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GIS-based onshore wind farm site selection using Fuzzy Multi-Criteria Decision Making methods. Evaluating the case of Southeastern Spain

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HIGHLIGHTS

- Evaluation of available sites to implant onshore wind farms.
- Combination of GIS and Fuzzy Multi-Criteria Decision Making (MCDM) methods.
- Fuzzy Analytic Hierarchy Process (FAHP) to obtain the weights of the criteria.
- Fuzzy TOPSIS (FTOPSIS) method to evaluate the alternatives.

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ABSTRACT

When it is necessary to select the best location to implant an onshore wind farm, the criteria that influence the decision-making are not always numerical values but can also include qualitative criteria in the form of labels or linguistic variables which can be represented through fuzzy membership. In this paper, some fuzzy approaches of different Multi-Criteria Decision Making (MCDM) methods are combined in order to deal with a trending decision problem such as onshore wind farm site selection. More specifically, the Fuzzy Analytic Hierarchy Process (FAHP) is applied to obtain the weights of the criteria, whereas the Fuzzy Technique for Order of Preference by Similarity to Ideal Solution (FTOPSIS) is used to evaluate the alternatives. A Geographic Information System (GIS) is applied to obtain the database of the alternatives and criteria which are transformed in a fuzzy decision matrix through triangular fuzzy numbers. The coast of the Murcia Region, located at the Southeast of Spain, has been chosen as the study area to carry out this evaluation.

1. Introduction

The necessary reduction in growth of greenhouse gas emissions [1] and the shortage in fossil fuels force the human beings to take advantage of the available resources, and that is why supportive policies worldwide have been promoted [2–7]. In order to fulfill the various energy policies of the European Union [8,9], in the late twentieth century sustainable development strategies were promoted [10] and the implantation of renewable energy (RE) facilities was encouraged [11]. The compliance of the objectives set by the European Union was the main reason why renewable energy facilities were promoted in Spain; for this purpose, the Government developed two energy plans [12,13]. In the second plan, a target was set in order to achieve an energy consumption of 20% through renewable energy by 2020. These energy policies enabled an impressive growth of renewable energy facilities, with wind energy being the resource that experienced the greatest growth (Fig. 1).

Despite the uncertainty created by changes in the Spanish legislative framework [15], which have caused a decrease in both public and private investments, economies of scale and the continuing development of these technologies have helped to reduce their manufacturing costs and encourage their implementation [16]. Furthermore, since Spain has a wind potential of 330 GW, it becomes necessary to continue promoting and encouraging the implementation of wind energy facilities in order to reach the 35 GW of accumulated wind power laid down as a specific target for 2020 [13,17].

When a promoter of RE facilities wants to implant an onshore wind farm, the first stage consists of selecting the best location. To deal with, Geographical Information Systems (GIS) serve as

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	Installed 2012	End 2012	Installed 2013	End 2013
EU Capacity (MW)				
Austria	296	1,377	308	1,684
Belgium	297	1,375	276	1,651
Bulgaria	158	674	7.1	681
Croatia	48	180	122	302
Cyprus	13	147	0	147
Czech Republic	44	260	9	269
Denmark	220	4,162	657	4,772
Estonia	86	269	11	280
Finland	89	288	162	448
France	814	7,623	631	8,254
Germany	2,297	30,989	3,238	33,730
Greece	117	1,749	116	1,865
Hungary*	0	329	0	329
Ireland	121	1,749	288	2,037
Italy	1,239	8,118	444	8,551
Latvia	12	60	2	62
Lithuania	60	263	16	279
Luxembourg	14	58	0	58
Malta	0	0	0	0
Netherlands	119	2,391	303	2,693
Poland	880	2,496	894	3,390
Portugal	155	4,529	196	4,724
Romania	923	1,905	695	2,599
Slovakia	0	3	0	3
Slovenia	0	0	2	2
Spain	1,110	22,784	175	22,959
Sweden	846	3,582	724	4,470
United Kingdom	2,064	8,649	1,883	10,531
Total EU-28	**12,102**	**106,454**	**11,159**	**117,289**
Total EU-15	**9,879**	**99,868**	**9,402**	**108,946**
Total EU-13	**2,224**	**6,586**	**1,757**	**8,343**

Fig. 1. Wind power installed in Europe by end of 2013 (cumulative) [14].

excellent software tools. GIS have been applied to evaluate the onshore wind techno-economical potential of regions and islands [18]; assessing the wake effect on the energy production of onshore wind farm [19]; identifying locations for large-scale microalgae cultivation in Western Australia [20]; and carrying out a spatial analysis of woodfuel in Northern Spain [21], to quote some of them. Sometimes, it is not only necessary to apply these types of geospatial tools, but also to take into account the restrictions and criteria which influence this kind of decision problem. For this reason, it becomes quite advisable to combine software tools such as GIS, which allows to obtain a database of suitable locations, with Multi-Criteria Decision Making (MCDM) methods, such as ELimination Et Choix Traduisant la Realité (ELECTRE) [22]; the Preference Ranking Organization Method for Enrichment Evaluation (PROMETHEE) [23]; Analytic Hierarchy Process (AHP) [24]; Analytic Network Process (ANP) [25]; Ordered Weighted Averaging (OWA) [26]; VIseKriterijumska Optimizacija I Kompromisno Resenje (VIKOR) [27]; or the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) [28].

The literature contains several MCDM methods which have been used in the field of wind farms locations; for instance, [29] carried out a sustainability assessment process for coastal beach exploitation based on AHP method. Lee et al. [30] also applied this methodology associated with benefits, opportunities, costs and risk (BOCR) to select a suitable wind farms project. Furthermore, this methodology has been combined with other decision methods to deal with decision problems such as evaluating of investment for wind farm construction [31] through the combination of AHP and TOPSIS methods, or deriving wind farm suitability index and classification under a combination of GIS - AHP with OWA [32]. Therefore, besides the fact that AHP can be combined with others MCDM methods, it enables to complement with GIS to facilitate the resolve of similar location problems. Recent studies, such as [33] or [34], provide clear proofs of their suitability.

However, it is quite common that, to select a suitable wind farm location, the criteria which have influenced in this selection problem may have a different nature. These criteria are not always composed of numerical values but may include qualitative criteria in the form of labels or linguistic variables. In this way, in many occasions, it is advisable to work with linguistic variables [35,36], which take values from a set of defined linguistic terms and can be represented through fuzzy membership [37].

The use of fuzzy logic and its combination with MCDM methods is being adopted in energy modeling since the beginning of this century. Some recent examples associated with the choice of the site of onshore wind farms are as follows: in Malaysia, the conventional TOPSIS method and a Fuzzy Analytic Hierarchy Process (FAHP) approach were utilized to choose the best wind site [38]. In Taiwan [39], Fuzzy Analytic Network Process (FANP) and BOCR were employed to select wind farm sites. In 2014 [40], FAHP was utilized in Turkey to asses alternative wind power plants. Accordingly, there are many researches in which the suitable combination of fuzzy logic and MCDM methods to choose wind farm sites has been shown. Recently, a review of the applications of fuzzy logic in renewable energy systems provides different combinations of both Multi-criteria decision models and fuzzy models in the field of RE [41]. This last review demonstrated that there is no previous study which combines Fuzzy TOPSIS (FTOPSIS) method with FAHP to select onshore wind farm sites i.e., this type of combination of fuzzy MCDM methods has not been carried out so far. This is the novelty regarding the present article. In fact, the present study not only allows to demonstrate the usefulness of GIS tools, but also shows how a combination of fuzzy approaches of different multi-criteria methods (FAHP and FTOPSIS, in this case) leads to solve a current decision problem such as onshore wind farm site selection.

These methods have been chosen mainly since these types of location problems include a very high number of alternatives and qualitative criteria coexist with quantitative criteria. The aforementioned methods do not require expert assessment for each of the alternatives which makes the calculations easier. Furthermore, these methods are particularly useful when the valuations of the alternatives on the basis of the criteria are not represented in the same units. We apply the FAHP approach to obtain the weight of the criteria, and the FTOPSIS method to evaluate the alternatives (which have been previously obtained via a GIS tool).

This paper presents an evaluation of available sites to implant onshore wind farms on the coast of the Murcia Region in the Southeast of Spain. In order to do this, a GIS tool will be used to provide the decision matrix which contains the alternatives to evaluate, and the proposed case will be solved through a combination of fuzzy approaches based on the TOPSIS and AHP methods (Fig. 2). This paper is divided into four parts: the first part describes the methodology used for the problem considered, i.e., the fuzzy MCDM methods used to solve the proposed location problem; in the second part, both the GIS and the proposed decision problem are presented, analyzed and discussed; in the third part, a sensitivity analysis of the results obtained is performed, and finally, the fourth part contains the main conclusions of this study.

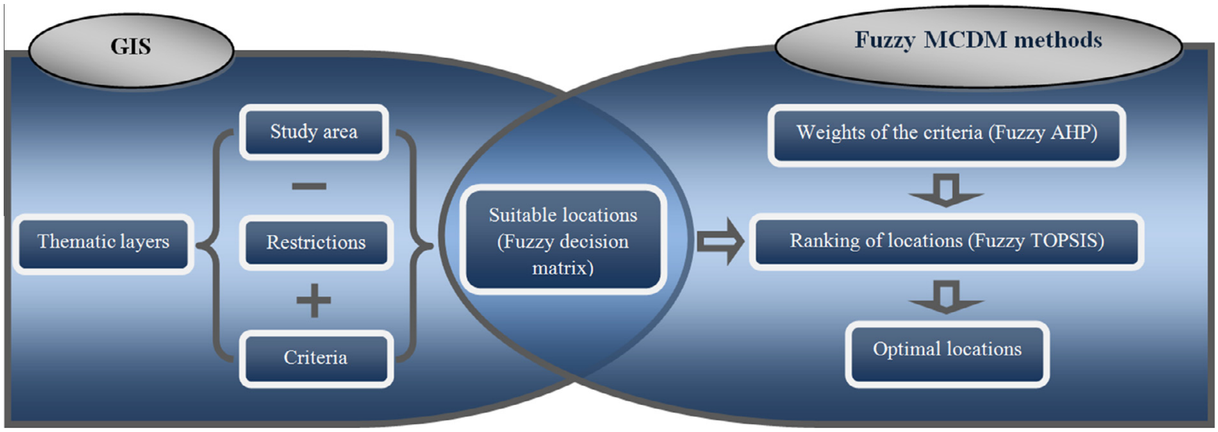

Fig. 2. Process scheme.

