, and Wu (2013) introduced a combined model via analytic network process (ANP), fuzzy Delphi method, and interpretive structural modeling for choosing suitable projects. Khalili-Damghani and Sadi-Nezhad (2013) presented a hybrid FMCGDM methodology to assess candidates (e.g., sustainable projects) regarding conflicted criteria. Taylan, Bafail, Abdulaal, and Kabli (2014) manipulated an integrated approach via analytic hierarchy process (AHP), technique for order performance by similarity to ideal solution (TOPSIS), and relative importance approaches to assess construction project selection problem (CPSP).

Moreover, Oztaysi (2015) proposed an interval type-2 fuzzy AHP method to handle selection problem of enterprise resource planning project. Salehi (2015) presented a hybridized MCDM model via AHP and višekriterijumsko kompromisno rangiranje (VIKOR) techniques to choose appropriate projects with fuzzy sets. Ibadov (2016) presented a fuzzy preference relation to evaluate the construction projects in pre-investment phase based on net present value (NPV), financing possibilities, level of organizational difficulty, and level of technological difficulty. Tabrizi, Torabi, and Ghaderi (2016) manipulated a hybridized method via decision making trial and evaluation laboratory model (DEMATEL) and utility-based multi-choice goal programming model to appraise influencing criteria and determine the optimal project portfolio, respectively. N. Prascevic and Z. Prascevic (2017) regarded a model via trapezoidal fuzzy AHP method and linear programming model for choosing best candidate construction project. Erdogan, Šaparauskas, and Turskis (2017) provided a method for selecting a contractor using the AHP approach. Leśniak, Kubek, Plebankiewicz, Zima, and Belniak (2018) presented fuzzy analytic hierarchy process (FAHP) to improve the efficiency of contractor bidding decisions. Özcan, Hamurcu, Alakaş, and Eren (2018) regarded a solution for project selection using constraint programming for urban rail transport. Salehi (2018) proposed an additive weighted fuzzy programming (AWFP) approach for solving multi-objective project selection problems in fuzzy environments. Ebrahiminejad, Shakeri, Ardeshir, and Zarandi (2018) provided a fuzzy-based approach for the selection of construction methods with object-oriented model.

In this respect, this paper presents a new integrated interval-valued intuitionistic MCGDM approach based on compromise solution method and linear assignment model to solve the CPSP. In this regard, criteria weights and relative importance of experts are determined based on novel indexes to increase the reliability of obtained ranking results.

The rest of this study is organized as follows. Section 1 represents the proposed model. Section 2 provides a case study about the CPSP. In Section 3, sensitivity analysis is realized. Finally, the obtained results and future suggestions for enhancing the proposed approach are reported in the last Section.

1. Proposed methodology

The purpose of the proposed algorithm is to provide a strategy for quantifying the priorities, ratings, and relative importance of DMs, criteria, and alternatives. With increasing the dimensions of the problem, in addition to maintaining the efficiency, the accuracy and reliability of the results increases with the collection of data over time, each DM's approach is compared with others. To appraise weights of evaluation factors, an approach is applied that is consistent with the concept of entropy. The DMs' comparison is made by analyzing DMs' judgments and comparing them with other ones. Because of the uncertainty in such problems, IVIF numbers are used to address this issue. One of the reasons for using IVIF numbers is the presence of membership degree, non-membership degree and hesitation degree in one number simultaneously. The steps of the algorithm are described as follows.

1.1. Calculating weights of criteria

Step 1: Creating decision matrix for each DM.

This step consists of creating decision matrices based on experts' judgments, while all matrix components are IVIF numbers. Let $P=\{p_1,p_2,\ldots,p_m\}$ be a set of projects, $C=\{c_1,c_2,\ldots,c_n\}$ be a set of criteria and $E=\{e_1,e_2,\ldots,e_g\}$ be a set of DMs. Suppose $\tilde{R}^{(d)}=\left(\tilde{r}_{ij}^{(d)}\right)_{m\times n}$ can be decision matrix with IVIF numbers, where $r_{ij}^{(k)}$ is evaluation of project p_i under consideration criterion c_j. Based on judgment of the e_k, $\tilde{r}_{ij}^{(k)}$ and $\tilde{R}^{(d)}$ are defined in Eqns (1) and (2), respectively.

$$\tilde{r}_{ij}^{(d)}=\left(\tilde{\mu}_{ij}^{(d)},\tilde{\vartheta}_{ij}^{(d)},\tilde{\pi}_{ij}^{(d)}\right)=\begin{pmatrix}\left[\mu_{ij}^{-(d)},\mu_{ij}^{+(d)}\right],\\ \left[\vartheta_{ij}^{-(d)},\vartheta_{ij}^{+(d)}\right],\\ \left[\pi_{ij}^{-(d)},\pi_{ij}^{+(d)}\right]\end{pmatrix}. \tag{1}$$

In Eqn (1), $\mu_{ij}^{-(d)}$ and $\mu_{ij}^{+(d)}$ denote the lower and upper limits of $\tilde{\mu}_{ij}^{(d)}$, respectively. $\tilde{\mu}_{ij}^{(d)}$ indicates membership degree of the project p_i to criterion c_j based on opinion of d-th DM. In the same way, $\vartheta_{ij}^{-(d)}$ and $\vartheta_{ij}^{+(d)}$ denote the lower and upper limits of $\tilde{\vartheta}_{ij}^{(d)}$, respectively. $\tilde{\vartheta}_{ij}^{(d)}$ indicates non-membership degree of the project p_i to criterion c_j based on opinion of d-th DM. Also, $\pi_{ij}^{-(d)}$ and $\pi_{ij}^{+(d)}$ denote the lower and upper limits of $\tilde{\pi}_{ij}^{(d)}$, respectively. $\tilde{\pi}_{ij}^{(d)}$ indicates hesitation degree of the project p_i to criterion c_j based on opinion of d-th DM.

