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Research Article

ELECTRE I-based Group Decision Methodology with Risk Preferences in an Imprecise Setting for Flexible Manufacturing Systems

Seyed Meysam Mousavi [a], Hossein Gitinavard [b], Behnam Vahdani [c,*]

[a] *Department of Industrial Engineering, Faculty of Engineering, Shahed University, Tehran, Iran*
[b] *Department of Industrial Engineering and Management Systems, Amirkabir University of Technology, Tehran, Iran*
[c] *Department of Industrial Engineering, Faculty of Industrial and Mechanical Engineering, Qazvin Branch, Islamic Azad University, Qazvin, Iran*

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Abstract

A new hesitant fuzzy set (HFS)-ELECTRE for multi-criteria group decision-making (MCGDM) problems is developed in this paper. In real-world applications, the decision makers (DMs)' opinions are often hesitant for decision problems; thus, considering the exact data is difficult. To address the issue, the DMs' judgments can be expressed as linguistic variables that are converted into the HFSs, considered as inputs in the ELECTRE method. Meanwhile, an appropriate tool among the fuzzy sets theory and their extensions is the HFSs since the DMs can assign their judgments for an alternative under the evaluation criteria by some membership degrees under a set to decrease the errors. Introduced hesitant fuzzy ELECTRE (HF-ELECTRE) method is elaborated based on the risk preference of each DM with assigning some degrees. Moreover, the weight of each DM is computed and implemented in the proposed procedure to reduce judgments' errors. Then, a new discordance HF index is provided. Pair-wise comparisons are used for outranking relations regarding HF information. Finally, the validation and verification of the proposed HF-ELECTRE method are demonstrated in a practical example of FMSs.

Keywords: ELECTRE method; Group decision analysis; HFSs; Flexible manufacturing systems (FMSs).

1. Introduction

Multi-criteria group decision making (MCGDM) assumes the problem of selecting or assessing possible alternatives according to several conflicting and incommensurate criteria by a cooperative group (Chen et al., 1992; Ebrahimnejad et al., 2012; Mousavi et al., 2014; Foroozesh et al., 2017a,b; Vahdani et al., 2014 a,b, 2017). MCGDM problems are very useful tools for real situations (Mojtahedi et al., 2010; Tavakkoli-Moghaddam et al., 2011; Mousavi et al., 2016, 2018, 2019; Mohagheghi et al., 2015, 2017a,b,c,d). When the complexity of the real-world increases, a group of the DMs cannot consider the judgments precisely. In this respect, the Decision makers (DMs) have assigned their opinions by incomplete or imprecise (fuzzy) information (Moradi et al., 2017,2018; Hajighasemi and Mousavi, 2018; Gitinavard et al., 2017a,b; Mousavi and Vahdani, 2016).

Elimination and choice translating reality (ELECTRE) method is broadly used in decision problems, introduced by Roy (1968), in which alternatives are dominated to recognize and omit alternatives (Bojković et al., 2010; Hatami-Marbini and Tavana, 2011; Vahdani et al., 2013). There are some studies in the literature that have considered the technique for solving MCGDM problems under uncertainty (e.g., Bisdorff, 2000; Montazer et al., 2009). In this regard, Chen and Hung (2009) applied the linguistic terms for stock portfolio selection in a fuzzy situation for indicating the opinion of the DMs to rate the performance of alternatives concerning each criterion, utilizing the ELECTRE method and maximizing deviation method. Vahdani and Hadipour (2011) based on interval-valued fuzzy sets developed an ELECTRE method.

Xu and Xia (2012) identified and eliminated alternatives in multi-attribute decision making (MADM) with intuitionistic fuzzy information. Devi and Yadav (2013) presented ELECTRE method with IFSs for evaluation of plant locations to handle the uncertainty of information, and then a plant location selection problem was solved by the presented method. Chen (2014) focused on outranking method via the GDM and interval type-2 fuzzy sets to address the supplier selection problem. Celik et al. (2016) developed the ELECTRE to assess the green service providers in the logistic industry.

The review indicates that there are some studies focused on the ELECTRE methods in fuzzy conditions. Most of these studies are based on the traditional fuzzy set (Zadeh, 1965). In the hesitant situations, the experts or DMs may assign their preferences in some membership degrees to a set. A desirable solution for these situations is to utilize the HFS that was introduced by Torra and Narukawa (2009) and Torra (2010). HFS theory seems to be

*Corresponding author Email address: b.vahdani@gmail.com

appropriate for illustrating their vagueness (e.g., Liao and Xu, 2013; Xu and Zhang, 2013; Zhang and Wei, 2013; Zhang et al., 2014).

In a hesitant fuzzy (HF) environment, several scholars have utilized these concepts and applications to the decision-making methods. Xu and Zhang (2013) developed TOPSIS method based on HF and interval-valued HF environments. Wei and Zhang (2014) extended VIKOR method to attend to correlative MADM problems based on HF setting and Shapley value. Gitinavard et al. (2016) presented a weighting and ranking method under interval-valued hesitant fuzzy sets. Qiaoping and Ouyang (2015) extended the TOPSIS method and also tailored entropy method to compute the criteria importance values. Besides, Tavakkoli-Moghaddam (2015) presented a TOPSIS method via interval-valued HF information to determine the criteria weights.

