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AN INTEGRATED HFLTS AND HF-TOPSIS APPROACH FOR WIND TURBINE SITE SELECTION PROBLEM

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ABSTRACT

A vast majority of decision problems consist of conflicting criteria and non-dominating alternatives. To solve such kinds of decision problems, multiple criteria decision-making (MCDM) techniques have widely been used in many fields, so far. Moreover, hybrid decision-making approaches are also developed by the integration of different MCDM techniques in order to utilize the benefits of those methods. The main aim in this study is to introduce an integrated decision-making method for decision problems under uncertainty. Within this approach, Hesitant Fuzzy Linguistic Term Sets (HFLTS) and Hesitant Fuzzy Technique for Order Preference by Similarity to Ideal Solution (HF-TOPSIS) are integrated. The HFLTS method is used for the determination of criteria weights and decision alternatives are evaluated by using the HF-TOPSIS technique. The applicability of the method is demonstrated on an application of the wind turbine location problem.

Keywords: Hesitant fuzzy sets, HFLTS, TOPSIS, Site selection, Wind energy.

1 INTRODUCTION

Decision making is defined as determination of the most appropriate alternative among all the determined alternatives for achieving a goal [1]. When decision makers face with decision problems with a number of criteria that conflicting with each other and a number of

alternatives, MCDM approaches are utilized for obtaining the solution [2]. MCDM is an evaluation process of alternatives for selection [3], ranking [4], classification [5], prioritization [6] or elimination [7] according to criteria that are usually weighted, conflicting with each other, in different measurement units and some of them take quantitative values [8].

There are hybrid methods that are developed for MCDM problems, in which different methods are used for determining criteria weights and evaluating alternatives. Strengths of different methods are integrated in hybrid methods, so weakness of using only one of these methods is eliminated and making rights decisions becomes easier for decision makers.

The most common approaches in the literature for determining criteria weights are AHP (Analytic Hierarchy Process) [9] and ANP (Analytic Network Process) [10] methods, which are developed by Thomas L. Saaty. These approaches provide evaluation of criteria and alternatives in terms of obtained importance degrees by using pairwise comparisons of criteria and alternatives according to the 1 – 9 importance scale. Although AHP assumes the decision problem is in a hierarchical structure and there is no interaction between criteria, ANP also takes interactions between criteria into account [11].

The number of methods in evaluation of alternatives is more. Some of these methods are TOPSIS, PROMETHEE (Preference Ranking Organization Method for Enrichment Evaluation), and ELECTRE (ELimination and Choice Expressing REality). These methods are used in many applications such as TOPSIS is used for mobile phone selection [12] and green supplier selection [13], PROMETHEE is used for ecotourism site evaluation [14] and analysis of countries [15], ELECTRE is used for policy evaluation [16] and layout design evaluation [17]. Also, there are different methods such as VIKOR (Vlsekriterijumska Optimizacija I KOmpromisno Resenje), ORESTE (French organization Rangement Et Synthese De Ronnees. Relationnelles'), MABAC (Multi-Attributive Border Approximation area Comparison), EDAS (Evaluation based on Distance from Average Solution), etc. Some applications of these methods can be in the studies [18-21].

Because of the requirement of making pairwise comparisons in AHP and ANP, the idea of using different methods is beneficial for alternatives evaluation. Similarly, alternative evaluation methods like TOPSIS, PROMETHEE, etc. requires criteria weights given by the decision maker. Therefore, analytic approaches for calculating criteria weights are required. Hybrid decision making approaches eliminate such disadvantages of MCDM methods.

Fuzzy logic is one of the common approaches to cope with uncertainties in problem data or existence of linguistic expressions for criteria and alternatives evaluation. Subjective personal evaluations or values that cannot be known exactly are expressed by using fuzzy logic [22]. Reader may refer to the review study of Hindi et al. [23] for the recent developments in fuzzy multi-criteria decision-making applications. Among various types of fuzzy sets, hesitant fuzzy sets (HFS) [24] are appropriate for dealing with hesitant feelings of decision makers at evaluation stage of criteria and alternatives.

The main aim of this study is to introduce a hybrid group MCDM method for decision problems under hesitant fuzzy environment. Within this method, group decision making (GDM) method based on HFLTS, which is proposed by Yavuz et al. [25] is integrated with hesitant fuzzy extension of TOPSIS [26]. Criteria weights are calculated using HFLTS based GDM method and decision alternatives are evaluated using HF-TOPSIS. An application on determination of the location of wind turbines is presented with a sensitivity analysis on criteria weight changes.

The main contributions of this study can be listed as follows:

- An integrated MCDM method under hesitant fuzzy uncertainty is introduced.
- An application of wind turbine location is presented.
- A sensitivity analysis for criteria weight changes is performed.

The remainder of the paper is as follows: in the 2nd section explanation of the integrated MCDM method is given. Next, the detailed information for wind turbine location application is presented in the 3rd section. Then, the sensitivity analysis results are explained in the 4th section. Finally, conclusions are made in the 5th part by sharing further research suggestions.

2 METHODOLOGY

MCDM problems are decision problems which consist multiple alternatives and multiple conflicting criteria [27]. These problems are generally expressed in a hierarchical or a network representation, by the way smaller sub-problems of the main decision problem are identified. Hierarchical or network representations make it easier for decision makers to handle complex decision problems [28].

For uncertain cases in decision analysis, it is very common to use fuzzy logic. Expression of uncertain elements that have ambiguous values or defined by linguistic terms in

a decision problem becomes easier by utilization of fuzzy logic. While mathematical operations are not possible for linguistic variables, numerical equivalent of these terms can be defined by fuzzy sets and these equivalents can be used in mathematical operations. Furthermore, uncertainties in parameter values can be modeled by fuzzy numbers. There is a wide range of applications of fuzzy extension of MCDM approaches like intuitionistic [29], q-rung orthopair [30], spherical [31], Pythagorean [32], decomposed [33] and hesitant fuzzy sets [34].