$$\tilde{R}^{(d)} = \begin{bmatrix} \tilde{r}_{11}^{(d)} & \tilde{r}_{12}^{(d)} & \cdots & \tilde{r}_{1n}^{(d)} \\ \tilde{r}_{21}^{(d)} & \tilde{r}_{22}^{(d)} & \cdots & \tilde{r}_{2n}^{(d)} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{r}_{m1}^{(d)} & \tilde{r}_{m2}^{(d)} & \cdots & \tilde{r}_{mn}^{(d)} \end{bmatrix}, \quad \forall d \in \{1,2,\ldots,g\}. \qquad (2)$$

The $\tilde{R}^{(d)}$ represents the views of the d-th DM, in which all candidate projects are evaluated according to the criteria.

Step 2: Calculating ideal and non-ideal rating for each criterion.

Based on the judgment of each DM, positive ideal rating (PIR) and negative ideal rating (NIR) are assigned to each criterion. Calculations of these numbers vary according to the nature of the criteria. The criteria are divided into two categories: profit criteria (f_1) and cost criteria (f_2). Calculations performed in Eqns (3)–(6) are based on the method presented by Eraslan (2015). $PIR_j^{(d)}$ represents the PIR for the j-th criterion based on the judgment of the d-th DM. The nature of each criterion determines how this indicator is calculated. If the criterion belongs to the set f_1, then Eqn (3) is used; otherwise, if the criterion belongs to the set f_2, then Eqn (4) is used. In the same way, $NIR_j^{(d)}$ indicates negative ideal rating for the j-th criterion based on the judgment of the d-th DM. If the criterion belongs to the set f_1, then Eqn (5) is used; otherwise, if the criterion belongs to the set f_2, then Eqn (6) is used.

$$PIR_j^{(d)} = \left(\left[\max_i \mu_{ij}^{-(d)}, \max_i \mu_{ij}^{+(d)}\right], \left[\min_i \vartheta_{ij}^{-(d)}, \min_i \vartheta_{ij}^{+(d)}\right]\right) = \left(\left[\mu_j^{-(d)}, \mu_j^{+(d)}\right], \left[\vartheta_j^{-(d)}, \vartheta_j^{+(d)}\right]\right) \quad if\ c_j \in f_1, \qquad (3)$$

$$PIR_j^{(d)} = \left(\left[\min_i \mu_{ij}^{-(d)}, \min_i \mu_{ij}^{+(d)}\right], \left[\max_i \vartheta_{ij}^{-(d)}, \max_i \vartheta_{ij}^{+(d)}\right]\right) = \left(\left[\mu_j^{-(d)}, \mu_j^{+(d)}\right], \left[\vartheta_j^{-(d)}, \vartheta_j^{+(d)}\right]\right) \quad if\ c_j \in f_2, \qquad (4)$$

$$NIR_j^{(d)} = \left(\left[\min_i \mu_{ij}^{-(d)}, \min_i \mu_{ij}^{+(d)}\right], \left[\max_i \vartheta_{ij}^{-(d)}, \max_i \vartheta_{ij}^{+(d)}\right]\right) = \left(\left[\kappa_j^{-(d)}, \kappa_j^{+(d)}\right], \left[\rho_j^{-(d)}, \rho_j^{+(d)}\right]\right) \quad if\ c_j \in f_1, \qquad (5)$$

$$NIR_j^{(d)} = \left(\left[\max_i \mu_{ij}^{-(d)}, \max_i \mu_{ij}^{+(d)}\right], \left[\min_i \vartheta_{ij}^{-(d)}, \min_i \vartheta_{ij}^{+(d)}\right]\right) = \left(\left[\kappa_j^{-(d)}, \kappa_j^{+(d)}\right], \left[\rho_j^{-(d)}, \rho_j^{+(d)}\right]\right) \quad if\ c_j \in f_2. \qquad (6)$$

Step 3: Calculating the dispersion index of each criterion.

The dispersion index of j-th criterion according to opinion of d-th DM is represented as $DP_j^{(d)}$ and defined as the sum of the maximum distance of the rating for each project that is rated under j-th criterion from $PIR_j^{(d)}$ and $NIR_j^{(d)}$. A distance measure proposed by Düğenci (2016) is used to calculate the dispersion index of j-th criterion. The proposed distance measure has advantages over the previous operators. $DP_j^{(d)}$ calculated in Eqn (7):

$$DP_j^{(d)} = \sum_{i=1}^{m} max\left\{d_p^t\left(\tilde{r}_{ij}^{(d)}, PIR_j^{(d)}\right), d_p^t\left(\tilde{r}_{ij}^{(d)}, NIR_j^{(d)}\right)\right\},$$
$$\forall j \in \{1,2,\ldots,n\}, d = \{1,2,\ldots,g\}. \qquad (7)$$