This paper presents a development of canonical ELECTRE method based on the HFSs theory to handle the hesitant situations for situations with hesitant fuzzy values (HFVs). Proposed method, taken risk preferences of the DMs, utilizes the truth-membership function to represent the degrees of satisfaction for alternatives according to a set of criteria. Also, a group of the DMs is considered to specify their preferences for the relative importance of each criterion and to rate the possible alternatives for the MCGDM problems. Hesitant fuzzy weighted averaging (HFWA) based approach is used to aggregate individual DMs' views for the relative weights of the criteria and to assess the possible alternatives concerning each criterion. Then, a new discordance HF measure is provided. The proposed HF-ELECTRE method also dominates the difficulties that arise from the ELECTRE method in HF environments. By using pair-wise comparisons, the outranking relations are expressed, and to indicate which alternative is preferable decision graphs are depicted in the HF environment.

The structure of the paper is as follows: section 2 presents preliminary concepts and definitions of HFSs. The proposed ELECTRE method in HFSs' situations is represented in section 3. The application of the introduced method is indicated by a numerical example in section 4. Section 5, provides some remarkable conclusions and future directions.

2. Basic Definitions

Some definitions are described for HFSs that are utilized in this paper.

Definition 1 (Torra, 2010). In HFSs, the major operators are defined as below:

Upper bound and lower bound

$$h^{+}(x)=max\ h(x) \qquad h^{-}(x)=min\ h(x) \tag{1}$$

α-upper bound and α-lower bound

$$h_{\alpha}^{+}(\mathrm{x})=\{h\in h(\mathrm{x})\,|\,\mathrm{h}\geq\alpha\} \qquad h_{\alpha}^{-}(\mathrm{x})=\{h\in h(\mathrm{x})\,|\,\mathrm{h}\leq\alpha\} \tag{2}$$

Complement

$$h^{c}(\mathrm{x})=\cup_{\gamma\in h(\mathrm{x})}\{1-\gamma\} \tag{3}$$

Union

$$h_1\cup h_2=\cup_{\gamma_1\in h_1,\gamma_2\in h_2}\max\{\gamma_1,\gamma_2\} \tag{4}$$

Intersection

$$h_1\cap h_2=\cup_{\gamma_1\in h_1,\gamma_2\in h_2}\min\{\gamma_1,\gamma_2\} \tag{5}$$

Definition 2 (Atanassov, 1989, 2000). Reference set of X is assumed. Then, an intuitionistic fuzzy set (IFS) of *E* on *X* is indicated by mathematical symbol (relation (6)). In addition, by considering the relation, membership degree has been indicated as $\mu_E(\mathrm{x}_i)$ and the non-membership degree has been indicated as $\nu_E(\mathrm{x}_i)$.

$$E=(\langle x_i,\mu_E(x_i),\nu_E(x_i)\rangle)\quad \forall x_i\in X \tag{6}$$

$$0\leq\mu_E(x_i)+\nu_E(x_i)\leq 1\quad \forall x_i\in X \tag{7}$$

Definition 3 (Xia and Xu, 2011). By above-mentioned operators and considering the relation between HFSs and IFSs, the following operations are obtained:

$$h_1\oplus h_2=\cup_{\gamma_1\in h_1,\gamma_2\in h_2}\{\gamma_1+\gamma_2-\gamma_1.\gamma_2\} \tag{8}$$

$$h_1\otimes h_2=\cup_{\gamma_1\in h_1,\gamma_2\in h_2}\{\gamma_1.\gamma_2\} \tag{9}$$

$$h^{\lambda}=\cup_{\gamma\in h}\{\gamma^{\lambda}\} \tag{10}$$

$$\lambda h=\cup_{\gamma\in h}\{1-(1-\gamma)^{\lambda}\} \tag{11}$$

Definition 4 (Xu and Xia, 2011). By considering the concept of HFSs and their relations, some distances are introduced. By extended Hamming distance and Euclidean distance, the generalized distance is presented.

For two HFEs as h_M and h_N the distance measure is presented:

$$d_{gh}\left(h_M, h_N\right)=\left(\frac{1}{l_{x_i}}\sum_{j=1}^{l_{x_i}}\left|h_M^{\sigma(j)}\left(x_i\right)-h_N^{\sigma(j)}\left(x_i\right)\right|^{\lambda}\right)^{\frac{1}{\lambda}} \tag{12}$$

where the jth largest values of h_M and h_N are indicated by $h_M^{\sigma(j)}$ and $h_N^{\sigma(j)}$. In addition, in generalized distance measure, if $\lambda=1$, the Hamming distance is resulted. If $\lambda=2$ the Euclidean distance is resulted.

Definition 5 (Xia and Xu, 2011) The HFWA operator is showed by Eq. (13) and HFWG is indicated by relation (14), those mentioned above are given as follows:

Let $h_j\left(j=1,2,...,n\right)$ be some of HFEs, then:

$$HFWA\left(h_1,h_2,...,h_n\right)=\underset{j=1}{\overset{n}{\oplus}}\left(w_j h_j\right)=\cup_{\gamma_1\in h_1,\gamma_2\in h_2,...,\gamma_n\in h_n}\left\{1-\prod_{j=1}^{n}\left(1-\gamma_j\right)^{w_j}\right\} \tag{13}$$

$$HFWG\left(h_1,h_2,...,h_n\right)=\underset{j=1}{\overset{n}{\otimes}}\left(h_j\right)^{w_j}=\cup_{\gamma_1\in h_1,\gamma_2\in h_2,...,\gamma_n\in h_n}\left\{\prod_{j=1}^{n}\left(\gamma_j\right)^{w_j}\right\} \tag{14}$$

where the weight vector of $h_j\left(j=1,2,...,n\right)$ is represented by $w=\left(w_1,w_2,...,w_n\right)^T$.