Table 1
Fuzzy scale of valuation in the pair-wise comparison process [46].

Labels	Verbal judgments of preferences between criterion i and criterion j	Triangular fuzzy scale and reciprocals
(II)	C_i and C_j is equally important	(1,1,1)/(1,1,1)
(M+I)	C_i is slightly more important than C_j	(2,3,4)/(1/4,1/3,1/2)
(+I)	C_i is strongly more important than C_j	(4,5,6)/(1/6,1/5,1/4)
(Mu+I)	C_i is very strongly more important than C_j	(6, 7, 8)/(1/8,1/7,1/6)
(Ex+I)	C_i is extremely more important than C_j	(8,9,9)/(1/9,1/9,1/8)

2. Methodology

2.1. Fuzzy sets

The fuzzy set theory, introduced by Zadeh [42] to deal with vague, imprecise and uncertain problems has been used as a modeling tool for complex systems that can be controlled by humans but are hard to define precisely. For instance, class of objects characterized by such commonly used adjectives as significant, serious, substantial and simple are fuzzy sets since there is no sharp transition from membership to non-membership. The main reason of that is that in a real world, there is not crisp or real boundaries which separate those objects which belong to the classes in question from those which do not [43]. A collection of objects (universe of discourse) X has a fuzzy set A described by a membership function f_A with values in the interval $[0,1]$ [44].

In this paper, we only make reference to the operations on a triangular membership function through the fuzzy number sets that will be used in the study case. The basic theory regarding the triangular fuzzy numbers (TFN) is described in detail in [45].

2.2. Analytic Hierarchy Process (AHP)

The AHP methodology, proposed by Saaty [24], has been accepted by the international scientific community as a robust and flexible MCDM tool to deal with complex decision problems. Basically, AHP has three underlying concepts: structuring the complex decision as a hierarchy of goal, criteria and alternatives, pair-wise comparison of elements at each level of the hierarchy with respect to each criterion on the preceding level, and finally, vertically synthesizing the judgements over the different levels of the hierarchy. AHP attempts to estimate the impact of each one of the alternatives on the overall objective of the hierarchy. In this case, we shall only apply the method in order to obtain the criteria weights.

We assume that the quantified judgements provided by the decision-maker on pairs of criteria (C_i, C_j) are contained in an $n \times n$ matrix as follows:

$$C = \begin{array}{c} \\ C_1 \\ C_2 \\ . \\ . \\ C_n \end{array} \begin{bmatrix} c_1 & c_2 & \cdots & c_n \\ c_{11} & c_{12} & \cdots & c_{1n} \\ c_{21} & c_{22} & \cdots & c_{2n} \\ . & . & \cdots & . \\ . & . & \cdots & . \\ c_{n1} & c_{n2} & \cdots & c_{n3} \end{bmatrix}$$

For instance, the c_{12} value represents an approximation of the relative importance of C_1 to C_2, i.e., $c_{12} \approx (w_1/w_2)$. This can be generalized and the statements below can be concluded:

1. $c_{ij} \approx (w_i/w_j)$, $i, j = 1,2,\ldots,n$.
2. $c_{ii} = 1$, $i = 1,2,\ldots,n$.
3. If $c_{ij} = \alpha$, $\alpha \neq 0$, then $a_{ji} = 1/\alpha$, $i = 1,2,\ldots,n$.
4. If C_i is more important than C_j, then $c_{ij} \cong (w_i/w_j) > 1$.

This implies that the matrix C should be a positive and reciprocal matrix with 1's on the main diagonal. Hence, the decision maker only needs to provide value judgments in the upper triangle of the matrix. The values assigned to c_{ij} according to the Saaty scale lie usually in the interval of 1–9 or their reciprocals. In our case, Table 1 presents the linguistic decision-maker's preferences in the pair-wise comparison process.

It can be shown that the number of judgments (L) needed in the upper triangle of the matrix is:

Table 2
Random index for different matrix orders [48].

n	1–2	3	4	5	6	7	8	9	10
RI	0.00	0.5247	0.8816	1.1086	1.2479	1.3417	1.4057	1.4499	1.4854

n	11	12	13	14	15
RI	1.5140	1.5365	1.5551	1.5713	1.5838

$$L = n(n-1)/2 \tag{1}$$

where n is the size of the matrix C.

The vector of weights is the eigenvector corresponding to the maximum eigenvalue "λ_{max}" of the matrix C. The traditional eigenvector method of estimating weights in AHP yields a way of measuring the consistency of the referee's preferences arranged in the comparison matrix. The consistency index (CI) is given by $CI = (\lambda_{max} - n)/(n-1)$.

If the referee shows some minor inconsistency, then $\lambda_{max} > n$, and Saaty proposes the following measure of the consistency ratio: $CR = CI/RI$, where RI (random index) is the average value of CI (Table 2) for random matrices using the Saaty scale [47], and Saaty only accepts a matrix as a consistent one if $CR < 0.1$.

In AHP problems, where the values are fuzzy, not crisp; instead of using λ as an estimator of the weight, we will use the geometric normalized average, expressed by the following expression:

$$w_i = \frac{\left(\prod_{j=1}^{n}(a_{ij}, b_{ij}, c_{ij})\right)^{1/n}}{\sum_{i=1}^{m}\left(\prod_{j=1}^{n}(a_{ij}, b_{ij}, c_{ij})\right)^{1/n}} \tag{2}$$

where (a_{ij}, b_{ij}, c_{ij}) is a fuzzy number.

Also, to obtain the weight vector, the normalizing operation must be used; this will be achieved through expression (3).

$$(w_{c_{ia}}, w_{c_{ib}}, w_{c_{ic}}) = \left[\frac{c_{ia}}{\sum_{i=1}^{n} c_{ic}}, \frac{c_{ib}}{\sum_{i=1}^{n} c_{ib}}, \frac{c_{ic}}{\sum_{i=1}^{n} c_{ia}}\right] \tag{3}$$

2.3. The fuzzy TOPSIS (FTOPSIS) method

Technique for Order Performance by Similarity to Ideal Solution (TOPSIS), one of the classical MCDM methods, was developed by Hwang and Yoon [28]. It is based on the concept that the chosen alternative should have the shortest distance from the positive ideal solution, and the farthest from the negative ideal solution (Fig. 3).

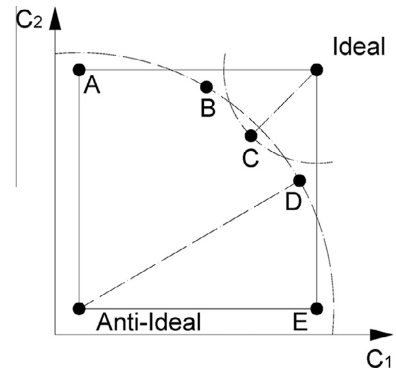

Fig. 3. Ideal alternative vs no anti-ideal alternative.

Thus, the solution is a compromise solution according to the decision-maker's preferences. The chosen alternative should have the shortest distance from the positive ideal solution (PIS), in our case (C), and the farthest from the negative ideal solution (NIS), in our case (B; D). In Fig. 3, the concepts of PIS and NIS are illustrated.

This approach is employed due to four reasons [49]:

(a) TOPSIS logic is rational and understandable;
(b) the computation processes are straightforward;
(c) the concept permits each criterion to be depicted in simple mathematical form when searching for the best alternatives for, and
(d) the importance weights are incorporated into the comparison procedures.

In this study, the fuzzy approach to TOPSIS method, which is very simple and easy to implement, was used to select the preference order of the alternatives. The MCDM that includes both numeric and linguistic labels can be expressed by a matrix.

The FTOPSIS method (Fig. 4) is derived from the generic TOPSIS method with minor differences, with the pertinent adaptation of the operations associated to the linguistic labels [50].

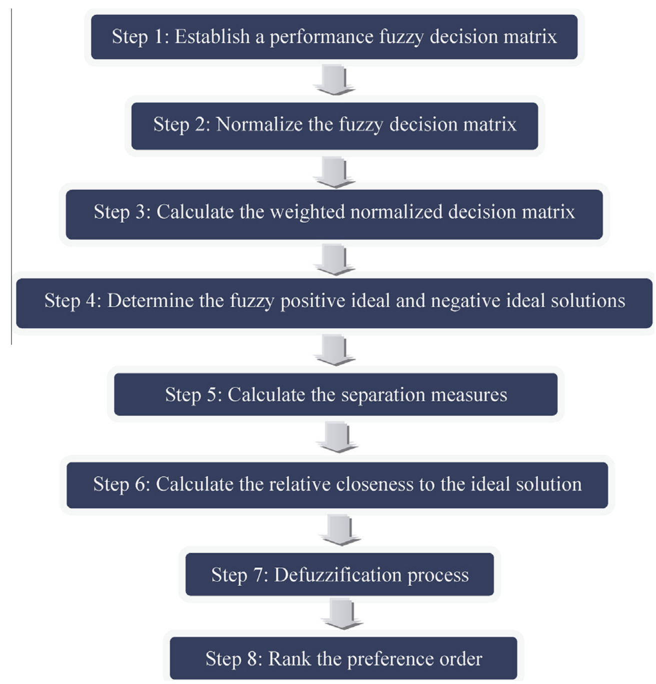

Fig. 4. The FTOPSIS algorithm.

Step 1. Establish a performance decision matrix

Starting with m alternatives A_i, $i = 1,\ldots,m$ which will be evaluated from the C_j criteria with $j = 1,\ldots,n$ a decision matrix will be obtained (Table 3):

Table 3
Decision matrix.

	w_1 C_1	w_2 C_2	... ...	w_j C_j	... ...	w_n C_n
A_1	x_{11}	x_{12}	...	x_{1j}	...	x_{1n}
A_2	x_{21}	x_{22}	...	x_{2j}	...	x_{2n}
...	...	...	...	...	...	...
A_m	x_{m1}	x_{m2}	...	x_{mj}	...	x_{mn}

Where x_{ij} represents the performance score of alternative A_i against criteria C_j and $W = [w_1, w_2, \ldots, w_n]$ is the weight vector associated with the criteria.