Hybrid MCDM approaches combining TOPSIS are very common in the literature. In general, weighting approaches are integrated with TOPSIS, in order to utilize weight values at the obtaining weighted normalized decision matrix step. In a similar manner, this study introduces a HFLTS based GDM [25] and HF-TOPSIS [26] integrated method. The method allows decision makers to determine the weight values for evaluation criteria and the order preference of decision alternatives under hesitant fuzzy uncertainty. Decision making framework within the integrated method is presented in Figure 1 along with a detailed explanation as follows:

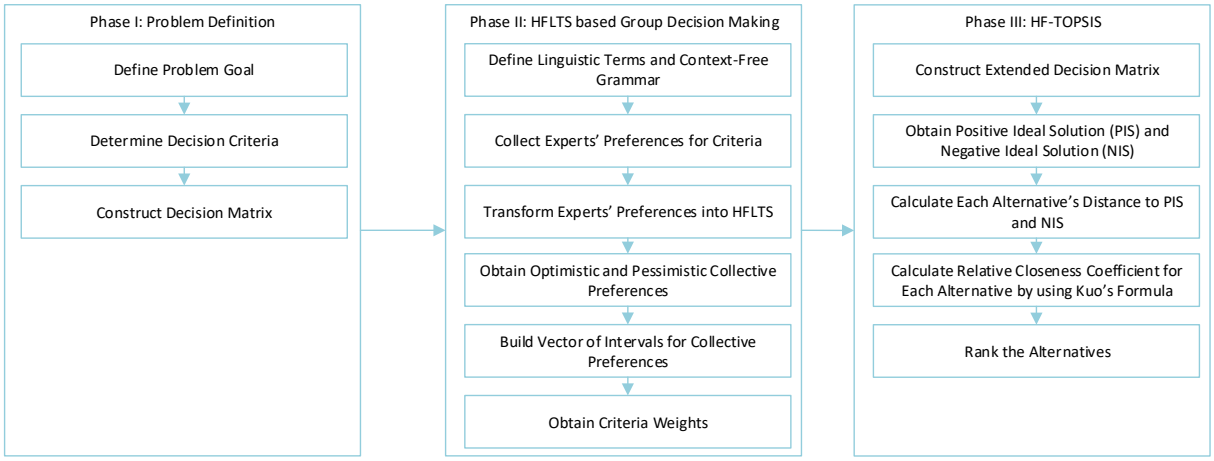


Figure 1. Flowchart of the decision-making approach.

2.1 Problem Definition

In this phase, decision problem definition is made. Problem definition consists the determination of the goal of the decision problem, effective evaluation criteria on the decision and alternatives for evaluation. Decision elements are represented in a hierarchical structure in this step and decision matrix of problem is constructed by asking experts' opinions.

2.2 HFLTS based Group Decision Making

The first study in the literature introducing the HFLTS concept for decision analysis is written by Rodriguez et al. [35]. Later, HFLTS concept is extended into GDM problems by Yavuz et al. [25] with their approach based on pairwise comparisons. Steps in this phase of the decision making procedure are as follows:

Step 1: Definition of linguistic terms and context – free grammar:

Pairwise comparisons are made in this method by using a context-free grammar. Context-free grammar explains the structure of linguistic expressions, in which linguistic terms are combined with relation terms. A seven-point linguistic scale is given in Table 1 along with their numeric equivalents that represents the linguistic terms starting from no importance to absolute importance.

Table 1. Linguistic terms with corresponding numeric values.

Numeric Value	Linguistic Term
0	no importance (n)
1	very little importance (vl)
2	little importance (l)
3	moderate importance (m)
4	high importance (h)
5	very high importance (vh)
6	absolute importance (a)

Linguistic terms are linked in context-free grammar by using relation terms. Hesitant feelings of experts can be expressed in this way. Expressions of “at least”, “at most”, “between”, “greater than”, “is” and “lower than” are the elements of relation terms set. An expression containing “at least” relation term indicates that the decision maker is hesitant about choosing a linguistic term among the terms with a numeric equivalent starting from he or she said to absolute importance. If a decision maker expresses his/her feeling using “at least very high”, it should be understood that the decision maker hesitant about saying very high and absolute importance terms. On the counter, “at most” expresses the hesitant situations from no importance to the indicated linguistic term. “between” relation term is used with two linguistic variables. A decision maker using “between” should be considered to be hesitant about defining his/her feelings with any of the linguistic terms between the first and the second variable in his/her expression. Moreover, “greater than” and “less than” are used for hesitant situations that state the importance is between the next (previous) term in the 7-point linguistic scale and absolute (no) importance. For certain evaluations “is” relation term is used.

Step 2: Collecting expert preferences for criteria:

Pairwise comparison matrices of criteria and sub-criteria evaluation using context-free grammar sentences are constructed here. Pairwise comparisons are collected for individual evaluation of each expert.

Step 3: Transformation of expert preferences into HFLTS:

Individual pairwise comparison matrices constructed in Step 2 using context-free grammar rules are transformed into HFLTSs. After this transformation, it becomes possible to aggregate expert preferences. Aggregated preferences are used in criteria weight calculations. According to the information given in Step 1, context-free grammar sentences are transformed into intervals that shows the terms with the lowest and greatest importance degree in each sentence.

Step 4: Obtaining pessimistic and optimistic collective preferences:

HFLTSs represented as intervals of linguistic terms are aggregated by using an appropriate operator. In this method, arithmetic mean operator is used to perform aggregation of HFLTS representation of expert opinions. In aggregated HFLTSs, lower and upper bound terms correspond to the pessimistic and optimistic collective preferences, respectively.

Step 5: Building the vector of intervals for collective preferences:

Numerical equivalents of pessimistic and optimistic collective preferences are shown as the vector of intervals.

Step 6: Obtaining priority values:

Midpoint of intervals are calculated and normalized value for each midpoint represents the corresponding criteria weight.

2.3 HF-TOPSIS

TOPSIS is one of the most known methods of MCDM literature and it was firstly introduced by Hwang and Yoon [36]. The method is based on the idea of finding the most appropriate alternative that has the least distance to the ideal solution and the most distance to the anti-ideal solution. In 2013, Xu and Zhang [26] extended the method into hesitant fuzzy uncertain environments. Within this extension, a group of experts make assessment on alternatives in views of each criterion assigning values in the [0, 1] interval. It can be also expressed that the experts are asked to evaluate how higher value each alternative can have.