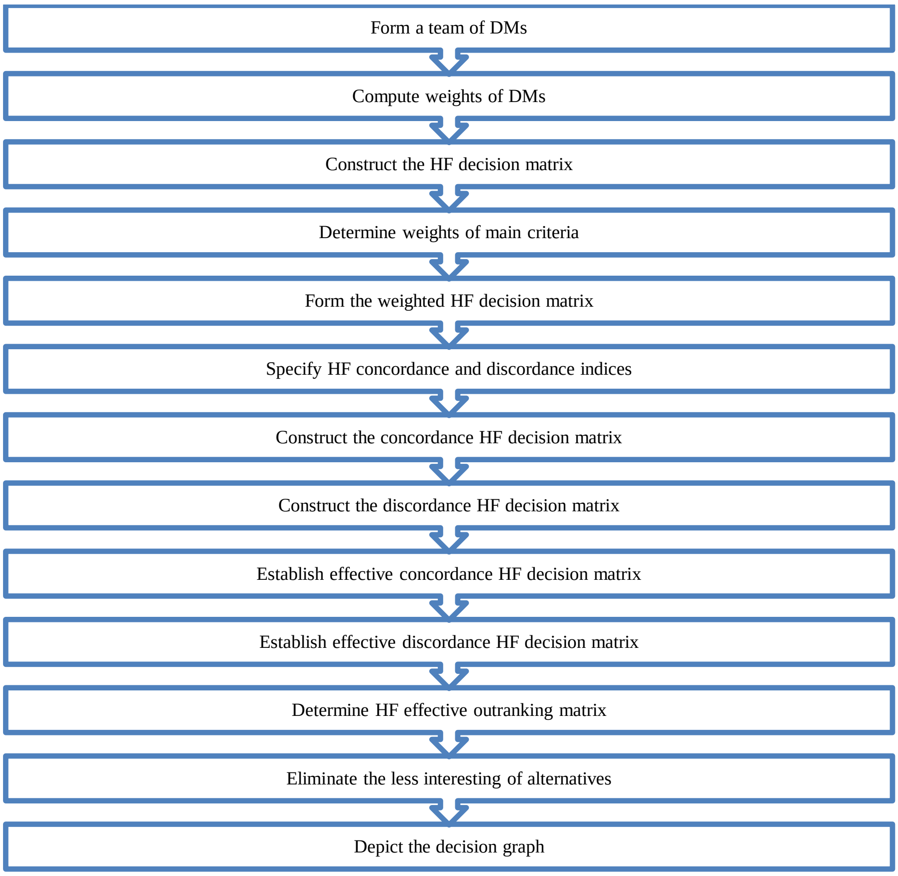

Fig. 1. Illustration of the novel HF-ELECTRE method

3. Proposed HF-ELECTRE Method

The novel HF-ELECTRE method is depicted in Figure 1.

Step 1. Express preferences by some DMs under the HF environment as given in Table 1.

Table 1
The membership degrees of HFSs by *k*th DM

	C_1	C_2	…	C_n
A_1	μ_{11}^k	μ_{12}^k	…	μ_{1n}^k
A_2	μ_{21}^k	μ_{22}^k	…	μ_{2n}^k
.	.	.	.	.
.	.	.	.	.
.	.	.	.	.
A_m	μ_{m1}^k	μ_{m2}^k	…	μ_{mn}^k

Step 2. Compute weights of the DMs (λ_k) based on the following relation:

$$\lambda_k = \frac{\sum_{i}^{m}\sum_{j}^{n}\mu_{ij}^k}{\sum_{k}^{K}\sum_{i}^{m}\sum_{j}^{n}\mu_{ij}^k} \quad (15)$$

$$\sum_{k=1}^{K}\lambda_k = 1 \quad (16)$$

Step 3. Form the HF decision matrix (r_{ij}) according to the aggregated opinions of DMs.

$$r_{ij} = HFWA\left(r_{ij}^{(1)}, r_{ij}^{(2)}, ..., r_{ij}^{(k)}\right) = \underset{k=1}{\overset{K}{\oplus}}\left(\lambda_k\, r_{ij}^{(k)}\right) = \cup_{\mu_{ij}^{(k)} \in r_{ij}^{(k)}}\left\{1-\prod_{k=1}^{K}\left(1-\mu_{ij}^{(k)}\right)^{\lambda_k}\right\} \quad (17)$$

Step 4. Figure out normalized weight of main criteria (w_j^*) regarding the DMs' judgments.

$$w_j^* = HFWA\left(\varpi_j^{(1)}, \varpi_j^{(2)}, ..., \varpi_j^{(k)}\right) = \underset{k=1}{\overset{K}{\oplus}}\left(\lambda_k\, \varpi_j^{(k)}\right) = \cup_{\varpi_j^{(k)} \in w_j^{(k)}}\left\{1-\prod_{k=1}^{K}\left(1-\varpi_j^{(k)}\right)^{\lambda_k}\right\} \quad (18)$$

$$w_j = \frac{w_j^*}{\sum_{j}^{n} w_j^*} \quad (19)$$

Step 5. Construct weighted HF decision matrix (r^{ω}).

$$r^{\omega} = \begin{bmatrix} w_1\mu_{11}(x_1) & w_2\mu_{12}(x_2) & \cdots & w_n\mu_{1n}(x_n) \\ w_1\mu_{21}(x_1) & w_2\mu_{22}(x_2) & \cdots & w_n\mu_{2n}(x_n) \\ \vdots & \vdots & \ddots & \vdots \\ w_1\mu_{m1}(x_1) & w_2\mu_{m2}(x_2) & \cdots & w_n\mu_{mn}(x_n) \end{bmatrix} \quad (20)$$