Step 2. Normalize the decision matrix

Obtain the associated normalized decision matrix. To do this, the value of each criterion is divided by the norm, so the scale is the same for all criteria.

$$n_{ij} = x_{ij} \Big/ \sqrt{\sum_{j=1}^{m}(x_{ij})^2}, \quad j = 1,\ldots, \quad n, i = 1,\ldots,m. \tag{4}$$

Step 3. Calculate the weighted normalized decision matrix

The elements of the matrix of weighted normalized decision V are calculated as:

$$v_{ij} = w_j \otimes n_{ij}, \quad j = 1, \ldots, n, \quad i = 1, \ldots, m, \tag{5}$$

where, w_j such that $1 = \sum_{j=1}^{n} w_j$ is the weight of the jth attribute or criterion. They are obtained in this paper using the AHP methodology.

Step 4. Determine the positive ideal (PIS) and negative ideal solution (NIS)

The positive ideal value set A^+ represents the best performance scores, while the negative A^- represents the worst.

$$\begin{aligned} A^+ &= \{v_1^+, \ldots, v_n^+\} = \left\{\left(\max_i v_{ij}, \quad j \in J\right)\left(\min_i v_{ij}, \quad j \in J'\right)\right\} \\ & \qquad i = 1, 2, \ldots, m \\ A^- &= \{v_1^-, \ldots, v_n^-\} = \left\{\left(\min_i v_{ij}, \quad j \in J\right)\left(\max_i v_{ij}, \quad j \in J'\right)\right\} \\ & \qquad i = 1, 2, \ldots, m \end{aligned} \tag{6}$$

where J is associated with the criteria that indicate profits of benefits and J' is associated with the criteria that indicate costs or losses.

Step 5. Calculate the separation measures

Calculation of the separation of each alternative with respect to the PIS and NIS, respectively:

$$d_i^+ = \left\{\sum_{j=1}^{n}\left(v_{ij} - v_j^+\right)^2\right\}^{\frac{1}{2}}, \quad i = 1, \ldots, m \tag{7}$$

$$d_i^- = \left\{\sum_{j=1}^{n}\left(v_{ij} - v_j^-\right)^2\right\}^{\frac{1}{2}}, \quad i = 1, \ldots, m \tag{8}$$

Step 6. Calculate the relative closeness to ideal solution

The ranking score R_i is calculated using this equation:

$$R_i = \frac{d_i^-}{d_i^+ + d_i^-}, \quad i = 1, \ldots, m \tag{9}$$

Such that:

If $R_i = 1 \rightarrow A_i = A^+$

If $R_i = 0 \rightarrow A_i = A^-$

Step 7. Defuzzification process

A defuzzification process [51] allows to transform fuzzy numbers into crisp values, i.e., real values:

$$I_{1/3,1/2}(R_i) = \frac{1}{3}\left(\frac{a_i + 4b_i + c_i}{2}\right), \quad i = 1, \ldots, m \tag{10}$$

where the $I_{1/3,1/2}(R_i) = 1$ values lie between 0 and 1. The closer the R_i value is to 1, the higher the priority of the ith alternative is.

Step 8. Rank the preference order

Rank the best alternatives according to $I_{1/3,1/2}(R_i)$ in descending order. The FTOPSIS method will be used in this case to evaluate alternatives, i.e., available locations to implant onshore wind farms.

3. The decision problem: GIS-based onshore wind farm site selection

3.1. A GIS tool to search available locations and generate the decision matrix

Although many commercial GIS tools are available nowadays (ArcGIS, IDRISI, etc.), the calculations presented in this paper were obtained using a free GIS version called gvSIG [52].

The first step was to select the study area, which in this study is the coastline of the Murcia Region, which covers an area of 4456.59 km^2 and it is composed by 13 municipalities (Fig. 5). Once the study area was established, the restrictions had to be considered, i.e., the zones in which due to the current situation of the territory (roads, railways, cities, etc.) or the legislative framework (European, national, regional and local regulations), it results impossible to build onshore wind farms.

3.1.1. Restrictions

The main idea in this phase was to eliminate the restrictions. In this case, they are those areas which have impediments to the installing of an onshore wind farm. In order to remove them, the mentioned GIS software was applied. To do that, it was necessary previously to obtain the layers of restrictions. That information was obtained through web map services of the national and regional administrations (Table 4).

Each restriction in Fig. 6 was defined in terms of its legislative framework. According to current legislations [54–58], it is not possible to implement solar farms in urban, protected and undeveloped lands (restriction 1). Furthermore, according to [55] and [59], areas of high landscape value, water infrastructures, military zones and cattle trails are protected zones (restriction 2). Also, no facility can be built in watercourses and streams and in their areas of influence according to [55] (restriction 3). Moreover, [54,60] establish conservation measures in the zones listed as archaeological, paleontological and cultural heritages (restriction 4). Roads and railroad networks (restriction 5) are also protected by their corresponding framework [61] as well as community interest sites-LICs (restriction 6) and the areas of special protection for birds-ZEPAs (restriction 7) which are protected through the Directive 92/43/EEC of 21 May 1992 [62]. The same applies to the Spanish Mediterranean coast (restriction 8) which is protected through [63] in which an area of influence of 100 m inland is established.

Once the editing process with gvSIG was performed and the restricted areas from the initial area of the coast in the Murcia Region were removed, a thematic layer was created enabling the visualization of suitable locations for onshore wind farms on the coast of the Murcia Region (shown in blue[1] in Fig. 7) and the creation of an extensive database (33,290 available locations) with cartographic and cadastral information of such locations. The percentage of available locations was found to be equal to 19.94% of the total coastal area, representing an area of 888.75 km^2.

3.1.2. Criteria

Once the study area was reduced to the available area to implant onshore wind farms (Fig. 7), the thematic layers that define the criteria that affect the decision making were entered into gvSIG (Fig. 8). To deal with, it was necessary to obtain these thematic layers and such an information was obtained by web map services from the national, regional administrations and private companies (Table 5). The criteria were identified from the existing bibliography [64–66] and have been agreed in conjunction with experts in

[1] For interpretation of color in Figs. 7 and 13, the reader is referred to the web version of this article.

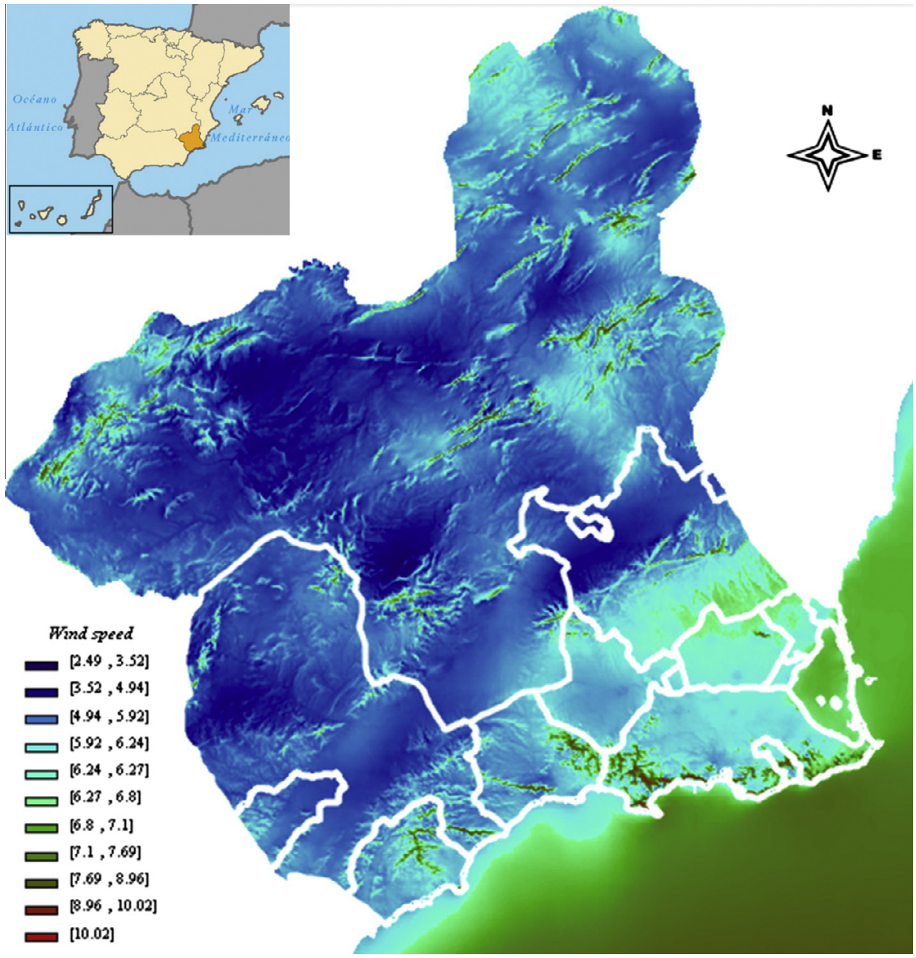

Fig. 5. Coastal areas of the Murcia Region selected for the study [53].

Table 4
Source, scale and resolution of the layers of legal restrictions used.

Thematic layer	Scale	Resolution	Source
Urban lands & Protected and undeveloped lands (restriction 1)	1:2000	0.2 m/pixel	Department of Public Works and Planning of the Region of Murcia
Areas of high landscape value & Water infrastructure, military zones and cattle trails (restriction 2)	1:5000	0.5 m/pixel	
Archaeological sites, Paleontological sites & Cultural heritage (restriction 4)			
Roads and Railroad network (restriction 5)			
Community interest sites (restriction 6)	1:50,000	0.5 m/pixel	General Management for Natural Heritage and Biodiversity of the Region of Murcia
Areas of special protection for birds (restriction 7)			
Watercourses and streams (restriction 3)	1:5000	0.2 m/pixel	General Management for the Environment of the Region of Murcia
Mediterranean coast (restriction 8)	1:1000	0.5 m/pixel	
Cadastral municipalities of the coastline of the Murcia	1:5000	0.5 m/pixel	General Management of Land Registry. Ministry of Economy and Finance

the field of RE. It is worth mentioning that any administrative or environmental aspect that would limit the construction of an onshore wind farm has been taken into account in the previous step, i.e., restrictions or limiting factors, such as acceptability of any kind and legislative framework, have been already considered. Thus, this second phase will take into account criteria that influence in the decision problem of selecting of wind farm sites.

Once the digital cartographic data of the criteria in the form of thematic layers were obtained (Fig. 8), it was necessary to carry out editing tasks through the GIS with the aim of obtaining a global thematic layer. This layer provides the decision matrix of alternatives and criteria. To do this, the suitable locations layer (Fig. 7) constituted the starting layer. Using the rest of the thematic layers of the criteria and GIS commands such as spatial link, filter, intersection, area, slope and buffers, it was possible to obtain the global thematic layer. This was associated with a decision matrix in the form of a table of attributes in which there were 33,290 alternatives to be evaluated (potential locations) based on 10 criteria. This table was saved in Excel format in order to apply the fuzzy MCDM methods described above.