In Eqn (7) for two parameters, p is the L_p norm and t determines the level of uncertainty. The distance between $\tilde{r}_{ij}^{(d)}$ and $PIR_j^{(d)}$ is calculated in Eqn (8):

$$d_p^t\left(\tilde{r}_{ij}^{(d)}, PIR_j^{(d)}\right) = \frac{\left\{\begin{array}{l} \left|t\left(\mu_{ij}^{-(d)} - \mu_j^{-(d)}\right) - \left(\vartheta_{ij}^{-(d)} - \vartheta_j^{-(d)}\right)\right|^p + \\ \left|t\left(\vartheta_{ij}^{-(d)} - \vartheta_j^{-(d)}\right) - \left(\mu_{ij}^{-(d)} - \mu_j^{-(d)}\right)\right|^p + \\ \left|t\left(\mu_{ij}^{+(d)} - \mu_j^{+(d)}\right) - \left(\vartheta_{ij}^{+(d)} - \vartheta_j^{+(d)}\right)\right|^p + \\ \left|t\left(\vartheta_{ij}^{+(d)} - \vartheta_j^{+(d)}\right) - \left(\mu_{ij}^{+(d)} - \mu_j^{+(d)}\right)\right|^p \end{array}\right\}^{\frac{1}{p}}}{(t+1)\sqrt[p]{4}}. \qquad (8)$$

Also, in the same way the distance between $\tilde{r}_{ij}^{(d)}$ and $NIR_j^{(d)}$ is calculated in Eqn (9):

$$d_p^t\left(\tilde{r}_{ij}^{(d)}, NIR_j^{(d)}\right) = \frac{\left\{\begin{aligned} &\left|t\left(\mu_{ij}^{-(d)} - \kappa_j^{-(d)}\right) - \left(\vartheta_{ij}^{-(d)} - \rho_j^{-(d)}\right)\right|^p + \\ &\left|t\left(\vartheta_{ij}^{-(d)} - \rho_j^{-(d)}\right) - \left(\mu_{ij}^{-(d)} - \kappa_j^{-(d)}\right)\right|^p + \\ &\left|t\left(\mu_{ij}^{+(d)} - \kappa_j^{+(d)}\right) - \left(\vartheta_{ij}^{+(d)} - \rho_j^{+(d)}\right)\right|^p + \\ &\left|t\left(\vartheta_{ij}^{+(d)} - \rho_j^{+(d)}\right) - \left(\mu_{ij}^{+(d)} - \kappa_j^{+(d)}\right)\right|^p \end{aligned}\right\}^{\frac{1}{p}}}{(t+1)\sqrt[p]{4}}. \tag{9}$$

Step 4: Computing relative importance of each criterion.

Final importance of each criterion is computed by Eqn (10):

$$W_j^{(d)} = \frac{DP_j^{(d)}}{\sum_{j=1}^{n} DP_j^{(d)}}, \qquad \forall d = \{1,2,\ldots,g\}. \tag{10}$$

Based on Eqn (10), the criterion that has a higher DP has a higher weight.

1.2. Calculating weights of DMs

Step 1: Defining an average matrix.

At this stage, based on all matrices of decision, the average matrix $\tilde{M} = \left(\tilde{m}_{ij}\right)_{m\times n}$ is defined in Eqn (11):

$$\tilde{m}_{ij} = \frac{\sum_{d=1}^{g} \tilde{r}_{ij}^{(d)}}{g} = \frac{\left(\begin{matrix}\left[1-\prod_{d=1}^{g}\mu_{ij}^{-(d)}, 1-\prod_{d=1}^{g}\mu_{ij}^{+(d)}\right], \\ \left[\prod_{d=1}^{g}\vartheta_{ij}^{-(d)}, \prod_{d=1}^{g}\vartheta_{ij}^{+(d)}\right]\end{matrix}\right)}{g} = \left(\begin{matrix}\left[\begin{matrix}\sqrt[g]{1-\left(1-\prod_{d=1}^{g}\mu_{ij}^{-(d)}\right)}, \\ \sqrt[g]{1-\left(1-\prod_{d=1}^{g}\mu_{ij}^{+(d)}\right)}\end{matrix}\right], \\ \left[\sqrt[g]{\prod_{d=1}^{g}\vartheta_{ij}^{-(d)}}, \sqrt[g]{\prod_{d=1}^{g}\vartheta_{ij}^{+(d)}}\right]\end{matrix}\right). \tag{11}$$

Step 2: Defining relative ideal matrix and non-ideal matrices.

Relative ideal matrix $\tilde{P}^{+} = \left(\tilde{p}_{ij}^{+}\right)_{m\times n}$ means the best judgment possible among DMs for alternatives, and relative non-ideal matrix $\tilde{P}^{-} = \left(\tilde{p}_{ij}^{-}\right)_{m\times n}$ means the worst possible judgment between the set of judgments of all DMs. These matrices are defined based on Eqns (12) and (13):

$$\tilde{p}_{ij}^{+} = \begin{cases} \max\limits_{d} \tilde{r}_{ij}^{(d)} & j \in f_1 \\ \min\limits_{d} \tilde{r}_{ij}^{(d)} & j \in f_2 \end{cases}, \quad \forall i \in \{1,2,\ldots,m\}, j \in \{1,2,\ldots,n\}. \tag{12}$$

$$\tilde{p}_{ij}^{-} = \begin{cases} \min\limits_{d} \tilde{r}_{ij}^{(d)} & j \in f_1 \\ \max\limits_{d} \tilde{r}_{ij}^{(d)} & j \in f_2 \end{cases}, \quad \forall i \in \{1,2,\ldots,m\}, j \in \{1,2,\ldots,n\}. \tag{13}$$

Step 3: Calculating decision matrix distance from average matrices, relative ideal and non-ideal matrices.