Difference of expert evaluations are defined as the hesitant uncertainty here; if two or more experts assess an alternative in terms of the same criteria with different values, then different assessment values are written as the elements of hesitant fuzzy set to the decision matrix. If they use the same value, it is written once. So, elements of the decision matrix may be in different lengths.

The calculations for the method require all elements in the same column of the decision matrix at the same length. In such situations, elements with smaller lengths are extended by inserting the minimal component of the hesitant fuzzy set. In other words, hesitant fuzzy sets with smaller length are extended in a pessimistic manner. At the end of extension process, extended decision matrix is obtained.

When, extended decision matrix is obtained, calculations for alternative evaluation can start. Since we use a [0,1] interval for alternative evaluation, no normalization is needed. Ideal and anti-ideal ideal solutions can be directly found. In the study that the method introduced [26], ideal and anti-ideal solution definitions are made by Xu and Zhang for benefit type criteria as follows:

$$\begin{aligned} A^{+} &= \left\{ x_j, \max_i \left\langle h_{ij}^{\sigma(\lambda)} \right\rangle \mid j = 1,2,\ldots,n \right\} \\ A^{-} &= \left\{ x_j, \min_i \left\langle h_{ij}^{\sigma(\lambda)} \right\rangle \mid j = 1,2,\ldots,n \right\} \end{aligned} \tag{1}$$

Similarly, we can define the ideal and anti-ideal solutions for cost type criteria, as follows:

$$\begin{aligned} A^{+} &= \left\{ x_j, \min_i \left\langle h_{ij}^{\sigma(\lambda)} \right\rangle \mid j = 1,2,\ldots,n \right\} \\ A^{-} &= \left\{ x_j, \max_i \left\langle h_{ij}^{\sigma(\lambda)} \right\rangle \mid j = 1,2,\ldots,n \right\} \end{aligned} \tag{2}$$

After determination of ideal and anti-ideal solutions, distance of alternatives to these solutions must be calculated. In the original form of TOPSIS [36], distances are calculated by using Euclidian distance measure. Euclidian distance measure for hesitant fuzzy environments was proposed by Xu and Xia [37] as follows:

$$d_i^{+} = \sum_{j=1}^{n} d\left(h_{ij}, h_j^{+}\right) w_j = \sum_{j=1}^{n} w_j \sqrt{\frac{1}{l} \sum_{\lambda=1}^{l} \left| h_{ij}^{\sigma(\lambda)} - \left(h_j^{\sigma(\lambda)} \right)^{+} \right|^2} \tag{3}$$

$$d_i^- = \sum_{j=1}^{n} d\left(h_{ij}, h_j^-\right) w_j = \sum_{j=1}^{n} w_j \sqrt{\frac{1}{l}\sum_{\lambda=1}^{l}\left|h_{ij}^{\sigma(\lambda)} - \left(h_j^{\sigma(\lambda)}\right)^-\right|^2} \tag{4}$$

Final step of the method is the calculation of relative closeness coefficient. Ranking of alternatives is determined using this measure and is calculated as follows:

$$C_i = \frac{d_i^-}{d_i^+ + d_i^-} \tag{5}$$

Since the most appropriate alternative is defined as the alternative with the greatest distance from the anti-ideal solution, the alternative with the greater value of relative closeness measure is the most appropriate one. Descending order of C_i values gives the ranking of alternatives.

3 APPLICATION OF THE WIND TURBINE LOCATION PROBLEM

Because of growing population and industrialization, energy demand has increased significantly and new energy generation sources have been tried to be found for sustainable energy supply against the increasing demand. Generation from renewable sources is considered as a possible supply source for this issue. Renewable energy sources may provide energy at low cost and in an environmentally friendly manner. Conversely, using renewable energy sources in generating energy brings some important challenges for consideration by decision makers. Besides its economic and environmental advantages, developing an energy system with renewable sources brings out some important decision problems for decision makers. For example, site selection for energy generation plant is one of the most important strategic decisions related to renewable energy systems. Site selection requires evaluation of a finite number of decision options in views of conflicting decision criteria, otherwise a wrong decision may cause waste of enterprise resources. In order to support site selection decision for renewable energy systems, the integrated decision-making approach introduced in the 2nd section can be used.

In this section, an application of wind turbine location problem is presented. To find the most appropriate location among a set of alternatives under consideration of several criteria simultaneously, the integrated HFLTS based GDM and HF-TOPSIS approach is utilized. Application steps are given as follows:

3.1 Phase I: Problem Definition

Determining the site of a wind turbine to be installed is the decision goal for the problem. There are several applications of wind turbine site selection in the literature, so far. Researchers used too many different MCDM techniques to determine the best location for wind turbines. MCDM techniques taken into account are ELECTRE II [38], COPRAS-F [39], Fuzzy VIKOR – AHP [40], Fuzzy AHP [41], Multi Attribute Choquet Integral [42], FANP – BOCR [43], Ideal Matter – Element Extension Method [44], Multi Criteria Spatial Methodology [45] and GIS – AHP [46]. Various criteria of site selection are taken into account in these studies. Evaluation criteria for site selection are presented in Table 2. Effective factors on site selection decision in this application were determined by considering practical issues and conditions regulated by laws in Turkey and the findings of literature review. The last column of Table 2 with asterisks * presents the criteria taken into account in this study.

Table 2. Site selection criteria for wind turbines in the literature.