Step 6. Compute HF concordance (S_{ef}) and discordance indices (I_{ef}).

$$S_{ef} = \left\{ j \mid \mu_{r_e^\omega}\left(x_j\right) \geq \mu_{r_f^\omega}\left(x_j\right) \right\} \tag{21}$$

$$I_{ef} = \left\{ j \mid \mu_{r_e^\omega}\left(x_j\right) < \mu_{r_f^\omega}\left(x_j\right) \right\} = J - S_{ef} \tag{22}$$

Step 7. Compute concordance HF decision matrix (CI).

$$\alpha_{ef} = \frac{\sum_{j \in S_{ef}} w_j}{\sum_{j \in J} w_j} \quad \text{and} \quad \sum_{j \in J} w_j = 1 \tag{23}$$

$$CI = \begin{bmatrix} - & \alpha_{12} & \cdots & \alpha_{1n} \\ \alpha_{21} & - & \cdots & \alpha_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \alpha_{m1} & \alpha_{m2} & \cdots & - \end{bmatrix} \tag{24}$$

Step 8. Establish discordance HF decision matrix (DCI).

$$\beta_{ef} = \frac{\underset{j \in I_{ef}}{Max}\left\{ d\left(r_{ej}^{\omega}, r_{fj}^{\omega}\right)\right\}}{\underset{j \in J}{Max}\left\{ d\left(r_{ej}^{\omega}, r_{fj}^{\omega}\right)\right\}} \tag{25}$$

$$\beta_{ef} = \frac{\underset{j \in I_{ef}}{Max}\left\{ \frac{1}{l_{x_i}} \sum_{j=1}^{l_{x_i}} \left| \mu_{r_{ej}^{\omega}}^{\sigma(j)}\left(x_i\right) - \mu_{r_{fj}^{\omega}}^{\sigma(j)}\left(x_i\right) \right| \right\}}{\underset{j \in J}{Max}\left\{ \frac{1}{l_{x_i}} \sum_{j=1}^{l_{x_i}} \left| \mu_{r_{ej}^{\omega}}^{\sigma(j)}\left(x_i\right) - \mu_{r_{fj}^{\omega}}^{\sigma(j)}\left(x_i\right) \right| \right\}} \tag{26}$$

$$DCI = \begin{bmatrix} - & \beta_{12} & \cdots & \beta_{1n} \\ \beta_{21} & - & \cdots & \beta_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \beta_{m1} & \beta_{m2} & \cdots & - \end{bmatrix} \tag{27}$$

Step 9. Provide effective concordance HF decision matrix (q_{ef}).

$$\bar{\alpha} = \mu_{CI_{ef}}\left(x_j\right) = \max_{i,j}\left(\mu_{CI_{ef}}\left(x_j\right)\right) \quad \forall i, j \tag{28}$$

$$q_{ef} = \begin{cases} 1 & \text{if } \alpha_{ef} \geq \bar{\alpha} \\ 0 & \text{if } \alpha_{ef} < \bar{\alpha} \end{cases} \tag{29}$$

Step 10. Establish effective discordance HF decision matrix (g_{ef}).

$$\bar{\beta} = \frac{1}{m(m-1)} \sum_{e=1}^{m} \sum_{f=1}^{m} \frac{\underset{j \in I_{ef}}{Max} \left\{ \left| \mu_{r_{ej}^{\omega}} - \mu_{r_{fj}^{\omega}} \right| \right\}}{\underset{j \in J}{Max} \left\{ \left| \mu_{r_{ej}^{\omega}} - \mu_{r_{fj}^{\omega}} \right| \right\}} \quad \forall e \neq f \tag{30}$$

$$\bar{\beta} = \frac{1}{m(m-1)} \sum_{e=1}^{m} \sum_{f=1}^{m} \frac{\underset{j \in I_{ef}}{Max} \left\{ \frac{1}{l_{x_i}} \sum_{j=1}^{l_{x_i}} \left| \mu_{r_{ej}^{\omega}}^{\sigma(j)}(x_i) - \mu_{r_{fj}^{\omega}}^{\sigma(j)}(x_i) \right| \right\}}{\underset{j \in J}{Max} \left\{ \frac{1}{l_{x_i}} \sum_{j=1}^{l_{x_i}} \left| \mu_{r_{ej}^{\omega}}^{\sigma(j)}(x_i) - \mu_{r_{fj}^{\omega}}^{\sigma(j)}(x_i) \right| \right\}} \quad \forall e \neq f \tag{31}$$

$$g_{ef} = \begin{cases} 1 & \text{if } \beta_{ef} \leq \bar{\beta} \\ 0 & \text{if } \beta_{ef} > \bar{\beta} \end{cases} \tag{32}$$

Step 11. Build HF outranking matrix (h_{ef}).

$$h_{ef} = q_{ef} \times g_{ef} \tag{33}$$

Step 12. Omit less interesting possible alternatives.

$$\begin{cases} h_{ef} = 1 & \text{for at least one unit element for } f = 1,2,\ldots,m; e \neq f \\ h_{ef} = 0 & \text{for all } i \text{ for } f = 1,2,\ldots,m;\ i \neq k, i \neq l \end{cases} \tag{34}$$

Step 13. Provide decision graph.
Graphical indication of relations is illustrated in Figure 2.