At this step, the distance between the three matrices, the $\tilde{P}^{+}$, $\tilde{P}^{-}$, and $\tilde{M}$ with the $\tilde{R}^{(d)}$ are computed. The distance between opinions of the d-th DM with relative ideal, relative non-ideal and average matrices, are indicated by $\beta^{(d)}$, $\gamma^{(d)}$, and $\alpha^{(d)}$, respectively as depicted in Figure 1. These indices are calculated according to Eqns (14)–(16).

$$\alpha^{(d)} = \sum_{i=1}^{m}\sum_{j=1}^{n} d_p^t\left(\tilde{r}_{ij}^{(d)}, \tilde{m}_{ij}\right), \qquad \forall d \in \{1,2,\ldots,g\}. \tag{14}$$

$$\beta^{(d)} = \sum_{i=1}^{m}\sum_{j=1}^{n} d_p^t\left(\tilde{r}_{ij}^{(d)}, \tilde{p}_{ij}^{+}\right), \qquad \forall d \in \{1,2,\ldots,g\}. \tag{15}$$

$$\gamma^{(d)} = \sum_{i=1}^{m}\sum_{j=1}^{n} d_p^t\left(\tilde{r}_{ij}^{(d)}, \tilde{p}_{ij}^{-}\right), \qquad \forall d \in \{1,2,\ldots,g\}. \tag{16}$$

Step 4: Computing weight of each DM.

Based on the three-distance obtained in the previous section, the weight of d-th DM is represented by $S^{(d)}$ and calculated based on Eqn (17).

$$S^{(d)} = \frac{1-\dfrac{\alpha^{(d)}}{\gamma^{(d)}+\beta^{(d)}}}{\sum_{d=1}^{g} 1-\dfrac{\alpha^{(d)}}{\gamma^{(d)}+\beta^{(d)}}}, \qquad \forall d \in \{1,2,\ldots,g\}. \tag{17}$$

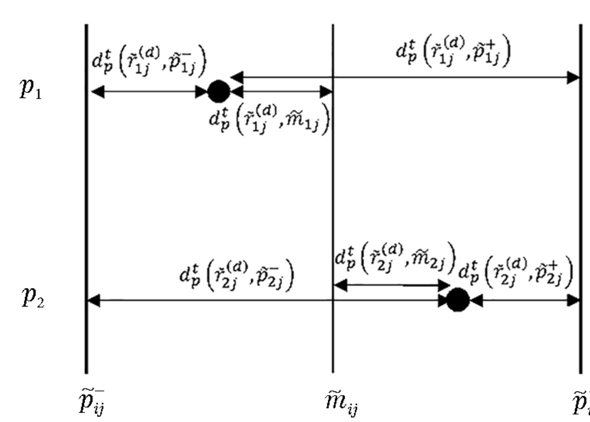

Figure 1. A variety of dispersion around the average matrix for two alternatives

1.3. Prioritization of projects

Step 1: Defuzzification of initial decision matrix.

Values of initial matrix $\tilde{R}^{(d)} = \left(\tilde{r}_{ij}^{(d)}\right)_{m\times n}$ are converted to the interval 0 to 1 by a generalized improved score function provided by Garg (2016). The converted matrix $X = \left(x_{ij}^{(d)}\right)_{m\times n}$ is calculated in Eqns (18) and (19):

$$x_{ij}^{(d)} = \frac{\mu_{ij}^{-(d)} + \mu_{ij}^{+(d)}}{2} + \sigma_1 \mu_{ij}^{-(d)}\left(1-\mu_{ij}^{-(d)} - \vartheta_{ij}^{-(d)}\right) + \sigma_2 \mu_{ij}^{+(d)}\left(1-\mu_{ij}^{+(d)} - \vartheta_{ij}^{+(d)}\right),$$

$$\forall i \in \{1,2,\ldots,m\}, j \in \{1,2,\ldots,n\}\ \forall j \in f_1, \quad (18)$$

$$x_{ij}^{(d)} = 1 - \frac{\mu_{ij}^{-(d)} + \mu_{ij}^{+(d)}}{2} - \sigma_1 \mu_{ij}^{-(d)}\left(1-\mu_{ij}^{-(d)} - \vartheta_{ij}^{-(d)}\right) - \sigma_2 \mu_{ij}^{+(d)}\left(1-\mu_{ij}^{+(d)} - \vartheta_{ij}^{+(d)}\right),$$

$$\forall i \in \{1,2,\ldots,m\}, j \in \{1,2,\ldots,n\}\ \forall j \in f_2, \quad (19)$$

where $\sigma_1 + \sigma_2 = 1$ and $\sigma_1, \sigma_2 \geq 0$ representing attitudinal characters of the above function.

Step 2: Calculating weighted matrix.

By considering weights of criteria and DMs in the matrix $X = \left(x_{ij}^{(d)}\right)_{m\times n}$, the weighted matrix $Y = \left(y_{ij}^{(d)}\right)_{m\times n}$ is calculated in Eqn (20):

$$y_{ij}^{(d)} = x_{ij}^{(d)} * W_j^{(d)} * S^{(d)},$$
$$\forall i \in \{1,2,\ldots,m\}, j \in \{1,2,\ldots,n\}, d \in \{1,2,\ldots,g\}. \quad (20)$$

Step 3: Calculating the score of each project.