Criteria	Sub-criteria	[39]	[40]	[41]	[42]	[45]	[46]	*
Environmental	Noise		+	+		+	+	+
	Bird habitats						+	+
	Impact on ecosystems		+	+		+		+
	Safety and aesthetics for airports						+	+
	Visual impact		+	+		+		
	Distance from natural reserves	+	+				+	+
	Distance to road							
	Distance to transmission lines				+			
Technical	Land topography and geology	+		+	+	+		+
	Average air density	+						
	Average wind speed	+		+	+		+	+
	Energy production capacity		+				+	
	Wind power density				+			+
Economic	Operation and maintenance cost	+	+	+				+
	Land cost	+		+	+			+
	Investment cost		+	+				
	Incentives		+					+
Social	Availability of land	+						+
	Availability of labor	+						+
	Distance from residential area	+		+	+			+
	Social acceptability		+	+				+
	Land use			+				
	Protected and cultural heritage						+	+

Main and sub-criteria for site selection are presented in Figure 2 and explained as follows:

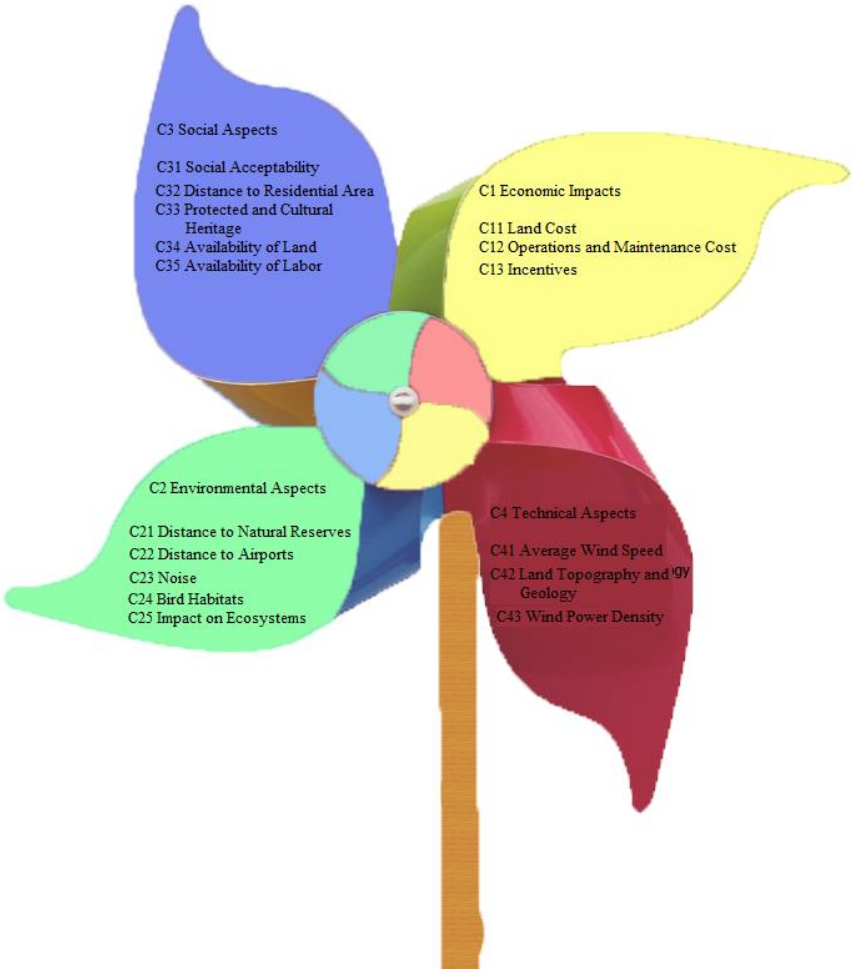


Figure 2. Flowchart of the decision-making approach.

Alternative scores with respect to decision criteria are presented in the decision matrix. Opinions of three experts which show how the alternatives have higher values in terms of each criterion in the interval [0, 1] were collected to form the decision matrix. Differing from membership description in many fuzzy applications, evaluation scores in this study represents the higher score value of the alternative. That means an evaluation close to zero shows a smaller score for the corresponding alternative and a value close to one shows a greater score value in views of the criterion of concern. Due to the insignificance of recurrent evaluation values in decision matrix, same evaluation score of experts were written only once in the decision matrix. Table 3 shows the evaluation of experts on alternatives:

Table 3. Decision matrix of the problem.

	C11	C12	C13	C21
A1	{0.9, 0.4, 0.2}	{0.3, 0.0}	{1.0, 0.3, 0.0}	{0.8, 0.1}
A2	{0.9, 0.8, 0.5}	{1.0, 0.3, 0.2}	{0.9, 0.8, 0.6}	{0.6, 0.5, 0.4}
A3	{0.8, 0.4}	{0.8, 0.7, 0.1}	{0.5, 0.3, 0.0}	{0.9, 0.6}
A4	{0.4, 0.2, 0.0}	{0.6, 0.3}	{0.6, 0.4, 0.1}	{0.9, 0.3, 0.2}
A5	{0.8, 0.7, 0.1}	{0.5, 0.4, 0.2}	{0.7, 0.4, 0.3}	{1.0, 0.1, 0.0}
A6	{0.5, 0.0}	{0.9, 0.6, 0.1}	{0.9, 0.5, 0.0}	{0.8, 0.5, 0.4}
	C22	**C23**	**C24**	**C25**
A1	{1.0, 0.9, 0.0}	{0.8, 0.6}	{0.8, 0.7, 0.0}	{0.9, 0.4, 0.0}
A2	{0.7, 0.6, 0.5}	{1.0, 0.0}	{0.9, 0.6, 0.2}	{1.0, 0.5, 0.3}
A3	{0.8, 0.2, 0.0}	{0.8, 0.7, 0.5}	{0.6, 0.4, 0.1}	{0.8, 0.6, 0.4}
A4	{0.9, 0.3, 0.2}	{0.9, 0.1}	{0.4, 0.1}	{0.3, 0.2, 0.1}
A5	{0.7, 0.3, 0.0}	{1.0, 0.2, 0.1}	{0.9, 0.7, 0.3}	{0.8, 0.6, 0.3}
A6	{0.9, 0.8}	{0.6, 0.4, 0.0}	{0.8, 0.6, 0.5}	{0.7}
	C31	**C32**	**C33**	**C34**
A1	{0.9, 0.6, 0.5}	{0.7, 0.4, 0.0}	{0.8, 0.6, 0.1}	{0.8, 0.2, 0.0}
A2	{0.5, 0.3, 0.1}	{0.8, 0.7, 0.2}	{0.8, 0.1}	{1.0, 0.9, 0.5}
A3	{0.9, 0.8}	{0.7, 0.5, 0.3}	{0.7, 0.5}	{0.9, 0.4}
A4	{0.7, 0.6, 0.1}	{0.4, 0.3, 0.1}	{1.0, 0.5, 0.2}	{0.9, 0.7, 0.0}
A5	{1.0, 0.7, 0.4}	{1.0, 0.9, 0.6}	{1.0, 0.7, 0.4}	{0.6, 0.3, 0.0}
A6	{0.3, 0.2, 0.0}	{0.7, 0.4}	{0.6, 0.5, 0.4}	{0.8, 0.3, 0.1}
	C35	**C41**	**C42**	**C43**
A1	{0.7, 0.6, 0.3}	{0.9, 0.3, 0.0}	{0.9, 0.7, 0.1}	{0.9, 0.3}
A2	{0.5, 0.4, 0.1}	{0.7, 0.3, 0.2}	{1.0, 0.2, 0.0}	{0.9, 0.8, 0.3}
A3	{0.6, 0.4, 0.0}	{1.0, 0.9, 0.3}	{1.0, 0.6, 0.5}	{0.9, 0.6, 0.3}
A4	{0.4, 0.2, 0.1}	{0.8, 0.7, 0.2}	{0.5, 0.2}	{0.6, 0.5, 0.2}
A5	{0.8, 0.5, 0.3}	{1.0, 0.6, 0.3}	{0.6, 0.2, 0.1}	{0.7, 0.6, 0.2}
A6	{1.0, 0.9, 0.5}	{0.8, 0.2, 0.0}	{0.9, 0.8, 0.6}	{0.8, 0.5, 0.2}