3.2. Problem structure

To assess the alternatives (plots) based on the criteria that were obtained in the previous section, a prior stage had to be performed. This was to obtain the weights of the criteria. After that, the

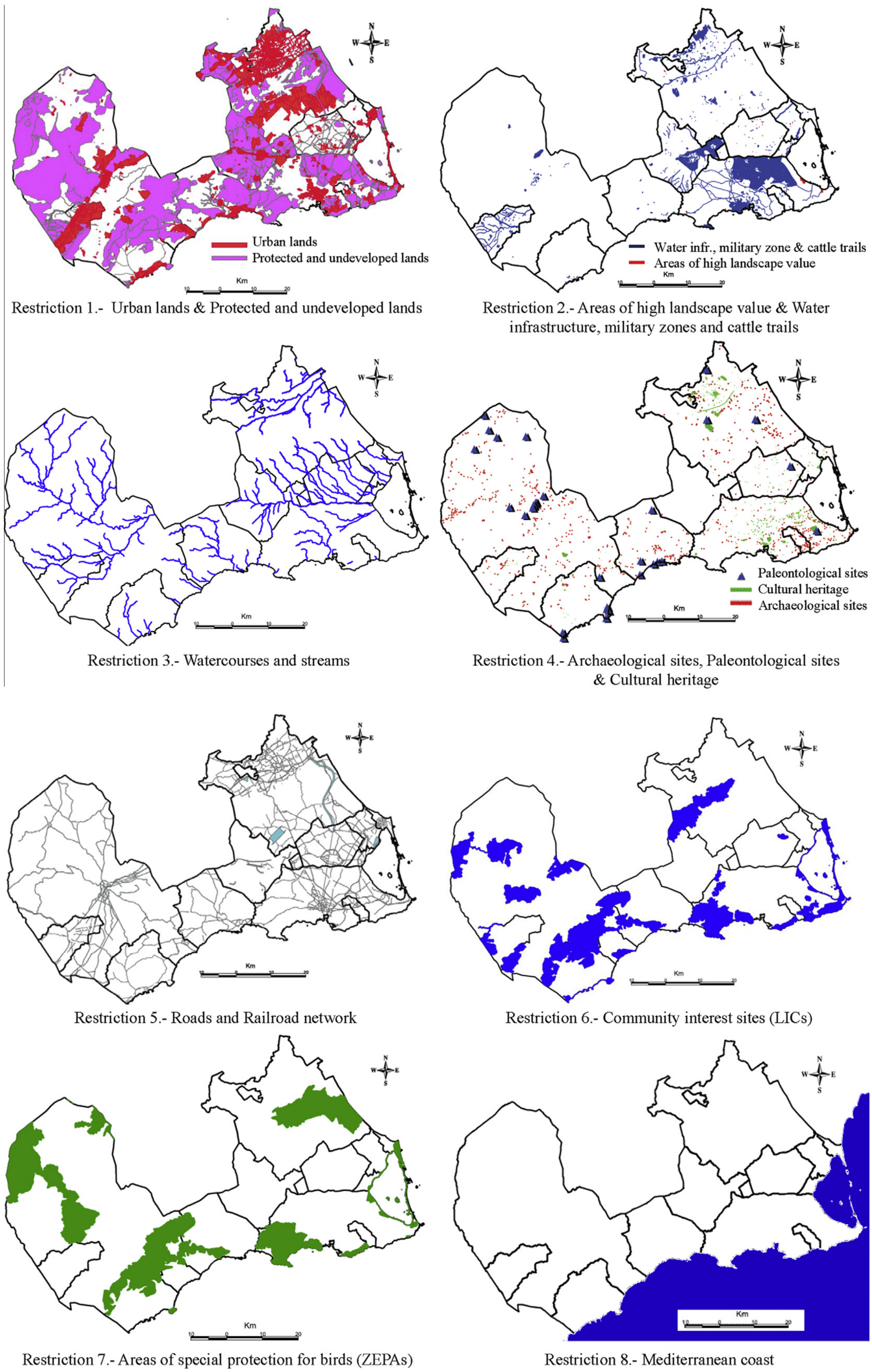

Fig. 6. Layers of legal restrictions to land use in Spanish legislation.

alternatives had to be assessed. The extraction of knowledge was performed by a group of experts which filled out a survey based on the application of the methodology described. The group of experts involved in the decision process of onshore wind farms consisted of three doctor engineers (experts E_1, E_2 and E_3) specialized in the type of facilities.

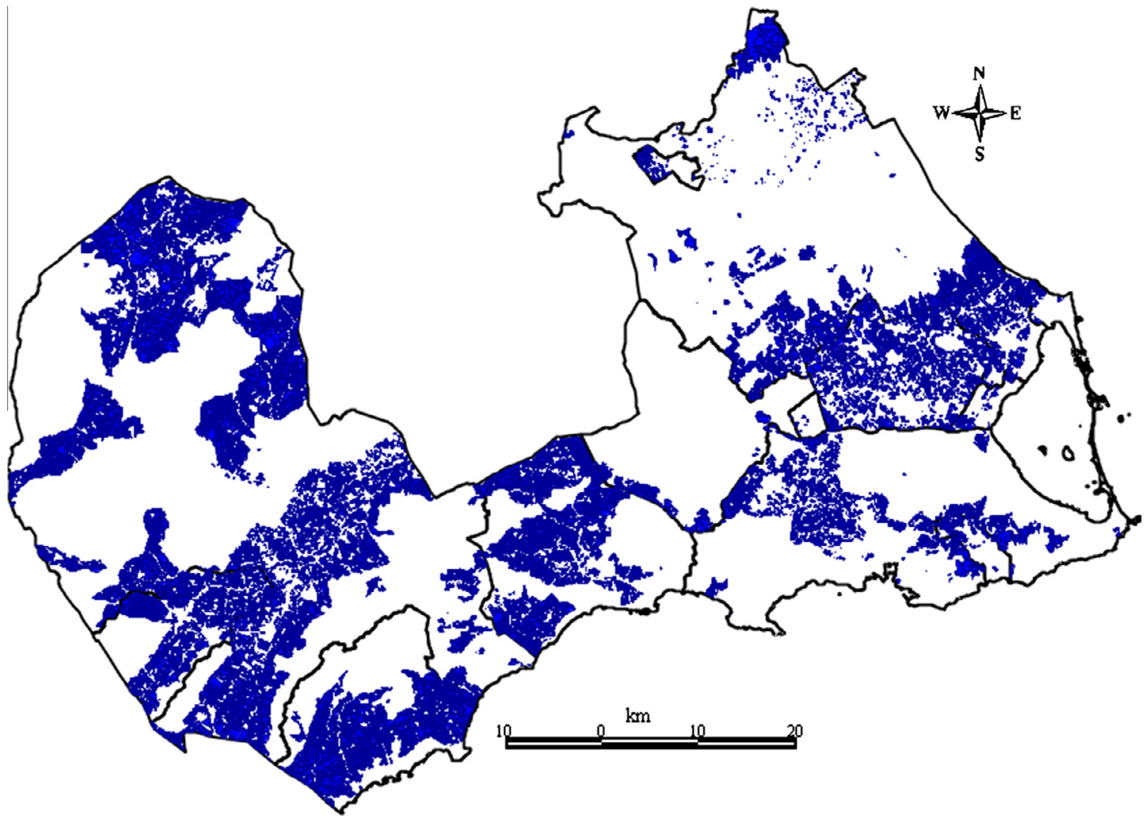

Fig. 7. Thematic layer of available locations to implement onshore wind farms.

3.2.1. Determination of the weight of the criteria

To determine the weights of the criteria, a fuzzy AHP survey was carried out. That survey consisted of a block of 3 questions:

Q1: Do you believe that the ten criteria considered have the same weight?

If the answer was yes, then $w_i = w_j = 1/n$ for all i,j. Thus, it will not be necessary to do anything else to obtain the weights of the criteria since these will all have the same value. Otherwise, i.e., if an expert considers that not all the criteria have equal importance, then it becomes appropriate to proceed to the next question of the survey.

The next step will be to find out which one criterion is more important than another. This degree of importance will be analyzed to be able to assign a weight to each criterion. For example, when indicating that a particular criterion has a higher weight than the rest of the criteria, it is declared that this is the most important criterion. Forthwith, the weights of the criteria will be used to quantify their importance.

The three experts have considered that certain criteria should have a greater weight than others. Therefore, those weights need to be determined.

Q2: List the criteria in descending importance

According to Table 6, the three experts believe that the importance is different, although they differ in the order of importance of the criteria. Once the expert has indicated the order of importance, the next question would be considered:

Q3: Compare the approach to be considered first with respect to that considered secondly and successively, using the following tags {(II), (M+I), (+I), (Mu+I), (Ex+I)} which correspond to the scale of valuation in the pair-wise comparison process (Table 1)

To determine the weights of the criteria, as has been discussed, a pair-wise comparison has been made. Using Expert 1 as an example, in Fig. 9 his appreciation by pair-wise comparison is shown. The meaning is as follows: criterion C_{10} is extremely more important than both C_4 and C_1, with respect to C_5 it is very strongly more important, with respect to both C_9 and C_2 it is strongly more important, with respect to C_8, C_7, C_6 and C_3 it is slightly more important and with respect to C_{10} is equally important.

This translated into the fuzzy numbers according to Table 1 gives Fig. 10.

Taking into account both [67] and the operation (2), the weights of the criteria (provided in Fig. 11) are obtained.

The information detailed above for E_1 would be also carried out by the other experts. The normalized weights associated with the corresponding criterion C_j, $j = 1,2,\ldots,10$, given by each expert can be seen in Table 7.