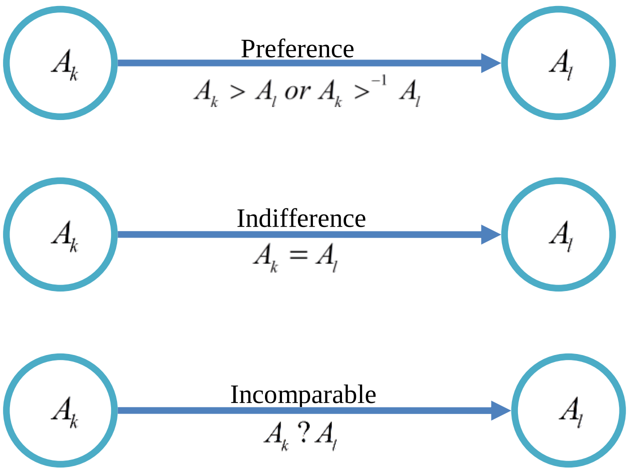

Fig. 1. Illustration of the binary relations

4. Practical Example

An example is presented to indicate the application of the novel extended method. This application example has been adopted from Vahdani et al. (2013). A company for manufacturing tractor components should assess and choose the most suitable alternative of flexible manufacturing systems (FMSs) for producing a group of products. In this problem, 5 alternatives (FMSs) considered as A_1, A_2, A_3, A_4 and A_5, which are specified and assessed by three DMs. Also, 5 selected criteria for an evaluation of possible alternatives are described below:

- Quality of results: C_1;
- Ease of use: C_2;
- Competitive: C_3;
- Adaptability: C_4;
- Expandability: C_5.

According to the above-mentioned selected criteria, the hierarchical structure of the numerical example is shown in Figure 3.

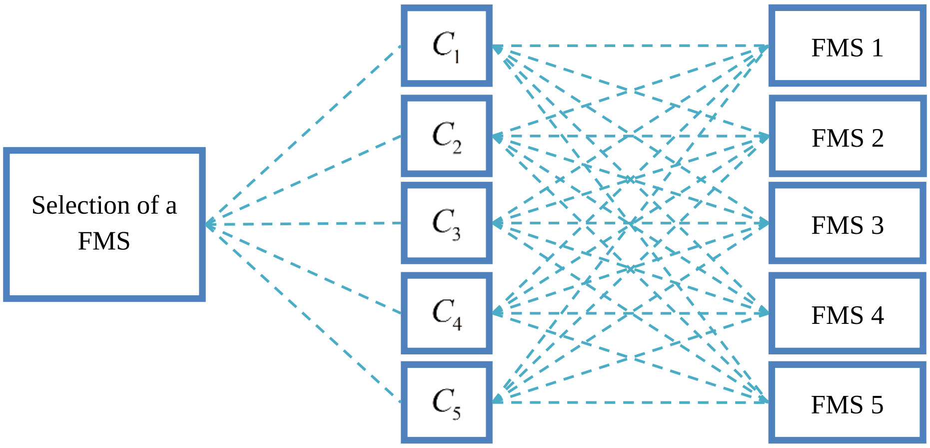

Fig. 2. Hierarchy structure of the FMS decision problem

Tables 2 and 3 describe the applied linguistic variables for criteria and alternatives, respectively. In complex problems, decision matrix could be shown with HFSs. Then, the rating of possible options and rating the importance of evaluation factors may be described by linguistic variables so that the values of linguistic variables are demonstrated as a closed interval of the HFSs. For these situations, the DMs' risk preferences are essential, optimists expect desirable results and select the upper bound of a closed interval of HFSs, defined by linguistic variables. Pessimists anticipate unfavorable results and select the lower bound of a closed interval of HFSs, defined by linguistic variables. For example, assume high for A_1 with respect to DM_1, linguistic variable in the table (i.e., high) defined by a closed interval of HFSs as [0.70, 0.80], optimists select 0.80 for this linguistic term, pessimists select 0.70 for this linguistic variable, and moderates choose the average between lower and upper bounds. In this decision problem, DM_1 is the pessimist, DM_2 is moderate and DM_3 is the optimist.

Table 2
Criteria rating variables

Linguistic variables	Interval-valued hesitant fuzzy element (IVHFE)	DMs' risk preferences		
		Pessimist	Moderate	Optimist
Very important (VI)	[0.90, 0.90]	0.90	0.90	0.90
Important (I)	[0.75, 0.80]	0.75	0.775	0.80
Medium (M)	[0.50, 0.55]	0.50	0.525	0.55
Unimportant (UI)	[0.35, 0.40]	0.35	0.375	0.40
Very unimportant (VUI)	[0.10, 0.10]	0.10	0.10	0.10

The committee of DMs is a heterogeneous group because all DMs have unequal importance. Thus, the importance has been represented in Table 4 and calculated by Eqs. (15) and (16) (Step 2). HF ratings of possible options are given in Table 5, and their respective HFVs are illustrated in Table 6. Aggregated HF decision matrix has been established with Eq. (17). Outcomes have been given in Table 7 (Step 3).