3.2 Phase II: Hesitant Fuzzy Linguistic Terms Set (HFLTS)

Step 1:

In this step, context-free grammar is defined. The seven-point linguistic scale given in Table 1 and relation terms explained in section 2.2 are the elements of context-free grammar.

Step 2:

This step is about collecting experts' opinions to perform pairwise comparisons of criteria. An expert group of three, which contains a researcher on energy systems, a renewable energy systems expert from the Ministry of Energy and Natural Resources of Türkiye, and a technical manager of a private wind turbine manufacturer company were asked to evaluate site selection criteria. Pairwise comparisons for criteria are provided in Table 4.

Table 4. Pairwise comparisons.

Expert		C1	C2	C3	C4
1	**C1**	-	at most h	at least m	lower than m
	C2	at least l	-	between vl and m	is m
	C3	at most m	between m and vh	-	at most l
	C4	greater than m	is m	at least h	`-
2	**C1**	-	is m	at least h	between m and h
	C2	is m	-	lower than h	at most m
	C3	at most l	greater than l	-	lower than m
	C4	between l and m	at least m	greater than m	-
3	**C1**	-	at least h	greater than h	between l and h
	C2	at most l	-	between m and h	between l and m
	C3	lower than l	between l and m	-	is l
	C4	between l and h	between m and h	is h	-

Step 3:

In the third step of the algorithm, data collected from experts in the form of context-free grammar sentences were converted into discrete sets. The linguistic terms with the lowest and greatest importance in each evaluation were expressed as the lower and upper elements of corresponding HFLTS for the statement and called as HFLTS envelope. HFLTS envelops for criteria evaluation are given in Table 5.

Table 5. HFTLS envelopes for criteria evaluation

Expert		C1	C2	C3	C4
1	**C1**	-	[n,h]	[m,a]	[n,l]
	C2	[l,a]	-	[vl, m]	[m, m]
	C3	[n,m]	[m, vh]	-	[n, l]
	C4	[h, a]	[m, m]	[h, a]	-
2	**C1**	-	[m, m]	[h, a]	[m, h]
	C2	[m, m]	-	[n, m]	[n, m]
	C3	[n, l]	[m, a]	-	[n, l]
	C4	[l, m]	[m, a]	[h, a]	-
3	**C1**	-	[h, a]	[vh, a]	[l, h]
	C2	[n, l]	-	[m, h]	[l, m]
	C3	[n, vl]	[l, m]	-	[l, l]
	C4	[l, h]	[m, h]	[h, h]	-

After obtaining HFLTS envelopes, optimistic and pessimistic collective preferences were calculated by the aggregation operator. Arithmetic mean operator was used for aggregation of HFLTS envelopes. Aggregated hesitant fuzzy elements are calculated by using the following

formula where s_i denotes the linguistic term and α_i is the corresponding numeric equivalent to the linguistic term:

$$\bar{x} = \Delta\left(\frac{1}{n}\sum_{i=1}^{n}\Delta^{-1}(s_i,\alpha_i)\right) = \Delta\left(\frac{1}{n}\sum_{i=1}^{n}\beta_i\right) \tag{6}$$

Pessimistic (H_{s^+}) and optimistic collective preferences (H_{s^-}) were defined according to the given formula:

$$\begin{aligned} H_{s^+} &= \max(s_i) = s_j, \quad s_i \in H_s \text{ and } s_i \le s_j \ \forall i; \\ H_{s^-} &= \min(s_i) = s_j, \quad s_i \in H_s \text{ and } s_j \le s_i \ \forall i \end{aligned} \tag{7}$$

Optimistic and pessimistic collective preferences for evaluation of main criteria were presented in Table 6, as follows:

Table 6. Pessimistic and optimistic collective preferences for main criteria.