The index $\psi_i^{(d)}$, which represents the rating of each project according to the judgment of DM *k*, is calculated in Eqn (21):

$$\psi_i^{(d)} = \sum_{j=1}^{n} y_{ij}^{(d)}, \quad \forall i \in \{1,2,\ldots,m\}, d \in \{1,2,\ldots,g\}. \quad (21)$$

Step 4: Accumulating values of indices of the projects.

The aggregate matrix $Z = \left(z_{ik}\right)_{m\times g}$ containing the $\psi_i^{(d)}$ index for all DMs is created in Eqn (22):

$$Z = \begin{bmatrix} \psi_1^{(1)} & \psi_1^{(2)} & \cdots & \psi_1^{(g)} \\ \psi_2^{(1)} & \psi_2^{(2)} & \cdots & \psi_2^{(g)} \\ \vdots & \vdots & \ddots & \vdots \\ \psi_m^{(1)} & \psi_m^{(2)} & \cdots & \psi_m^{(g)} \end{bmatrix}. \quad (22)$$

Step 5: Ranking based on linear assignment method.

Assignment matrix $\rho = (\rho)_{m\times m}$ is formed, in which the rows represent the projects and the columns are ranked. Eventually, the decision variable h_{ij}, which is the result of solving the following linear programming model, determines the rank of each project.

$$\max \sum_{i=1}^{m}\sum_{j=1}^{m} \rho_{ij} h_{ij}; \quad (23)$$

s.t.:

$$\sum_{i=1}^{m} h_{ij} = 1 \qquad \forall j \in \{1,2,\ldots,m\}; \quad (24)$$

$$\sum_{j=1}^{m} h_{ij} = 1 \qquad \forall i \in \{1,2,\ldots,m\}; \quad (25)$$

$$h_{ij} \in \{0,1\}. \quad (26)$$

2. Case study

In this section, the efficiency of the proposed algorithm is measured for the evaluation of energy projects. Thereupon, to demonstrate the performance of the algorithm for selecting sustainable energy projects, a case study presented by Kaya and Kahraman (2011) is provided.

Seven energy projects in different fields are proposed as evaluation options. Conventional (P1), nuclear (P2), solar (P3), wind (P4), hydraulic (P5), biomass (P6) and combined heat and power (CHP) (P7). The evaluation criteria are: efficiency (C1), exergy (rational efficiency) (C2), investment cost (C3), operation and maintenance cost (C4), NO_X emission (C5), CO_2 emission (C6), land use (C7), social acceptability (C8), and job creation (C9).

According to the literature review on the application of the MCDM techniques to the energy issues by Wang, Jing, Zhang, and Zhao (2009), it is clear that evaluation criteria for alternative energy sources can be grouped into four main categories: Technical, economic, environmental, and social. Each of these aspects has sub-criteria. Some sub-criteria have been used more than others. The classification and relationship of these sub-criteria with the main criteria are shown in Figure 2. In fact, these criteria and sub-criteria are the most frequently used evaluation criteria in energy planning and energy management studies based on a careful review of the literature (Wang et al., 2009; Kaya & Kahraman, 2011).

Table 1 shows the corresponding IVIF numbers of linguistic variables. Tables 2, 3 and 4 contain comments of DMs for projects' ratings.

Results of weights of criteria and weights of DMs are shown in Tables 5 and 6, respectively. The parameters that are used to calculate the distance measure are $p = 1$ and $t = 2$.

The ranking of projects and comparisons with other methods are presented in Table 7.