Table 3
Alternatives rating variables

		DMs' risk preferences		
Linguistic variables	IVHFE	Pessimist	Moderate	Optimist
Extremely good (EG)/extremely high (EH)	[1.00, 1.00]	1.00	1.00	1.00
Very very good (VVG)/very very high (VVH)	[0.90, 0.90]	0.90	0.90	0.90
Very good (VG)/very high (VH)	[0.80, 0.90]	0.80	0.85	0.90
Good (G)/high (H)	[0.70, 0.80]	0.70	0.75	0.80
Medium good (MG)/medium high (MH)	[0.60, 0.70]	0.60	0.65	0.70
Fair (F)/medium (M)	[0.50, 0.60]	0.50	0.55	0.60
Medium bad (MB)/medium low (ML)	[0.40, 0.50]	0.40	0.45	0.50
Bad (B)/low (L)	[0.25, 0.40]	0.25	0.325	0.40
Very bad (VB)/very low (VL)	[0.10, 0.25]	0.10	0.175	0.25
Very very bad (VVB)/very very low (VVL)	[0.10, 0.10]	0.10	0.10	0.10

Table 4
The weight of each decision maker

	DM_1	DM_2	DM_3
DM's weight	0.318483	0.330806	0.350711

Table 5
Ratings of the alternatives based on linguistic variables

Criteria	Alternatives	Decision makers		
		DM_1	DM_2	DM_3
C_1	A_1	H	H	MH
	A_2	VG	G	VG
	A_3	VG	VG	VG
	A_4	VH	VH	H
	A_5	F	F	MG
C_2	A_1	MG	MG	G
	A_2	MB	MB	MB
	A_3	VVG	VG	VG
	A_4	VVG	VG	VG
	A_5	MB	F	F
C_3	A_1	G	G	VG
	A_2	VG	G	VG
	A_3	VG	G	G
	A_4	VG	G	G
	A_5	G	MG	MG
C_4	A_1	H	H	H
	A_2	MB	F	MB
	A_3	VH	H	H
	A_4	H	MH	MH
	A_5	M	MH	M
C_5	A_1	MG	MG	MG
	A_2	MH	MH	M
	A_3	VG	G	VG
	A_4	G	G	F
	A_5	MB	F	MB

Table 6
Rating of alternatives based on HF elements

Criteria	Alternatives	Decision makers		
		DM_1	DM_2	DM_3
C_1	A_1	0.70	0.75	0.70
	A_2	0.80	0.75	0.90
	A_3	0.80	0.85	0.90
	A_4	0.80	0.85	0.80
	A_5	0.50	0.55	0.70
C_2	A_1	0.60	0.65	0.80
	A_2	0.40	0.45	0.50
	A_3	0.90	0.85	0.90
	A_4	0.90	0.85	0.90
	A_5	0.40	0.55	0.60
C_3	A_1	0.70	0.75	0.90
	A_2	0.80	0.75	0.90
	A_3	0.80	0.75	0.80
	A_4	0.80	0.75	0.80
	A_5	0.70	0.65	0.70
C_4	A_1	0.70	0.75	0.80
	A_2	0.40	0.55	0.50
	A_3	0.80	0.75	0.80
	A_4	0.70	0.65	0.70
	A_5	0.50	0.65	0.60
C_5	A_1	0.60	0.65	0.70
	A_2	0.60	0.65	0.60
	A_3	0.80	0.75	0.90
	A_4	0.70	0.75	0.60
	A_5	0.40	0.55	0.50

Table 7
Aggregated HF decision matrix

	C_1	C_2	C_3	C_4	C_5
A_1	0.717559	0.699875517	0.80787	0.754997	0.654014
A_2	0.831145	0.453134088	0.831145	0.488258	0.617285
A_3	0.857398	0.885645834	0.784678	0.784678	0.831145
A_4	0.818156	0.885645834	0.784678	0.684305	0.687576
A_5	0.596328	0.526779357	0.684305	0.589096	0.488258

By utilizing Table 1, the relative importance of criteria has been defined with linguistic weighting terms and has been appraised with the DMs in Table 8. Also, in this table, the normalized aggregated weighted of each criterion is calculated by Eqs.(18) and (19) (Step 4). In addition, table 9 shows the values for evaluation of criteria importance. Weighted HF decision matrix has been presented in Table 10 (Step 5). Employing Eqs. (21) and (22), the HF concordance and discordance indices have been given as follows (Step 6):

$$\left[S_{1,2}=\{2,4,5\}, I_{1,2}=\{1,3\}\right],\left[S_{1,3}=\{3\}, I_{1,3}=\{1,2,4,5\}\right], \left[S_{1,4}=\{3,4\}, I_{1,4}=\{1,2,5\}\right]$$
$$\left[S_{1,5}=\{1,2,3,4,5\}, I_{1,5}=\{\}\right],\left[S_{2,1}=\{1,3\}, I_{2,1}=\{2,4,5\}\right],\left[S_{2,3}=\{3\}, I_{2,3}=\{1,2,4,5\}\right]$$
$$\left[S_{2,4}=\{1,3\}, I_{2,4}=\{2,4,5\}\right],\left[S_{2,5}=\{1,3,5\}, I_{2,5}=\{2,4\}\right],\left[S_{3,1}=\{1,2,4,5\}, I_{3,1}=\{3\}\right]$$
$$\left[S_{3,2}=\{1,2,4,5\}, I_{3,2}=\{3\}\right], \left[S_{3,4}=\{1,2,3,4,5\}, I_{3,4}=\{\}\right],\left[S_{3,5}=\{1,2,3,4,5\}, I_{3,5}=\{\}\right] \quad (35)$$
$$\left[S_{4,1}=\{1,2,5\}, I_{4,1}=\{3,4\}\right], \left[S_{4,2}=\{2,4,5\}, I_{4,2}=\{1,3\}\right],\left[S_{4,3}=\{\}, I_{4,3}=\{1,2,3,4,5\}\right]$$
$$\left[S_{4,5}=\{1,2,3,4,5\}, I_{4,5}=\{\}\right],\left[S_{5,1}=\{\}, I_{5,1}=\{1,2,3,4,5\}\right],\left[S_{5,2}=\{2,4\}, I_{5,2}=\{1,3,5\}\right]$$
$$\left[S_{5,3}=\{\}, I_{5,3}=\{1,2,3,4,5\}\right],\left[S_{5,4}=\{\}, I_{5,4}=\{1,2,3,4,5\}\right]$$