Analyzing the above table, it is observed that the criterion which stands out above all the others is wind speed (C_{10}). However, for the rest of criteria, certain differences can be appreciated among them. In order to use the weights of the criteria provided by the experts in the latest stage of evaluating alternatives, it is necessary to unify them. To deal with, it will carry out an homogeneous aggregation (considering that all experts are equally important in the decision problem) by the arithmetic average. The weights of each criterion (Table 8) and their graphical representation (Fig. 12) were as follows:

Through homogeneous aggregation it is observed that the most important criterion is C_{10} (wind speed), while the second most important is C_7 (distance to cities). The least important criteria

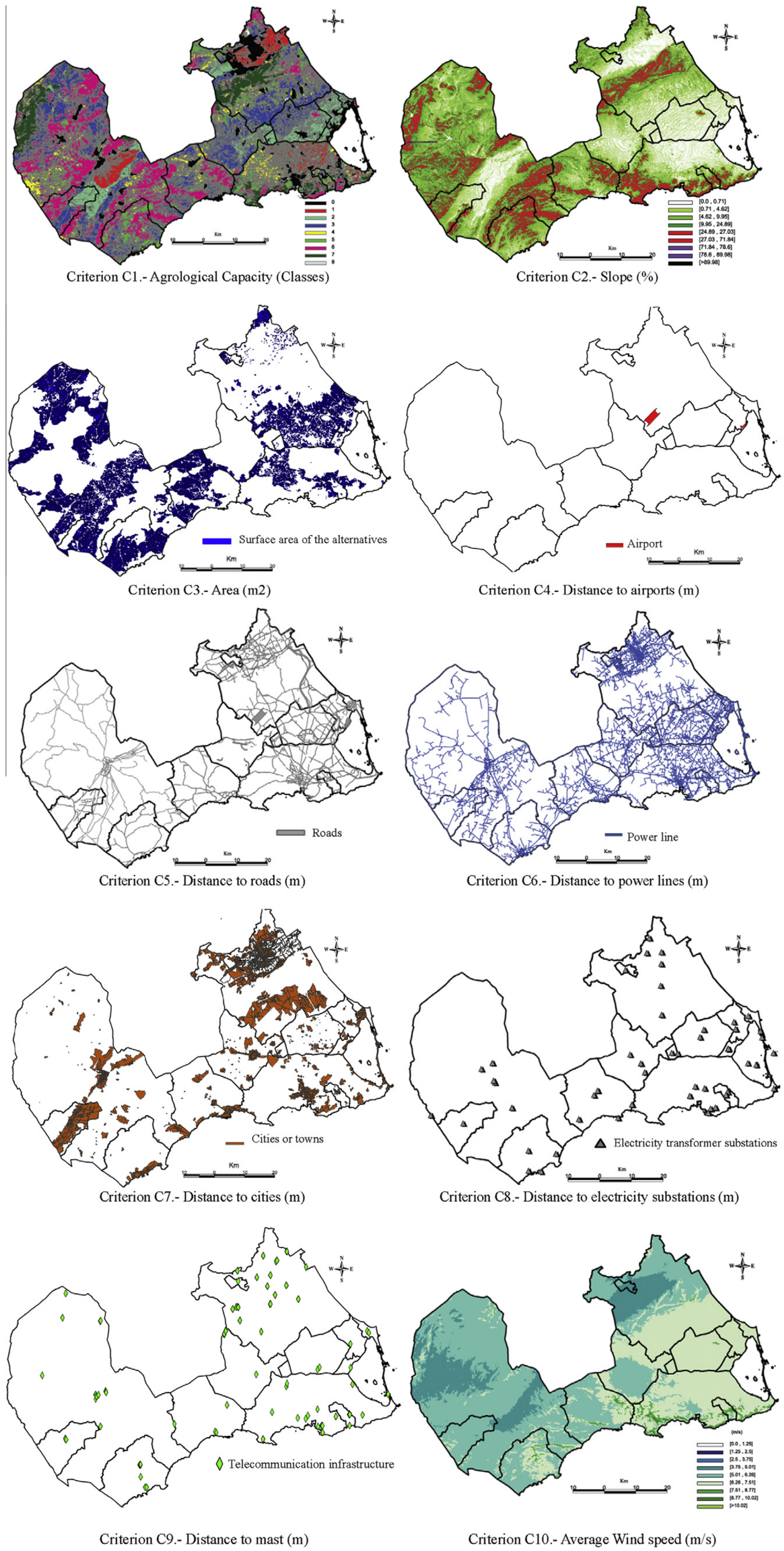

Fig. 8. Layers of criteria.

Table 5
Source, scale and resolution of the layers of the used criteria.

Thematic layer	Scale	Resolution	Source
Agrological Capacity (criterion 1)	1:5000	0.5 m/pixel	General Management of Land Registry. Ministry of Economy and Finance.
Slope (criterion 2)	1:12,500	25 m/pixel	National Geographic Institute
Area (criterion 3) Distance to main airports (criterion 4) Distance to main roads (criterion 5) Distance to cities (criterion 7)	1:5000	0.5 m/pixel	Department of Public Works and Planning of the Region of Murcia
Distance to power lines (criterion 6) Distance to electricity substations (criterion 8)	1:50,000	0.5 m/pixel	Iberdrola company
Distance to mast (criterion 9)	1:5000	0.5 m/pixel	Ministry of Industry, energy and tourism
Average Wind speed (criterion 10)	1:50,000	100 m/pixel	Institute for Energy Diversification and Saving IDEA

Table 6
Order of importance of criteria for each expert.

E_1	$C_{10} > C_3 = C_6 = C_7 = C_8 > C_2 = C_9 > C_5 > C_1 = C_4$
E_2	$C_{10} > C_2 = C_5 = C_6 = C_7 = C_8 > C_1 = C_4 = C_3 = C_9$
E_3	$C_{10} > C_7 > C_2 = C_5 = C_8 > C_3 = C_6 > C_1 = C_4 = C_9$

$$\begin{array}{cc} & \begin{array}{cccccccccc} C_{10} & C_3 & C_6 & C_7 & C_8 & C_2 & C_9 & C_5 & C_1 & C_4 \end{array} \\ C_{10} & \left[\begin{array}{cccccccccc} II & M+I & M+I & M+I & M+I & +I & +I & Mu+I & Ex+I & Ex+I \end{array}\right] \end{array}$$

Fig. 9. Valuations given by E_1.

$$\begin{array}{c} \\ C_{10} \\ C_3 \\ C_6 \\ C_7 \\ C_8 \\ C_2 \\ C_9 \\ C_5 \\ C_1 \\ C_4 \end{array} \begin{array}{c} C_{10} \\ \left[\begin{array}{c} (1,1,1) \\ (1/4,1/3,1/2) \\ (1/4,1/3,1/2) \\ (1/4,1/3,1/2) \\ (1/4,1/3,1/2) \\ (1/6,1/5,1/4) \\ (1/6,1/5,1/4) \\ (1/8,1/7,1/6) \\ (1/9,1/9,1/8) \\ (1/9,1/9,1/8) \end{array}\right] \end{array} = \left[\begin{array}{c} (0.255, 0.323, 0.373) \\ (0.064, 0.108, 0.187) \\ (0.064, 0.108, 0.187) \\ (0.064, 0.108, 0.187) \\ (0.064, 0.108, 0.187) \\ (0.043, 0.065, 0.093) \\ (0.043, 0.065, 0.093) \\ (0.032, 0.046, 0.062) \\ (0.028, 0.036, 0.047) \\ (0.028, 0.036, 0.047) \end{array}\right]$$

Fig. 11. Criteria weight for E_1.

were shown to be C_1 and C_4 (agrological capacity and distance to airports, respectively). In order to verify the consistence of the AHP method, the consistency ratio (*CR*) was calculated by each expert. This value was less than 0.1, so it was possible to demonstrate the consistence of the method and therefore, it was not necessary to revise the judgements of the experts.

3.2.2. Obtaining assessments of the alternatives

Once the criteria weights were obtained, the alternatives for each of the criteria had to be evaluated. In this step, criteria C_1 and C_2 were valuated using linguistic labels associated to triangular fuzzy numbers (Table 9). The first criterion, called agrological capacity (C_1), divides the field into agrological classes from very low to very high capacity, where "very low" refers to the best agrological capacity for the development of agricultural cultivation and "very high" means the worst agrological capacity. From the point of view of the optimal location for renewable facilities, the field should present a high class (the least adequate for the development of agriculture is better to implement an RE installation). Therefore, linguistic labels have been assigned so a field having a very low linguistic label for agrological capacity represents a field unsuitable to implant a wind farm, while a field with a high linguistic label will be an optimal area for this type of facilities, as well. The same procedure will be applied to the slope (C_2) criterion, in this case linguistic labels will be assigned to triangular fuzzy numbers according to whether the field presents a greater or lesser slope, since to implant onshore wind farms it is necessary for the slope of the field to not be too pronounced. If an alternative presents a low slope (<5%), a "very good" linguistic label will be assigned and on the other hand, if an alternative has a high slope, then a "very bad" linguistic label will be assigned, since the

Table 7
Weights of criteria by the three experts.

	Expert 1 (E_1)	Expert 2 (E_2)	Expert 3 (E_3)
C_1	[0.028, 0.036, 0.047]	[0.048, 0.051, 0.060]	[0.038, 0.044, 0.054]
C_2	[0.043, 0.065, 0.093]	[0.054, 0.066, 0.081]	[0.056, 0.078, 0.107]
C_3	[0.064, 0.108, 0.187]	[0.048, 0.051, 0.060]	[0.042, 0.056, 0.071]
C_4	[0.028, 0.036, 0.047]	[0.048, 0.051, 0.060]	[0.038, 0.044, 0.054]
C_5	[0.032, 0.046, 0.062]	[0.054, 0.066, 0.081]	[0.056, 0.078, 0.107]
C_6	[0.064, 0.108, 0.187]	[0.054, 0.066, 0.081]	[0.042, 0.056, 0.071]
C_7	[0.064, 0.108, 0.187]	[0.054, 0.066, 0.081]	[0.085, 0.131, 0.214]
C_8	[0.064, 0.108, 0.187]	[0.054, 0.066, 0.081]	[0.056, 0.078, 0.107]
C_9	[0.043, 0.065, 0.093]	[0.048, 0.051, 0.060]	[0.038, 0.044, 0.054]
C_{10}	[0.255, 0.323, 0.373]	[0.429, 0.463, 0.483]	[0.338, 0.392, 0.429]

Table 8
Weights of criteria through experts' homogeneous aggregation.