Optimistic Preferences					**Pessimistic Preferences**				
	C1	**C2**	**C3**	**C4**		**C1**	**C2**	**C3**	**C4**
C1	-	4.33	6.00	3.33	**C1**	-	2.33	4.00	1.00
C2	3.67	-	3.33	3.00	**C2**	1.67	-	1.33	1.67
C3	2.00	4.67	-	2.00	**C3**	0.00	2.67	-	0.67
C4	4.33	4.33	5.33	-	**C4**	2.67	3.00	4.00	-

After the determination of pessimistic and optimistic collective preferences, vector of intervals was calculated by using collective preference values. This operation helps in converting the linguistic values into numeric values denoted as interval utilities within the decision process. Midpoint of each element in interval utilities vector was normalized in order to obtain criteria weights. Results of these calculations summarized in Table 7, as follows:

Table 7. Calculation of criteria weights for main criteria

Criteria	**Linguistic Intervals**	**Interval utilities**	**Midpoints**	**Weights**
C1	[(l,.44); (vh,-.44)]	[2.44, 4.56]	3.50	0.294
C2	[(l,-.44); (m, .33)]	[1.56, 3.33]	2.44	0.206
C3	[(vl, .11); (m, -.11)]	[1.11, 2.89]	2.00	0.168
C4	[(m, .22); (vh, -.33)]	[3.22, 4.67]	3.94	0.332

Importance of evaluation criteria can be understood from criteria weights. A criterion with a greater weighting value is considered to be more important than a criterion with a lower value. Based on these results, it can be said that technical aspects are the most important factor

for choosing a location for a wind turbine. Technical factors are followed by economic, environmental and social criteria, respectively. Similar evaluations and calculations were also made for sub-criteria. Since sharing details for sub-criteria evaluation would be limited in comparison to its benefits, only the calculation results were provided in Table 8, as follows:

Table 8. Main and sub-criteria weights.

Criteria	Sub-criteria	Weight	Local Weight	Global Weight
C1		0.294		
	C11		0.306	0.090
	C12		0.296	0.087
	C13		0.398	0.117
C2		0.206		
	C21		0.161	0.033
	C22		0.114	0.023
	C23		0.264	0.054
	C24		0.233	0.048
	C25		0.228	0.047
C3		0.168		
	C31		0.214	0.036
	C32		0.108	0.018
	C33		0.194	0.033
	C34		0.283	0.048
	C35		0.200	0.034
C4		0.332		
	C41		0.374	0.124
	C42		0.243	0.081
	C43		0.383	0.127

The results of the weighting calculations show that the most important aspect of the choice of the wind turbine site is being affected by wind power density (C43) from technical aspects with a weight value 0.127. C43 is followed by average wind speed (C41) from technical aspects (C42) and incentives (C13) with weighting values of 0.124 and 0.117, respectively. For decision makers in wind turbine installment projects, it can be strongly recommended based on these results that they should consider placement of wind turbines to sites with a good wind power density, a higher measurement data of average wind speed and places with priority in incentives policies of governments.

3.3 Phase III: HF-TOPSIS

As it is expressed in section 3.1, decision matrix of alternative evaluation has elements with various lengths. Some elements contain three different evaluations, while some has one or

two evaluation scores. To perform calculations with HF-TOPSIS method, it is required for the elements in the same column of the decision matrix to be at the same length. To do so, elements at smaller length must be extended to the length of the element with highest length by inserting the smallest evaluation score in it. This operation is defined as extension according to the pessimistic case. Extended decision matrix for the application is given in Table 9.

Table 9. Extended decision matrix of the problem.

	C11	**C12**	**C13**	**C21**
A1	{0.9, 0.4, 0.2}	{0.3, 0.0, 0.0}	{1.0, 0.3, 0.0}	{0.8, 0.1}
A2	{0.9, 0.8, 0.5}	{1.0, 0.3, 0.2}	{0.9, 0.8, 0.6}	{0.6, 0.5, 0.4}
A3	{0.8, 0.4, 0.4}	{0.8, 0.7, 0.1}	{0.5, 0.3, 0.0}	{0.9, 0.6, 0.6}
A4	{0.4, 0.2, 0.0}	{0.6, 0.3, 0.3}	{0.6, 0.4, 0.1}	{0.9, 0.3, 0.2}
A5	{0.8, 0.7, 0.1}	{0.5, 0.4, 0.2}	{0.7, 0.4, 0.3}	{1.0, 0.1, 0.0}
A6	{0.5, 0.0, 0.0}	{0.9, 0.6, 0.1}	{0.9, 0.5, 0.0}	{0.8, 0.5, 0.4}
	C22	**C23**	**C24**	**C25**
A1	{1.0, 0.9, 0.0}	{0.8, 0.6, 0.6}	{0.8, 0.7, 0.0}	{0.9, 0.4, 0.0}
A2	{0.7, 0.6, 0.5}	{1.0, 0.0, 0.0}	{0.9, 0.6, 0.2}	{1.0, 0.5, 0.3}
A3	{0.8, 0.2, 0.0}	{0.8, 0.7, 0.5}	{0.6, 0.4, 0.1}	{0.8, 0.6, 0.4}
A4	{0.9, 0.3, 0.2}	{0.9, 0.1, 0.1}	{0.4, 0.1, 0.1}	{0.3, 0.2, 0.1}
A5	{0.7, 0.3, 0.0}	{1.0, 0.2, 0.1}	{0.9, 0.7, 0.3}	{0.8, 0.6, 0.3}
A6	{0.9, 0.8}	{0.6, 0.4, 0.0}	{0.8, 0.6, 0.5}	{0.7, 0.7, 0.7}
	C31	**C32**	**C33**	**C34**
A1	{0.9, 0.6, 0.5}	{0.7, 0.4, 0.0}	{0.8, 0.6, 0.1}	{0.8, 0.2, 0.0}
A2	{0.5, 0.3, 0.1}	{0.8, 0.7, 0.2}	{0.8, 0.1, 0.1}	{1.0, 0.9, 0.5}
A3	{0.9, 0.8, 0.8}	{0.7, 0.5, 0.3}	{0.7, 0.5, 0.5}	{0.9, 0.4, 0.4}
A4	{0.7, 0.6, 0.1}	{0.4, 0.3, 0.1}	{1.0, 0.5, 0.2}	{0.9, 0.7, 0.0}
A5	{1.0, 0.7, 0.4}	{1.0, 0.9, 0.6}	{1.0, 0.7, 0.4}	{0.6, 0.3, 0.0}
A6	{0.3, 0.2, 0.0}	{0.7, 0.4, 0.4}	{0.6, 0.5, 0.4}	{0.8, 0.3, 0.1}
	C35	**C41**	**C42**	**C43**
A1	{0.7, 0.6, 0.3}	{0.9, 0.3, 0.0}	{0.9, 0.7, 0.1}	{0.9, 0.3, 0.3}
A2	{0.5, 0.4, 0.1}	{0.7, 0.3, 0.2}	{1.0, 0.2, 0.0}	{0.9, 0.8, 0.3}
A3	{0.6, 0.4, 0.0}	{1.0, 0.9, 0.3}	{1.0, 0.6, 0.5}	{0.9, 0.6, 0.3}
A4	{0.4, 0.2, 0.1}	{0.8, 0.7, 0.2}	{0.5, 0.2, 0.2}	{0.6, 0.5, 0.2}
A5	{0.8, 0.5, 0.3}	{1.0, 0.6, 0.3}	{0.6, 0.2, 0.1}	{0.7, 0.6, 0.2}
A6	{1.0, 0.9, 0.5}	{0.8, 0.2, 0.0}	{0.9, 0.8, 0.6}	{0.8, 0.5, 0.2}