Table 8
Linguistic variables for assessing the criteria weights

	C_1	C_2	C_3	C_4	C_5
DM_1	UI	M	VI	VUI	M
DM_2	UI	I	VI	VUI	M
DM_3	VUI	M	I	UI	UI

Table 9
HFVs for criteria weights and their aggregations

	C_1	C_2	C_3	C_4	C_5
DM_1	0.35	0.50	0.90	0.10	0.50
DM_2	0.375	0.775	0.90	0.10	0.525
DM_3	0.10	0.55	0.80	0.40	0.40
Aggregated HF weight	0.113296	0.254182	0.352014	0.088479	0.192029

Table 10
HF normalized weighted decision matrix

	C_1	C_2	C_3	C_4	C_5
A_1	0.081297	0.177895412	0.284382	0.066801	0.12559
A_2	0.094166	0.115178304	0.292575	0.0432	0.118537
A_3	0.09714	0.22511479	0.276218	0.069427	0.159604
A_4	0.092694	0.22511479	0.276218	0.060546	0.132035
A_5	0.067562	0.133897569	0.240885	0.052122	0.09376

Concordance HF matrix via Eqs. (23) and (24) is calculated (Step 7); e.g., α_{12} has been obtained via Eq. (36):

$$I_{12}=\frac{\sum_{j\epsilon S_{12}} w_j}{\sum_{j\epsilon J} w_j}=\frac{0.2541815+0.0884787+0.1920295}{1}=0.5346896 \quad (36)$$

$$CI = \begin{pmatrix} - & 0.5346896 & 0.3520142 & 0.4404929 & 1 \\ 0.4653104 & - & 0.3520142 & 0.4653104 & 0.6573398 \\ 0.6479858 & 0.6479858 & - & 1 & 1 \\ 0.5595071 & 0.5346896 & 0 & - & 1 \\ 0 & 0.3426602 & 0 & 0 & - \end{pmatrix}$$

Discordance HF matrix via Eqs. (25)-(27) is calculated (Step 8); e.g., β_{12} has been computed as follows:

$$\beta_{12} = \frac{max_{j\in I_{12}}\{d_h(r_{ej}^{\omega}, r_{fj}^{\omega})\}}{max_{j\in J}\{d_h(r_{ej}^{\omega}, r_{fj}^{\omega})\}} = \frac{max\{|\mu_{11}-\mu_{21}|, |\mu_{13}-\mu_{23}|\}}{max\{|\mu_{11}-\mu_{21}|, |\mu_{12}-\mu_{22}|, |\mu_{13}-\mu_{23}|, |\mu_{14}-\mu_{24}|, |\mu_{15}-\mu_{25}|\}}$$

$$= \frac{\max\{0.0128688, 0.0081933\}}{\max\{0.0128688, 0.0627171, 0.0081933, 0.0236008, 0.0070531\}} = 0.2051888 \tag{37}$$

$$DCI = \begin{pmatrix} - & 0.2051888 & 1 & 1 & 0 \\ 1 & - & 1 & 1 & 0.3621465 \\ 0.1728904 & 0.1487863 & - & 0 & 0 \\ 0.1728904 & 0.1487863 & 1 & - & 0 \\ 1 & 1 & 1 & 1 & - \end{pmatrix} \tag{38}$$

Concordance HF matrix has been determined via Eqs. (28) and (29) as follows (Step 9):

$$\bar{I} = \max_{i,j}\left(\mu_{r_{ij}^{\omega}}\right) (\forall i = 1,2,3,4,5; j = 1,2,3,4,5)$$

$$= max \begin{Bmatrix} - & 0.5346896 & 0.3520142 & 0.4404929 & 1 \\ 0.4653104 & - & 0.3520142 & 0.4653104 & 0.6573398 \\ 0.6479858 & 0.6479858 & - & 1 & 1 \\ 0.5595071 & 0.5346896 & 0 & - & 1 \\ 0 & 0.3426602 & 0 & 0 & - \end{Bmatrix} = 1 \tag{39}$$

The following holds for F:

$$F = \begin{pmatrix} - & 0 & 0 & 0 & 1 \\ 0 & - & 0 & 0 & 0 \\ 0 & 0 & - & 1 & 1 \\ 0 & 0 & 0 & - & 1 \\ 0 & 0 & 0 & 0 & - \end{pmatrix}, \tag{40}$$

Discordance HF matrix has been determined via Eqs. (30)-(32) as follows (Step 10):

$$\bar{\beta} = \sum_{e=1}^{5}\sum_{f=1}^{5}\frac{\beta_{ef}}{5(5-1)}$$

$$= \frac{(0.2051888 + 1 + 1 + 1 + 1 + 1 + 0.3621465 + 0.1728904 + 0.1487863 + 0.1728904 + 0.1487863 + 1 + 1 + 1 + 1 + 1)}{(5 \times 4)} \tag{41}$$

$$= 0.5605344$$

Matrix G is obtained by:

$$G = \begin{pmatrix} - & 1 & 0 & 0 & 1 \\ 0 & - & 0 & 0 & 1 \\ 1 & 1 & - & 1 & 1 \\ 1 & 1 & 0 & - & 1 \\ 0 & 0 & 0 & 0 & - \end{pmatrix}. \tag{42}$$