Experts' homogeneous aggregation	
C_1	[0.0378, 0.0436, 0.0535]
C_2	[0.0508, 0.0697, 0.0936]
C_3	[0.0512, 0.0717, 0.1061]
C_4	[0.0378, 0.0436, 0.0535]
C_5	[0.0473, 0.0635, 0.0833]
C_6	[0.0532, 0.0766, 0.1128]
C_7	[0.0673, 0.1015, 0.1605]
C_8	[0.0579, 0.0840, 0.1247]
C_9	[0.0426, 0.0532, 0.0691]
C_{10}	[0.3406, 0.3926, 0.4283]

$$\begin{array}{cc} & \begin{array}{cccccccccc} C_{10} & C_3 & C_6 & C_7 & C_8 & C_2 & C_9 & C_5 & C_1 & C_4 \end{array} \\ C_{10} & \left[\begin{array}{cccccccccc} (1,1,1) & (2,3,4) & (2,3,4) & (2,3,4) & (2,3,4) & (4,5,6) & (4,5,6) & (6,7,8) & (8,9,9) & (8,9,9) \end{array}\right] \end{array}$$

Fig. 10. Matrix of decision making for E_1.

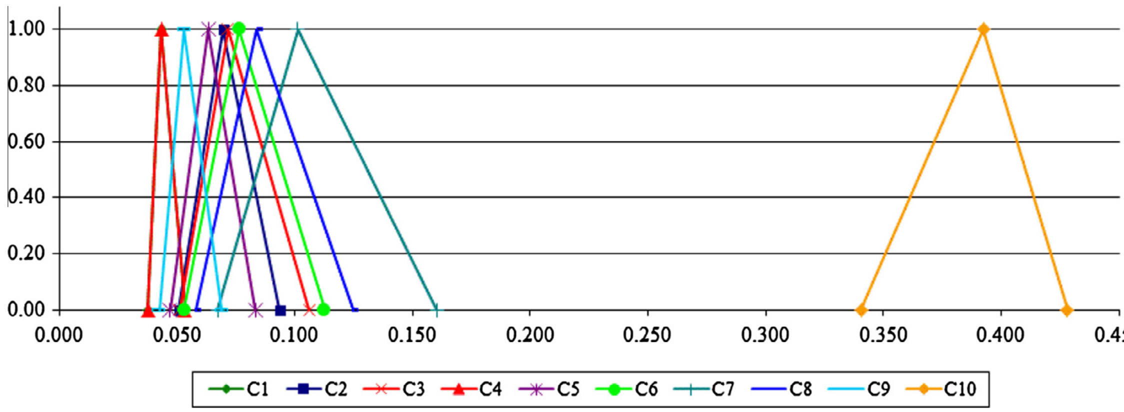

Fig. 12. Graphical representation of weights.

Table 9
Linguistic labels of criteria C_1 and C_2.

Location of onshore wind farms			
Agrological capacity (C_1)		Slope (C_2)	
Linguistic labels	Triangular fuzzy numbers	Linguistic labels	Triangular fuzzy numbers
Very low	(0,1,2)	Very good	(0,0,5)
Low	(1.5,2.5,3.5)	Good	(5,7.5,10)
Medium	(3,4,5)	Regular	(10,15,20)
High	(4.5,5.5,6.5)	Bad	(20,25,30)
Very high	(6,7,8)	Very bad	(30,35,40)

corresponding triangular fuzzy numbers will be associated with these labels.

Criteria C_3, C_4, C_5, C_6, C_7, C_8 and C_9 were determined numerically, i.e., these criteria were defined with numerical values (for example "a") provided directly by the GIS software but defined by a triangular fuzzy number (a,a,a). The remaining criterion (C_{10}), due to its characteristics, was defined by triangular fuzzy numbers instead of by linguistic labels. The values of this criterion were defined by the following expression:

$$(X_i-\sigma, X_i, X_i+\sigma) \qquad \sigma=\sqrt{\frac{\sum_{i=1}^{n}(X_i-\overline{X})^2}{N}} \tag{11}$$

where $\overline{X}$ represents the mean and σ is the standard deviation.

Thus, the corresponding information of the criteria for the 33,290 alternatives was obtained through the table of attributes (decision matrix) of the global thematic layer provided by the GIS software. This decision matrix was composed by a mixture of crisp numerical values, triangular fuzzy numbers and linguistic labels, since the criteria are different in nature.

Due to the size of such a decision matrix (made up of 33,290 registers), it is impossible to show it fully in a clear and coherent manner. Thus, its structure is represented schematically (Table 10).

Where x_{ij} represents the value of alternative A_i with respect to the criterion C_j and, $W = [w_1, w_2, \ldots, w_{10}]$ is the weight vector associated with that criteria.

Once the set of criteria was selected, and the weight of the criteria obtained (Table 8), the TOPSIS method was used to obtain a measure of the effect produced by each alternative with respect to each criterion. This method is particularly useful for those problems for which the values of the alternatives are not represented by the same units, which is the case in our study. Namely, linguistic labels are used for the criteria C_1 and C_2, numerical values for the criteria C_3, C_4, C_5, C_6, C_7, C_8, and C_9, and triangular fuzzy numbers for the criterion C_{10}.

To solve a problem considering both numerical values and linguistic labels modeled by triangular fuzzy numbers, the TOPSIS method must be adapted to the operations of the theory of fuzzy sets.

3.3. Results and discussion

As a result of the defuzzification process carried out to execute the decision rule, the alternatives were sorted according to a Ranking, which allows the decision maker to evaluate the different alternatives. In the evaluation of alternatives to accommodate onshore wind farms, 33,290 alternatives were analyzed by means of the FTOPSIS method; this provides a Ranking for each of the alternatives.

All the obtained values were classified with four sets of results as a function of their reliability to be used as a location for an onshore wind farm. This grouping enables an easy visual representation using a color code: blue-excellent, green-very good, yellow-good and red-poor (Fig. 13). According to the last step of the FTOPSIS method, the 10 Top-ranked locations to accommodate onshore wind farms (Fig. 14) are the locations which achieved $I_{1/3,1/2}$ (R_i) coefficients close to 1. Since it is impossible to show the decision matrix fully in a clear and coherent manner, then the fuzzy values of the 10 Top-ranked locations will be provided in the decision matrix of Appendix A. That appendix will have two objectives:

1. Showing how each one of the steps of FTOPSIS method (for the 10 Top-ranked locations) has been elaborated. So, an application example of this methodology is provided in order to be applied, not only for this study case, but also for any similar actual location problem.

Table 10
Fuzzy decision matrix for the location of plots for onshore wind farms.

	w_1 C_1	w_2 C_2	w_3 C_3	w_4 C_4	w_5 C_5	w_6 C_6	w_7 C_7	w_8 C_8	w_9 C_9	w_{10} C_{10}
A_1	$\tilde{x}_{1\,1}$	$\tilde{x}_{1\,2}$	$x_{1\,3}$	$x_{1\,4}$	$x_{1\,5}$	$x_{1\,6}$	$x_{1\,7}$	$x_{1\,8}$	$x_{1\,9}$	$x_{1\,10}$
A_2	$\tilde{x}_{2\,1}$	$\tilde{x}_{2\,2}$	$x_{2\,3}$	$x_{2\,4}$	$x_{2\,5}$	$x_{2\,6}$	$x_{2\,7}$	$x_{2\,8}$	$x_{2\,9}$	$x_{2\,10}$
...	...	...	...	...	...	...	...	...	...	...
A_{33290}	$\tilde{x}_{33290\,1}$	$\tilde{x}_{33290\,2}$	$x_{33290\,3}$	$x_{33290\,4}$	$x_{33290\,5}$	$x_{33290\,6}$	$x_{33290\,7}$	$x_{33290\,8}$	$x_{33290\,9}$	$x_{33290\,10}$

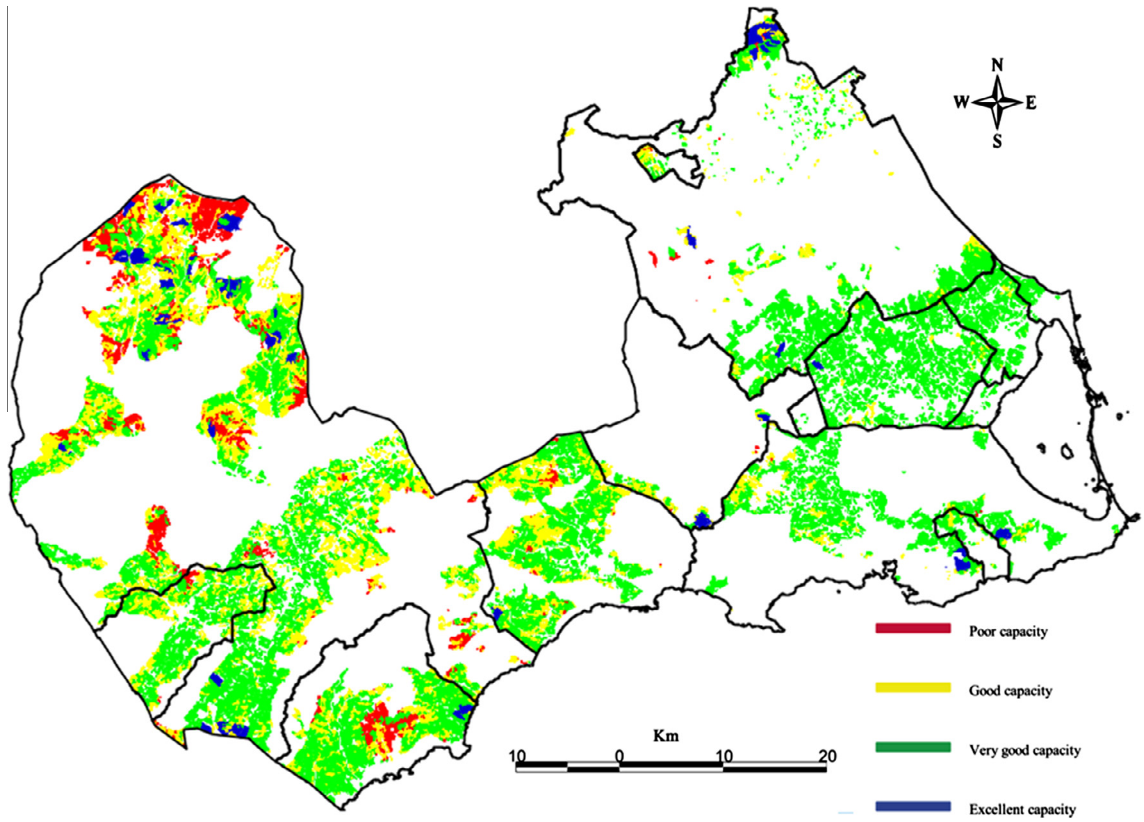

Fig. 13. Map of the capacity to accommodate onshore wind farms on the coast of the Murcia Region.