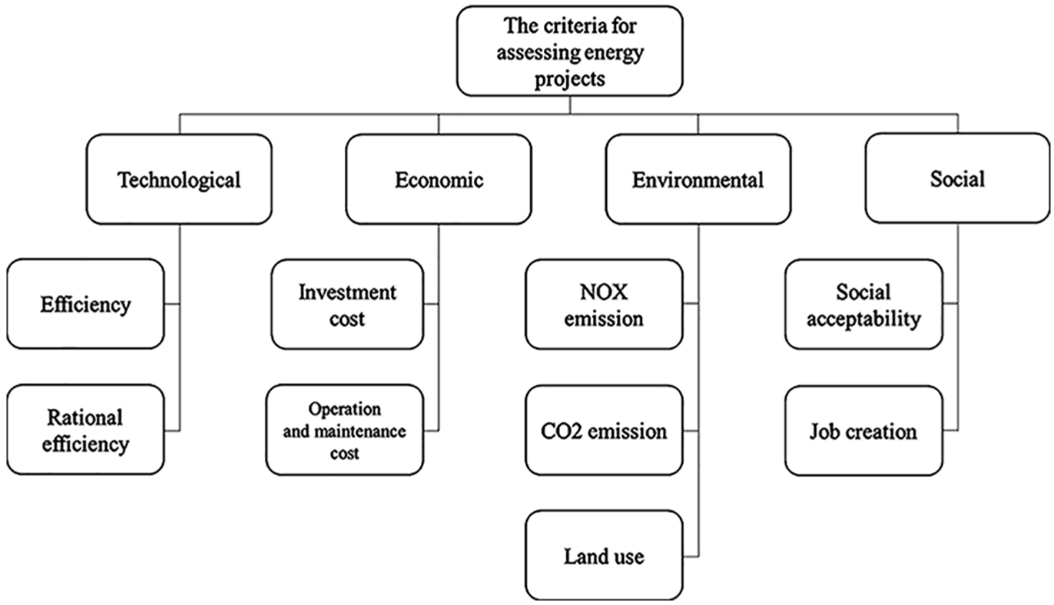

Figure 2. Hierarchical chart of criteria and sub-criteria

Table 1. Linguistic variables and corresponding IVIF numbers

Linguistic terms	IVIF numbers
Extremely high (EH)/ Extremely good (EG)	$([1,1],[0,0])$
Very very high (VVH)/Very very good (VVG)	$([0.9,0.9],[0.1,0.1])$
Very high (VH)/Very good (VG)	$([0.7333,0.825],[0,0.125])$
High (H)/Good (G)	$([0.6333,0.725],[0.1,0.225])$
Medium high (MH)/ Medium good (MG)	$([0.5333,0.625],[0.2,0.325])$
Medium (M)/Fair (F)	$([0.4333,0.525],[0.3,0.425])$
Medium low (ML)/ Medium bad (MB)	$([0.3333,0.425],[0.4,0.525])$
Low (L)/ Bad (B)	$([0.15,0.2875],[0.45,0.6375])$
Very low (VL)/ Very bad (VB)	$([0,0.1375],[0.6,0.7875])$
Very very low (VVL)/ Very very bad (VVB)	$([0.1,0.1],[0.9,0.9])$

Table 2. Judgment matrix of DM1

Criteria	Energy projects						
	Conventional	Nuclear	Solar	Wind	Hydraulic	Biomass	CHP
Efficiency	G	VG	F	MP	MG	F	F
Rational efficiency	G	F	F	MG	G	MG	MG
Investment cost	MG	VP	F	G	MG	F	F
Maintenance cost	MG	VG	F	G	F	F	MP
NO_X emission	VP	MP	VG	G	MP	G	F
CO_2 emission	VP	MP	G	VG	P	G	F
Land use	P	MP	VG	VG	MP	MG	MG
Social acceptability	MP	P	G	VG	F	G	G
Job creation	MG	P	F	F	G	G	MG

Table 3. Judgment matrix of DM2

Criteria	Energy projects						
	Conventional	Nuclear	Solar	Wind	Hydraulic	Biomass	CHP
Efficiency	VG	G	MP	F	F	F	MG
Rational efficiency	MG	VG	F	MG	G	F	F
Investment cost	G	MP	MG	G	MG	MG	F
Maintenance cost	F	VG	F	G	F	F	MP
NO_X emission	VP	MP	VG	G	MP	G	F
CO_2 emission	MP	MP	G	VG	P	G	F
Land use	VP	VP	G	G	MP	MG	G
Social acceptability	P	MP	G	VG	F	G	MG
Job creation	G	G	MG	F	MG	G	MG

Table 4. Judgment matrix of DM3

Criteria	Energy projects						
	Conventional	Nuclear	Solar	Wind	Hydraulic	Biomass	CHP
Efficiency	VG	VG	F	P	G	F	MG
Rational efficiency	VG	VG	F	MG	G	MG	F
Investment cost	MG	VP	F	G	MG	F	MG
Maintenance cost	MG	VG	F	VG	F	MG	F
NO_X emission	MP	P	G	VG	MP	G	F
CO_2 emission	MP	MP	G	VG	P	G	F
Land use	P	MP	G	G	MP	MG	MG
Social acceptability	MP	MP	G	VG	F	G	G
Job creation	MG	G	F	F	G	MG	MG

Table 5. Weights of decision makers

Decision makers	$\alpha^{(d)}$	$\beta^{(d)}$	$\gamma^{(d)}$	$S^{(d)}$
DM1	2.14	3.25	2.08	0.36
DM2	2.61	2.61	2.72	0.31
DM3	2.34	1.71	3.62	0.34

Table 6. Weights of criteria based on each decision maker

Criteria	Decision makers		
	DM1	DM2	DM3
C1	0.09	0.10	0.13
C2	0.04	0.08	0.08
C3	0.13	0.08	0.15
C4	0.09	0.10	0.09
C5	0.15	0.16	0.14
C6	0.15	0.13	0.14
C7	0.12	0.16	0.11
C8	0.12	0.13	0.11
C9	0.10	0.05	0.05

The results prove that the proposed method has been able to guarantee optimal prioritization. The priority of all projects is the same in all three rating approaches, except for the two projects, i.e. solar and biomass. Although the indicators of these two projects are so close together, there is no significant superiority between them.

3. Sensitivity and comparative analyses

In this section, sensitivity and comparative analyses are provided to prepare an overall insight from the behaviour of the proposed model (Borgonovo & Plischke, 2016). Meanwhile, the sensitivity analysis can help the users to observe the robustness and sensitiveness of obtained results versus inputs' changes. Moreover, the comparative analysis, in addition to some comparisons that are represented in Table 7, is discussed to illustrate the verification and ability of the proposed approach regarding the recent literature. However, the criteria weights are changed to test the obtained ranking' results in the process of sensitivity analysis.