Finally, the HF effective outranking matrix is found via Eq. (33) (Step 11).

$$H = F \cdot G = \begin{pmatrix} - & 0 & 0 & 0 & 1 \\ 0 & - & 0 & 0 & 0 \\ 0 & 0 & - & 1 & 1 \\ 0 & 0 & 0 & - & 1 \\ 0 & 0 & 0 & 0 & - \end{pmatrix} \cdot \begin{pmatrix} - & 1 & 0 & 0 & 1 \\ 0 & - & 0 & 0 & 1 \\ 1 & 1 & - & 1 & 1 \\ 1 & 1 & 0 & - & 1 \\ 0 & 0 & 0 & 0 & - \end{pmatrix} = \begin{pmatrix} - & 0 & 0 & 0 & 1 \\ 0 & - & 0 & 0 & 0 \\ 0 & 0 & - & 1 & 1 \\ 0 & 0 & 0 & - & 1 \\ 0 & 0 & 0 & 0 & - \end{pmatrix} \quad (43)$$

According to the H, the lesser attractive options are specified and removed (Step 12). A_5 is dominated by A_1, A_2, A_3 and A_4. In addition, A_4 is dominated by A_3. The rankings of the proposed method along with other two fuzzy methods, namely IF-TOPSIS and IF-ELECTRE, are given in Table 11. Problem graph is demonstarted in Fig. 4., and four relationships between A_1, A_2, A_3, A_4 and A_5 exist (Step 13).

Table 11
Results of proposed HF-ELECTRE method and three recent fuzzy decision-making methods

Alternatives	Incomparable alternatives	Submissive alternatives	Ranking by proposed HF-ELECTRE	Ranking by Roa (2007) method	Ranking by the IF-TOPSIS	Ranking by the IF-ELECTRE
A_1	A_2	A_5	2	2	3	2
A_2	A_1,A_3,A_4,A_5	-	3	3	4	3
A_3	A_1,A_2	A_4,A_5	1	1	1	1
A_4	A_1,A_2	A_5	4	4	2	4
A_5	A_2	-	5	5	5	5

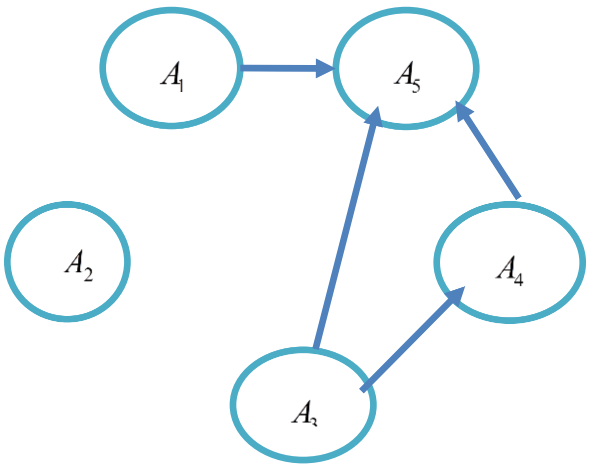

Fig. 4. Decision graph for the practical example

The results and comparison with the studies of Roa (2007) and IF-ELECTRE method are depicted in table 9. FMSs are well-known issues in the literature of manufacturing problems. In this respect, one of the main differences between the proposed approach and these methods is modeling of uncertainty. The methods are developed under fuzzy environments; however, the HFS versus the IFS could lead to more flexibility in computations and appropriate solutions. Also, the preferences DMs' opinions are considered in the procedure of the evaluation method based on their risk preferences. In this case, three levels of DMs' risk preferences are regarded as pessimist, moderate, and optimist. In addition, some operations are extended to develop a new uncertain version of ELECTRE method which have not been proposed previously. To address this, each DM's importance is determined by a new relation (Step 2) and considered in the procedure of DMs' judgments aggregation (i.e., about the rating of HF decision matrix and criteria weights) (Steps 3 and 4). Moreover, some new relations are defined to establish the discordance HF decision matrix (Step 8) and effective discordance HF decision matrix (Step 10).

5. Concluding Remarks and Future Researches

HFSs are known as suitable tools to handle imprecise information by allowing a group of DMs to define their precedence by some membership degrees for a possible candidate under a set to reduce the errors. Consequently, this extension of fuzzy sets theory could help the DMs to handle complex decisions by considering the membership function to represent the satisfaction degrees. A novel ELECTRE method was tailored based on HF information regarding the risk preferences of the DMs to solve the MCGDM problems. In this respect, the assessment of each candidate among the conflicting criteria and the weight of each criterion were defined by linguistic variables, which were converted into HFSs. Also, the DMs' weights were computed and applied in the process of the proposed HF-ELECTRE method to decrease the judgments' errors. HFWA operator has been used based on DMs' weights to aggregate opinions of the DMs about the rating of candidates under conflicted criteria and evaluating the relative significance of factors. A new discordance HF index has been extended under HF environments. Finally, a practical example in FMSs and a comparative analysis were prepared to display the practicality of proposed HF-ELECTRE method. The comparative analysis showed that the procedure of proposed method was similar to the IF-ELECTRE because of closely related concepts of the IFSs and HFSs. For future research, the proposed approach can be developed to enhance the method by providing interval based membership values for an element under a set.

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