2. Comparing the obtained results (Table 12, 1st column) to other Fuzzy MCDM methods in order to provide consistence and verify the validity of the proposed methodology.

By carrying out an analysis of the zones shown in Fig. 13, we can see that alternatives with an excellent capacity coexist with other poor alternatives in the western zone of the coast. This territory is one of the more mountainous zones of the Murcia Region and therefore, includes land with major gradients and steep slopes. Consequently, this zone offers both a greater number of excellent alternatives to accommodate onshore wind farms but also a lot of poor alternatives.

The south-eastern zone of the coast is completely different; although there are only some excellent alternatives, the majority of suitable locations in that territory have very good capacity to implant wind farms. One of the main reasons for this is the high urban occupation of the zone, which means that there are many alternatives close to cities and therefore close to electricity substations and power lines (criteria which were defined above as influencing the decision).

Continuing the analysis by zones, it should also be highlighted that although the northern zone is relatively large, it only offers a very limited number of alternatives, since it includes large areas of protected land (defined as LICs or ZEPAs). Therefore, there is little territory available to accommodate onshore wind farms since the majority of its land is listed as urban land or non-urban land but under special protection.

4. Sensitivity analysis

In order to verify and analyze the validity of the results obtained above, a sensitivity analysis was carried out. In this way, two types of considerations were made; firstly, all the alternatives (33,290 suitable locations) were re-analyzed using the FTOPSIS method but with the assumption that all the criteria have the same weight. Secondly, the best alternatives (10 Top-ranked locations) were analyzed with the FTOPSIS method and other fuzzy MCDM methods with the aim of comparing the order of priority of these alternatives.

4.1. Variation of the weights

The results for the best potential locations obtained by applying the FTOPSIS method for the 33,290 alternatives assuming that all the criteria have the same importance are displayed in Table 11.

From the table above, we can see that although the order of importance is not exactly the same, there are only small differences between the best and the second best alternatives, i.e., the best potential locations remain the best although all the criteria had the same weight.

4.2. Comparative with other fuzzy MCDM methods

In order to carry out a sensitivity analysis according to different points of view and hence, to provide consistence to the obtained results, a comparative study among fuzzy MCDM methods was implemented. To do so, the fuzzy normalized decision matrix consisting of the 10 Top-ranked locations were used at first. That decision matrix and each one of the steps of FTOPSIS method can be seen in Appendix A. The FTOPSIS method was applied again in order to compare the obtained priority order of the best locations with the following fuzzy MCDM methods: the fuzzy Weighted Sum Model (WSM) method [68], as well as two versions of the AHP methodology; the Fuzzy AHP [69,70] and the Fuzzy revised AHP [71] i.e., the "ideal mode" AHP [72].

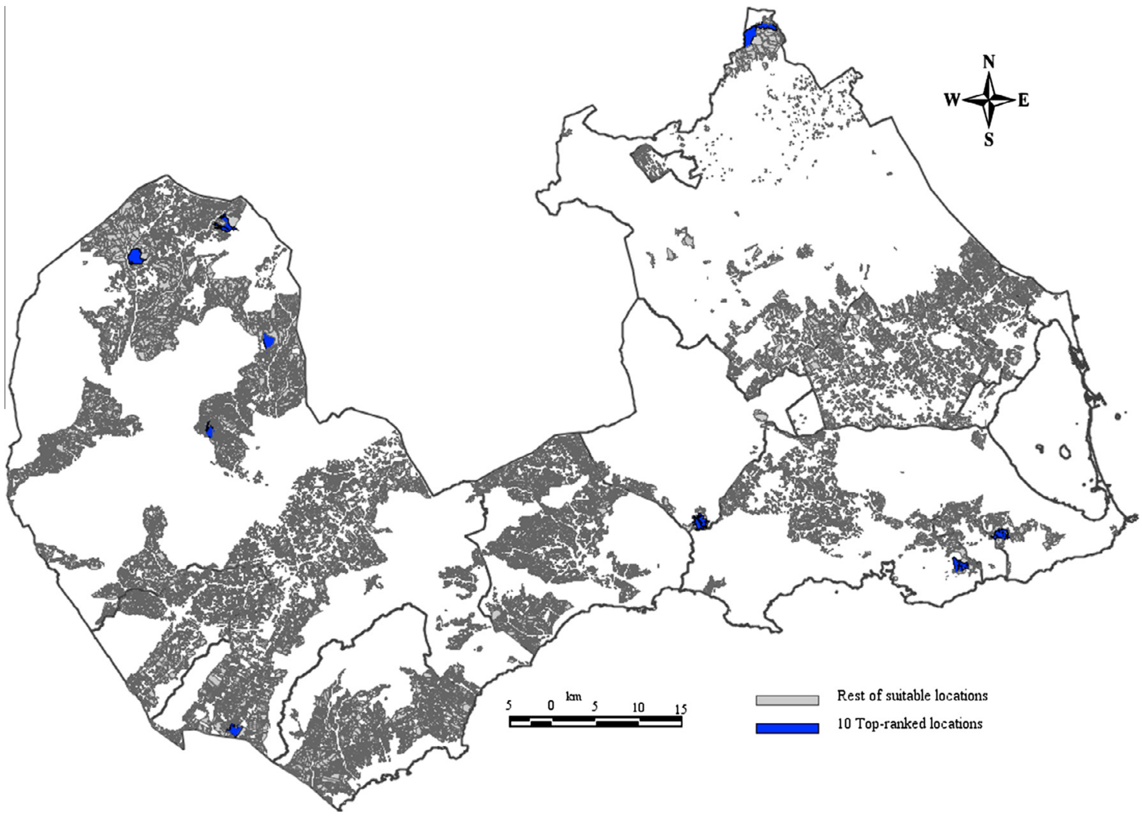

Fig. 14. Ten Top-ranked locations to accommodate onshore wind farms on the coast of the Murcia Region.

Table 11
Comparison of the Top-ranked alternatives according to FTOPSIS method.

Alternatives	Weights through experts group (Table 8)		All the criteria with the same weight	
	$I_{1/3,1/2}$ $(R_i)_{TOPSIS}$	Ranking	$I_{1/3,1/2}$ $(R_i)_{TOPSIS}$	Ranking
A20070	0.893	2	0.836	1
A5879	0.908	1	0.835	2
A13797	0.805	3	0.756	3
A37281	0.799	4	0.745	4
A28450	0.796	5	0.742	5
A21039	0.712	6	0.697	6
A13952	0.708	7	0.666	7
A36919	0.701	8	0.656	8
A18013	0.628	9	0.587	9
A6063	0.620	10	0.580	10

Table 12
Comparison with other Fuzzy MCDM methods.

Alternatives	Fuzzy TOPSIS Ranking[a]	Fuzzy WSM Ranking	Fuzzy AHP Ranking	Fuzzy revised AHP Ranking
A5879	3	2	2	2
A20070	5	4	5	3
A13797	10	8	7	10
A37281	8	10	10	8
A28450	6	7	8	5
A21039	1	1	1	1
A13952	9	6	6	7
A36919	4	9	9	6
A18013	7	5	4	9
A6063	2	3	3	4

[a] The attainment of these values is detailed in Appendix A.

We can see from the obtained results shown in Table 12 that not only is the best alternative obtained by the FTOPSIS method the same as that obtained by the rest of fuzzy MCDM methods (alternative A_{21039} is the best for all the fuzzy MCDM methods), but the positions of the subsequent best alternatives are also very similar. Their position fluctuates only over one or two positions regarding the order of these methods.

5. Conclusions

This paper shows the possibility of combining geographic visualization tools (GIS) with fuzzy techniques for decision support such as the FAHP and the FTOPSIS method to solve location problems in the context of onshore wind farms. It is worth mentioning that it becomes possible to consider the significant technical criteria that influence this kind of decision problems, even being different in nature. Following the above, the main contribution in this paper is to show how qualitative criteria could be together with quantitative criteria via a combination of fuzzy MCDM methods to evaluate potential wind farm locations.

As a result, the sensitivity analysis highlight that the best alternatives are independent of the weights of the criteria that influence the decision. In particular, it follows that the first ten alternatives appear as best, although there are a slight difference between the first and the second one. Furthermore, additional comparisons have been carried out with other fuzzy MCDM methods (Fuzzy WSM, Fuzzy AHP and Fuzzy revised AHP, in this case). As a consequence of this, it yields that the priority order of the best alternatives is very similar.

Therefore, this study not only shows the usefulness of GIS tools, but also how a combination of fuzzy approaches of different multicriteria methods (FAHP and FTOPSIS, in this case) enables to solve a trending decision problem such as onshore wind farm site selection. Furthermore, the present work also complements previous studies in which the criteria that influenced the decision were defined by crisp values instead of linguistic labels or triangular fuzzy numbers.

Finally, it should be emphasized that this work consists of a location study takes into account significant technical criteria and the experience of an advisory group of experts, as well. To extend this work, a further study regarding additional relevant criteria, such as economic aspects (price of land) or even institutional factors, may be carried out.

Acknowledgement

This work is partially supported by the DGICYT under project TIN2014-55024-P.

Appendix A. Fuzzy TOPSIS method of the ten Top-ranked locations

Step 1: Decision matrix.