Two new approaches provided in this paper compute weights of criteria as well as weights of the DMs using decision matrix data without obtaining mental judgments. For this reason and to investigate the effect of these two meth-

Table 7. Results of prioritization of projects and comparison of different methods

Projects	Rating by the presented method	Rating and scoring by Kaya and Kahraman (2011) method	Rating and scoring by Afsordegan, Sánchez, Agell, Zahedi, and Cremades (2016) method
Conventional	7	7 (0.056)	7 (0.485)
Nuclear	5	5 (0.059)	5 (0.517)
Solar	2	3 (0.079)	3 (0.660)
Wind	1	1 (0.089)	1 (0.732)
Hydraulic	6	6 (0.059)	6 (0.507)
Biomass	3	2 (0.080)	2 (0.682)
CHP	4	4 (0.068)	4 (0.584)

Table 8. Sensitivity analysis of three scenarios and comparing with Papapostolou et al. (2017) method

Projects	Rating based on the proposed method			Rating and scoring by Papapostolou et al. (2017) method
	Rating without computing weights of criteria	Rating without computing weights of DMs	Rating without computing weights of criteria and DMs	
Conventional	5	7	5	6 (0.454)
Nuclear	7	5	7	7 (0.440)
Solar	3	2	3	3 (0.629)
Wind	1	1	1	1 (0.730)
Hydraulic	6	6	6	5 (0.477)
Biomass	2	3	2	2 (0.653)
CHP	4	4	4	4 (0.545)

ods, the problem is solved without considering these two kinds of weights. Moreover, the case study is solved based on the fuzzy TOPSIS approach which was introduced by Papapostolou, Karakosta, and Doukas (2017) study. In their proposed approach, the DMs' weights are not calculated, and the criteria weights are considered based on mental judgments. The results are reported in Table 8.

Based on information, the DMs are in agreement with each other for evaluating projects, and confirming each other's opinions. Also, after solving the problem, regardless of weights of the criteria it is pointed out that the rankings of the projects changed (see Table 8). As reported in Table 8, if the problem is resolved without considering the weights of DMs and criteria, the projects' ranking is consistent with the Papapostolou et al. (2017) method. Also, the candidate ranking with criteria and experts' weights computations is consistent with the two other methods that are presented in Table 7. Therefore, it can be concluded that the proposed approach has a suitable performance regarding the other approaches by computing the two weights of criteria and DMs.

Furthermore, the criteria weights are changed based on some scenarios to check their influences on the obtained ranking results. In scenario 1, weights of C1 and C2 in the technical group are changed. In scenario 2, weights of C3 and C4 in the economic group are altered. In addition, in scenario 3, the weights of C5 and C6, in scenario 4, weights of the C5 and C7, and in scenario 5, weights of the C6 and C7 in environmental group are changed. Also, in scenario 6, the weights of C8 and C9 are changed. Finally, in the scenario 7, all criteria weights are considered the same. As indicated in Table 9, changing the criteria weights leads the ranking results to four different groups. The first group includes the P4; the second group includes P3 and P6; the third group includes P7; and the latter group includes P1, P2, and P5. As a result, P4's superiority to other existing projects could be accepted more confidently.

In sum, the results obtained from the above computations can be provided as follows:

– Firstly, determining the weights of criteria and DMs has increased the versatility and efficiency of the algorithm, unlike the previous studies;
– Secondly, calculating weights of the criteria is more important than calculating weights of the DMs in this decision problem;
– Thirdly, there is no significant difference between DMs for the project ranking;
– Fourthly, wind, solar and biomass candidates are in the category of the best projects, while wind has a comparative advantage;
– Fifthly, C5 to C8 are the most important criteria for all DMs in the computations. This consensus also confirms the proximity of the weights reached for the DMs; and

Table 9. Sensitivity analysis on weights of criteria by switching with each other