Based on the extended form of evaluation scores and the type of evaluation criteria (benefit (B) or cost (C) type), ideal and anti-ideal solutions can be determined using Eq. (1) and (2). Ideal and anti-ideal solutions are presented in Table 10.

By using Eq. (3), (4) and (5) and the data in Table 9 and Table 10, it is possible to calculate distance of each alternative to ideal and anti-ideal solutions and relative closeness coefficient. Calculation results for d_i^+, d_i^- and C_i are presented in Table 11, as follows:

Table 10. Ideal and anti-ideal solutions.

	C11 (C)	C12 (C)	C13 (B)	C21 (B)
A^+	{0.4, 0.0, 0.0}	{0.3, 0.0, 0.0}	{1.0, 0.8, 0.6}	{1.0, 0.6, 0.6}
A^-	{0.9, 0.8, 0.5}	{1.0, 0.7, 0.3}	{0.5, 0.3, 0.0}	{0.6, 0.1 0.0}
	C22 (B)	**C23 (C)**	**C24 (B)**	**C25 (C)**
A^+	{1.0, 0.9, 0.8}	{0.6, 0.0, 0.0}	{0.9, 0.7, 0.5}	{0.3, 0.2, 0.0}
A^-	{0.7, 0.2, 0.0}	{1.0, 0.7, 0.5}	{0.4, 0.1, 0.0}	{1.0, 0.7, 0.7}
	C31 (B)	**C32 (B)**	**C33 (C)**	**C34 (B)**
A^+	{1.0, 0.8, 0.8}	{1.0, 0.9, 0.6}	{0.6, 0.1, 0.1}	{1.0, 0.9, 0.5}
A^-	{0.3, 0.2, 0.0}	{0.4, 0.3, 0.0}	{1.0, 0.7, 0.5}	{0.6, 0.2, 0.0}
	C35 (B)	**C41 (B)**	**C42 (B)**	**C43 (B)**
A^+	{1.0, 0.9, 0.5}	{1.0, 0.9, 0.3}	{1.0, 0.8, 0.6}	{0.9, 0.8, 0.3}
A^-	{0.4, 0.2, 0.0}	{0.7, 0.2, 0.0}	{0.5, 0.2, 0.0}	{0.6, 0.3, 0.0}

Table 11. Distance to ideal and anti-ideal solutions, relative closeness coefficient values and ranking.

	d_i^+	d_i^-	C_i	Rank
A1	0.3332	0.3007	0.474	3
A2	0.2946	0.2980	0.503	1
A3	0.2971	0.2653	0.472	4
A4	0.3129	0.2553	0.449	6
A5	0.3159	0.2598	0.451	5
A6	0.2911	0.2866	0.496	2

According to the TOPSIS method, the most appropriate alternative is the farthest from the anti-ideal solution. Therefore, the greatest value of relative closeness coefficient represents the best alternative. Based on this information and the results given in Table 11, it can be concluded that the most appropriate site for the wind turbine is A2. Full ranking of alternative sites is found as A2 > A6 > A1 > A3 > A5 > A4. While there are better alternatives than A2 in many evaluation criteria, taking all criteria into account simultaneously make A2 as the best alternative. This is the main benefit of using MCDM approaches in complex strategic decisions.

4 SENSITIVITY ANALYSIS

The main purpose of sensitivity analysis is to see the effect of problem input changes on the outputs. In this section, a sensitivity analysis is presented to see the change of incentives criterion (C13) weight on alternative rankings. Incentives criterion is analyzed, because it is one of the most important criteria in views of investors' assessments. In this study, incentives criterion has the third highest weight value among all 16 evaluation sub-criteria according to experts' aggregated opinions.

For the performed sensitivity analysis in this study, weight of incentives criterion is changed at a number of percent change (*PC*) levels. For each value of *PC*, new weight value of incentives criterion (w_i) is calculated by using Eq. (8) and weight value of other criteria (w_j) were calculated by Eq. (9) [47]:

$$w_i = w_{i0} + w_{i0} \times PC \tag{8}$$

$$w_j = (1 - w_i) \times \frac{(w_{j0})}{(1 - w_{i0})} \tag{9}$$

In order to show an example for new weight value calculation in sensitivity analysis, new weight values of C13 and C11 is calculated for the case $PC = -0.2$ as follows:

$$w_{C_{13}} = w_{C_{13},0} + w_{C_{13},0} \times PC = 0.117 + 0.117 \times (-0.2) = 0.094$$

$$w_{C_{11}} = (1 - w_{C_{13}}) \times \frac{(w_{C_{11},0})}{(1 - w_{C_{13},0})} = (1 - 0.094) \times \frac{(0.090)}{(1 - 0.117)} = 0.092$$

Eight levels of *PC* and the initial weight values were analyzed in the sensitivity analysis. Weight values taken into account in these nine cases were calculated using Eq. (8) and Eq. (9) and are presented in Table 12, as follows:

Table 12. Criteria weights for various levels of PC.