DM	Scenarios	Weights of criteria									Project rankings
		C1	C2	C3	C4	C5	C6	C7	C8	C9	
DM1	main	0.09	0.04	0.13	0.09	0.15	0.15	0.12	0.12	0.10	$p_4 \succ p_3 \succ p_6 \succ p_7 \succ p_5 \succ p_2 \succ p_1$
	1	0.04	0.09	0.13	0.09	0.15	0.15	0.12	0.12	0.10	$p_4 \succ p_3 \succ p_6 \succ p_7 \succ p_5 \succ p_1 \succ p_2$
	2	0.09	0.04	0.09	0.13	0.15	0.15	0.12	0.12	0.10	$p_4 \succ p_3 \succ p_6 \succ p_7 \succ p_5 \succ p_2 \succ p_1$
	3	0.09	0.04	0.13	0.09	0.15	0.15	0.12	0.12	0.10	$p_4 \succ p_3 \succ p_6 \succ p_7 \succ p_5 \succ p_2 \succ p_1$
	4	0.09	0.04	0.13	0.09	0.12	0.15	0.15	0.12	0.10	$p_4 \succ p_3 \succ p_6 \succ p_7 \succ p_5 \succ p_2 \succ p_1$
	5	0.09	0.04	0.13	0.09	0.15	0.12	0.15	0.12	0.10	$p_4 \succ p_3 \succ p_6 \succ p_7 \succ p_5 \succ p_2 \succ p_1$
	6	0.09	0.04	0.13	0.09	0.15	0.15	0.12	0.10	0.12	$p_4 \succ p_3 \succ p_6 \succ p_7 \succ p_5 \succ p_2 \succ p_1$
	7	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	$p_4 \succ p_3 \succ p_6 \succ p_7 \succ p_5 \succ p_1 \succ p_2$
DM2	main	0.10	0.08	0.08	0.10	0.16	0.13	0.16	0.13	0.05	$p_4 \succ p_3 \succ p_6 \succ p_7 \succ p_2 \succ p_5 \succ p_1$
	1	0.08	0.10	0.08	0.10	0.16	0.13	0.16	0.13	0.05	$p_4 \succ p_3 \succ p_6 \succ p_7 \succ p_2 \succ p_5 \succ p_1$
	2	0.10	0.08	0.10	0.08	0.16	0.13	0.16	0.13	0.05	$p_4 \succ p_3 \succ p_6 \succ p_7 \succ p_5 \succ p_2 \succ p_1$
	3	0.10	0.08	0.08	0.10	0.13	0.16	0.16	0.13	0.05	$p_4 \succ p_3 \succ p_6 \succ p_7 \succ p_2 \succ p_5 \succ p_1$
	4	0.10	0.08	0.08	0.10	0.16	0.13	0.16	0.13	0.05	$p_4 \succ p_3 \succ p_6 \succ p_7 \succ p_2 \succ p_5 \succ p_1$
	5	0.10	0.08	0.08	0.10	0.16	0.16	0.13	0.13	0.05	$p_4 \succ p_3 \succ p_6 \succ p_7 \succ p_2 \succ p_5 \succ p_1$
	6	0.10	0.08	0.08	0.10	0.16	0.13	0.16	0.05	0.13	$p_4 \succ p_3 \succ p_6 \succ p_7 \succ p_2 \succ p_5 \succ p_1$
	7	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	$p_4 \succ p_3 \succ p_6 \succ p_7 \succ p_2 \succ p_5 \succ p_1$
DM3	main	0.13	0.08	0.15	0.09	0.14	0.14	0.11	0.11	0.05	$p_4 \succ p_6 \succ p_3 \succ p_7 \succ p_1 \succ p_5 \succ p_2$
	1	0.08	0.13	0.15	0.09	0.14	0.14	0.11	0.11	0.05	$p_4 \succ p_6 \succ p_3 \succ p_7 \succ p_1 \succ p_5 \succ p_2$
	2	0.13	0.08	0.09	0.15	0.14	0.14	0.11	0.11	0.05	$p_4 \succ p_6 \succ p_3 \succ p_7 \succ p_1 \succ p_2 \succ p_5$
	3	0.13	0.08	0.15	0.09	0.14	0.14	0.11	0.11	0.05	$p_4 \succ p_6 \succ p_3 \succ p_7 \succ p_1 \succ p_5 \succ p_2$
	4	0.13	0.08	0.15	0.09	0.11	0.14	0.14	0.11	0.05	$p_4 \succ p_6 \succ p_3 \succ p_7 \succ p_1 \succ p_5 \succ p_2$
	5	0.13	0.08	0.15	0.09	0.14	0.11	0.14	0.11	0.05	$p_4 \succ p_6 \succ p_3 \succ p_7 \succ p_1 \succ p_5 \succ p_2$
	6	0.13	0.08	0.15	0.09	0.14	0.14	0.11	0.05	0.11	$p_4 \succ p_6 \succ p_3 \succ p_7 \succ p_1 \succ p_5 \succ p_2$
	7	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	$p_4 \succ p_6 \succ p_3 \succ p_7 \succ p_1 \succ p_5 \succ p_2$

– Sixthly, among three DMs of this case study, the most optimistic judgment belongs to the third DM. Also, the most pessimistic judgment belongs to the first DM.

To solve real-world decision-making problems, the simplicity of decision method, low computational time, and reduction of the amount of calculations are important issues. Regarding the comparisons of the decision methods, it can be noted that Afsordegan et al. (2016) method and the proposed method with less computation have been able to solve the decision problem in comparison with Kaya and Kahraman (2011) method. In the method presented by Kaya and Kahraman (2011), it was necessary to obtain pairwise comparisons that increased the risk of receiving incorrect information, in addition to increasing the complexity of the decision problem. In these methods, the solving time and the complexity of calculations increases by rising the dimensions of the problem. Consequently, the proposed approach in this study with criteria and DMs' weights computation provides more accurate and reliable outputs by increasing the dimensions of the problem.

Conclusions and future suggestions

The MCDM approach is one of critical tool which has assist contractors to choose the most appropriate construction project to reduce their risks and costs. Thus, this study proposed a new integrated interval-valued intuitionistic fuzzy group MCDM model via compromise solution and linear assignment approaches to evaluate the candidate construction projects, appropriately. Meanwhile, the interval-valued intuitionistic fuzzy sets (IVIFSs) could help DMs to cope with imprecise information and vague situations by presenting the linguistic terms instead of crisp values. Furthermore, the criteria weights and the expertise of DMs were calculated by presented novel indexes to decrease the errors of judgments. Further, a case study about the CPSP was considered to represent the feasibility and implication procedure of the proposed approach. For future suggestions, the proposed method can be improved based on hierarchical structure and considering interdependencies of criteria to provide all aspects of evaluation criteria of CPSPs.

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Author contributions

The original idea was designed by R. Davoudabadi and S.M. Mousavi. Subsequently, the model was developed with J. Šaparauskas' collaboration. H. Gitinavard has also completed and edited the article. At the end, the paper has been reviewed and approved by R. Davoudabadi, S.M. Mousavi and J. Šaparauskas.

Disclosure statement

The authors declare that they have any competing financial, professional, or personal interests from other parties.

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