Change	C11	C12	C13	C21	C22	C23	C24
-0.200	0.092	0.089	0.094	0.034	0.024	0.055	0.049
-0.150	0.092	0.089	0.099	0.034	0.023	0.055	0.049
-0.100	0.091	0.088	0.105	0.033	0.023	0.055	0.049
-0.050	0.091	0.088	0.111	0.033	0.023	0.054	0.048
0.000	0.090	0.087	0.117	0.033	0.023	0.054	0.048
0.050	0.089	0.086	0.123	0.033	0.023	0.054	0.048
0.100	0.089	0.086	0.129	0.033	0.023	0.053	0.047
0.150	0.088	0.085	0.135	0.032	0.023	0.053	0.047
0.200	0.088	0.085	0.140	0.032	0.022	0.053	0.047
-0.200	0.037	0.018	0.034	0.049	0.035	0.127	0.083
-0.150	0.037	0.018	0.034	0.049	0.035	0.126	0.083
-0.100	0.036	0.018	0.033	0.049	0.034	0.126	0.082
-0.050	0.036	0.018	0.033	0.048	0.034	0.125	0.082
0.000	0.036	0.018	0.033	0.048	0.034	0.124	0.081
0.050	0.036	0.018	0.033	0.048	0.034	0.123	0.080
0.100	0.036	0.018	0.033	0.047	0.034	0.122	0.080
0.150	0.035	0.018	0.032	0.047	0.033	0.122	0.079
0.200	0.035	0.018	0.032	0.047	0.033	0.121	0.079

It is aimed to analyze the effect of weight change on alternatives ranking. Alternative rankings are obtained for each scenario defined by percent weight change of C13. Ranking of alternatives according to percent weight change of C13 is presented as shown in Figure 3.

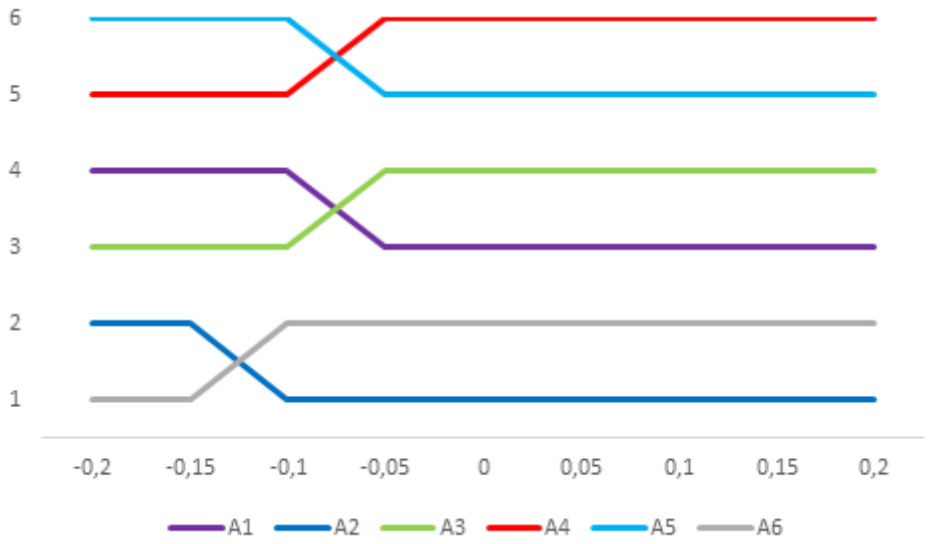


Figure 3. Ranking of alternatives with respect to weight change of C13.

It is clear to see that weight change of C13 causes differences in ranking order. A2 is the best alternative according to the initial weight values. However, a decrease about 13% on criterion weight of C13 doesn't change rank of A2. A decrease about 8% makes A3 as the third option for decision makers and A1 becomes the fourth. Also, A4 and A5 changes their positions in ranking list, when the weight decrease of C13 is about 8%.

As a result of the analysis, it is possible to say that incentives policies for wind energy should have been made carefully. Long term plans for regions that will be supported must have been developed. Change of incentives policies can lead to different investment plans. Building decision models and obtaining criteria weights for particular regions is extremely important.

5 CONCLUSION

Increasing population in the world and rapid industrialization brings the world a major challenge of energy shortages. Today, energy is essential for daily life and sustainable energy supply is extremely important for the sustainability of modern societies. Due to the rapid deterioration of environment, global warming and depletion of fossil fuels, renewable energy becomes the primary solution to the energy challenges. Some types of renewable energy resources are solar, wind, biomass, and wave and tidal energy.

In this study, a strategic decision problem related to wind energy systems is taken into account. Evaluation of the alternative installation sites for a wind turbine is modeled as a MCDM problem. To determine the best location for a wind turbine, a hesitant fuzzy method integrating HFLTS based GDM and HF-TOPSIS is introduced. The reason for modelling the problem with a hesitant fuzzy based method is to cope with hesitant feelings of decision makers in the analysis process.

The introduced method was tested with an application. Evaluation criteria weights were calculated by using HFLTS based GDM and HF-TOPSIS was used to evaluate alternative sites. Because of obtaining a solution easily via this approach, it is possible to consider the method as a reference for decision analysis studies that contain conflicting factors and a finite number of alternatives. By following the same steps, evaluation of decision alternatives in different site selection problems can be made by this method.

This study may be extended by utilizing the help of GIS to take digital map data into account. Similar to the approach in Kabak et al. [48], a pre-evaluation on a digital map can be performed to determine a small number of locations firstly. Then, the final evaluation can be performed by HF-TOPSIS method. By the way, a continuous solution space can be considered in the site selection analysis under hesitant fuzzy uncertainty. Also, hesitant fuzzy linguistic expressions can be used in HF-TOPSIS method, like Aktas and Kabak used in HF-VIKOR in their study on energy storage technology evaluation [49].

Conflict of Interest Statement

There is no conflict of interest between the authors.

Statement of Research and Publication Ethics

The study is complied with research and publication ethics.

Artificial Intelligence (AI) Contribution Statement

This manuscript was entirely written, edited, analyzed, and prepared without the assistance of any artificial intelligence (AI) tools. All content, including text, data analysis, and figures, was solely generated by the authors.

Contributions of the Authors

Koksal Aktas: Formal analysis, data curation, visualization, writing, review and editing.

Ahmet Aktas: Conceptualization, methodology, validation, software, writing original draft.

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