Weight	C_1			C_2			C_3			C_4			C_5		
	0.0378	0.0436	0.0535	0.0508	0.0697	0.0936	0.0512	0.0717	0.1061	0.0378	0.0436	0.0535	0.0473	0.0635	0.0833
A5879	4.5	5.5	6.5	10	15	20	1843681.8	1843681.8	1843681.8	27662.7	27662.7	27662.7	1651.3	1651.3	1651.3
A6063	1.5	2.5	3.5	5	8	10	1019231.8	1019231.8	1019231.8	29337.7	29337.7	29337.7	149.9	149.9	149.9
A13797	4.5	5.5	6.5	5	8	10	1459838.7	1459838.7	1459838.7	46816.1	46816.1	46816.1	1391.9	1391.9	1391.9
A13952	4.5	5.5	6.5	5	8	10	1214563.2	1214563.2	1214563.2	63184.9	63184.9	63184.9	25.0	25.0	25.0
A18013	4.5	5.5	6.5	5	8	10	1029892.8	1029892.8	1029892.8	53490.2	53490.2	53490.2	25.0	25.0	25.0
A20070	4.5	5.5	6.5	10	15	20	1869381.2	1869381.2	1869381.2	60916.0	60916.0	60916.0	25.0	25.0	25.0
A21039	3.0	4.0	5.0	0	0	5	1342150.4	1342150.4	1342150.4	52368.2	52368.2	52368.2	5261.3	5261.3	5261.3
A28450	3.0	4.0	5.0	10	15	20	1437455.7	1437455.7	1437455.7	15580.6	15580.6	15580.6	346.1	346.1	346.1
A36919	4.5	5.5	6.5	10	15	20	1213962.3	1213962.3	1213962.3	15622.2	15622.2	15622.2	25.0	25.0	25.0
A37281	6.0	7.0	8.0	10	15	20	1449796.8	1449796.8	1449796.8	19622.2	19622.2	19622.2	314.2	314.2	314.2

Weight	C_6			C_7			C_8			C_9			C_{10}		
	0.0532	0.0766	0.1128	0.0673	0.1015	0.1605	0.0579	0.0840	0.1247	0.0426	0.0532	0.0691	0.3406	0.3926	0.4283
A5879	2128.3	2128.3	2128.3	1035.9	1035.9	1035.9	2591.5	2591.5	2591.5	4079.8	4079.8	4079.8	3.2	5.2	7.2
A6063	1483.9	1483.9	1483.9	2493.2	2493.2	2493.2	5109.9	5109.9	5109.9	5576.9	5576.9	5576.9	3.3	5.3	7.2
A13797	1.0	1.0	1.0	61.8	61.8	61.8	9657.8	9657.8	9657.8	5939.2	5939.2	5939.2	3.0	5.0	7.0
A13952	1.0	1.0	1.0	225.6	225.6	225.6	11797.9	11797.9	11797.9	12435.5	12435.5	12435.5	3.1	5.1	7.1
A18013	1316.5	1316.5	1316.5	1567.6	1567.6	1567.6	2977.3	2977.3	2977.3	7134.8	7134.8	7134.8	2.4	4.3	6.3
A20070	1.0	1.0	1.0	0.0	0.0	0.0	22601.2	22601.2	22601.2	2249.0	2249.0	2249.0	3.5	5.5	7.5
A21039	629.2	629.2	629.2	2747.8	2747.8	2747.8	22572.2	22572.2	22572.2	4802.8	4802.8	4802.8	3.1	5.1	7.1
A28450	1.0	1.0	1.0	21.1	21.1	21.1	4575.5	4575.5	4575.5	5557.5	5557.5	5557.5	4.6	6.6	8.6
A36919	1.0	1.0	1.0	120.1	120.1	120.1	1636.5	1636.5	1636.5	608.4	608.4	608.4	5.1	7.1	9.1
A37281	1.0	1.0	1.0	0.0	0.0	0.0	1522.7	1522.7	1522.7	741.7	741.7	741.7	4.3	6.3	8.3

Step 2: Normalized decision matrix.

Weight	C_1			C_2			C_3			C_4			C_5		
	0.0378	0.0436	0.0535	0.0508	0.0697	0.0936	0.0512	0.0717	0.1061	0.0378	0.0436	0.0535	0.0473	0.0635	0.0833
A5879	0.2309	0.3355	0.4875	0.2031	0.4082	0.8165	0.4118	0.4118	0.4118	0.2062	0.2062	0.2062	0.2893	0.2893	0.2893
A6063	0.0770	0.1525	0.2625	0.1015	0.2041	0.4082	0.2277	0.2277	0.2277	0.2187	0.2187	0.2187	0.0263	0.0263	0.0263
A13797	0.2309	0.3355	0.4875	0.1015	0.2041	0.4082	0.3261	0.3261	0.3261	0.3490	0.3490	0.3490	0.2438	0.2438	0.2438
A13952	0.2309	0.3355	0.4875	0.1015	0.2041	0.4082	0.2713	0.2713	0.2713	0.4710	0.4710	0.4710	0.0044	0.0044	0.0044
A18013	0.2309	0.3355	0.4875	0.1015	0.2041	0.4082	0.2300	0.2300	0.2300	0.3987	0.3987	0.3987	0.0044	0.0044	0.0044
A20070	0.2309	0.3355	0.4875	0.2031	0.4082	0.8165	0.4176	0.4176	0.4176	0.4541	0.4541	0.4541	0.0044	0.0044	0.0044
A21039	0.1539	0.2440	0.3750	0.0000	0.0000	0.2041	0.2998	0.2998	0.2998	0.3904	0.3904	0.3904	0.9216	0.9216	0.9216
A28450	0.1539	0.2440	0.3750	0.2031	0.4082	0.8165	0.3211	0.3211	0.3211	0.1161	0.1161	0.1161	0.0606	0.0606	0.0606
A36919	0.2309	0.3355	0.4875	0.2031	0.4082	0.8165	0.2712	0.2712	0.2712	0.1165	0.1165	0.1165	0.0044	0.0044	0.0044
A37281	0.3079	0.4270	0.6000	0.2031	0.4082	0.8165	0.3238	0.3238	0.3238	0.1463	0.1463	0.1463	0.0550	0.0550	0.0550

Weight	C_6			C_7			C_8			C_9			C_{10}		
	0.0532	0.0766	0.1128	0.0673	0.1015	0.1605	0.0579	0.0840	0.1247	0.0426	0.0532	0.0691	0.3406	0.3926	0.4283
A5879	0.7150	0.7150	0.7150	0.2486	0.2486	0.2486	0.0713	0.0713	0.0713	0.2185	0.2185	0.2185	0.1348	0.2937	0.6212
A6063	0.4985	0.4985	0.4985	0.5983	0.5983	0.5983	0.1406	0.1406	0.1406	0.2987	0.2987	0.2987	0.1371	0.2967	0.6259
A13797	0.0003	0.0003	0.0003	0.0148	0.0148	0.0148	0.2658	0.2658	0.2658	0.3181	0.3181	0.3181	0.1246	0.2799	0.6001
A13952	0.0003	0.0003	0.0003	0.0541	0.0541	0.0541	0.3247	0.3247	0.3247	0.6661	0.6661	0.6661	0.1312	0.2888	0.6137
A18013	0.4423	0.4423	0.4423	0.3762	0.3762	0.3762	0.0819	0.0819	0.0819	0.3822	0.3822	0.3822	0.0986	0.2448	0.5463
A20070	0.0003	0.0003	0.0003	0.0000	0.0000	0.0000	0.6220	0.6220	0.6220	0.1205	0.1205	0.1205	0.1467	0.3098	0.6459
A21039	0.2114	0.2114	0.2114	0.6594	0.6594	0.6594	0.6212	0.6212	0.6212	0.2573	0.2573	0.2573	0.1311	0.2887	0.6136
A28450	0.0003	0.0003	0.0003	0.0051	0.0051	0.0051	0.1259	0.1259	0.1259	0.2977	0.2977	0.2977	0.1925	0.3716	0.7405
A36919	0.0003	0.0003	0.0003	0.0288	0.0288	0.0288	0.0450	0.0450	0.0450	0.0326	0.0326	0.0326	0.2133	0.3996	0.7835
A37281	0.0003	0.0003	0.0003	0.0000	0.0000	0.0000	0.0419	0.0419	0.0419	0.0397	0.0397	0.0397	0.1812	0.3563	0.7171

Step 3: Weighted normalized decision matrix.

	C_1			C_2			C_3			C_4			C_5		
A5879	0.0087	0.0146	0.0261	0.0103	0.0285	0.0764	0.0211	0.0295	0.0437	0.0078	0.0090	0.0110	0.0137	0.0184	0.0241
A6063	0.0029	0.0066	0.0140	0.0052	0.0142	0.0382	0.0117	0.0163	0.0242	0.0083	0.0095	0.0117	0.0012	0.0017	0.0022
A13797	0.0087	0.0146	0.0261	0.0052	0.0142	0.0382	0.0167	0.0234	0.0346	0.0132	0.0152	0.0187	0.0115	0.0155	0.0203
A13952	0.0087	0.0146	0.0261	0.0052	0.0142	0.0382	0.0139	0.0195	0.0288	0.0178	0.0205	0.0252	0.0002	0.0003	0.0004
A18013	0.0087	0.0146	0.0261	0.0052	0.0142	0.0382	0.0118	0.0165	0.0244	0.0151	0.0174	0.0213	0.0002	0.0003	0.0004
A20070	0.0087	0.0146	0.0261	0.0103	0.0285	0.0764	0.0214	0.0299	0.0443	0.0172	0.0198	0.0243	0.0002	0.0003	0.0004
A21039	0.0058	0.0106	0.0201	0.0000	0.0000	0.0191	0.0153	0.0215	0.0318	0.0148	0.0170	0.0209	0.0436	0.0585	0.0768
A28450	0.0058	0.0106	0.0201	0.0103	0.0285	0.0764	0.0164	0.0230	0.0341	0.0044	0.0051	0.0062	0.0029	0.0038	0.0050
A36919	0.0087	0.0146	0.0261	0.0103	0.0285	0.0764	0.0139	0.0194	0.0288	0.0044	0.0051	0.0062	0.0002	0.0003	0.0004
A37281	0.0116	0.0186	0.0321	0.0103	0.0285	0.0764	0.0166	0.0232	0.0344	0.0055	0.0064	0.0078	0.0026	0.0035	0.0046

	C_6			C_7			C_8			C_9			C_{10}		
A5879	0.0380	0.0548	0.0807	0.0167	0.0252	0.0399	0.0041	0.0060	0.0089	0.0093	0.0116	0.0151	0.0459	0.1153	0.2660
A6063	0.0265	0.0382	0.0562	0.0403	0.0607	0.0960	0.0081	0.0118	0.0175	0.0127	0.0159	0.0206	0.0467	0.1165	0.2681
A13797	0.0000	0.0000	0.0000	0.0010	0.0015	0.0024	0.0154	0.0223	0.0331	0.0136	0.0169	0.0220	0.0424	0.1099	0.2570
A13952	0.0000	0.0000	0.0000	0.0036	0.0055	0.0087	0.0188	0.0273	0.0405	0.0284	0.0354	0.0460	0.0447	0.1134	0.2628
A18013	0.0235	0.0339	0.0499	0.0253	0.0382	0.0604	0.0047	0.0069	0.0102	0.0163	0.0203	0.0264	0.0336	0.0961	0.2340
A20070	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0360	0.0522	0.0776	0.0051	0.0064	0.0083	0.0500	0.1216	0.2766
A21039	0.0112	0.0162	0.0238	0.0444	0.0669	0.1058	0.0360	0.0522	0.0775	0.0110	0.0137	0.0178	0.0447	0.1134	0.2628
A28450	0.0000	0.0000	0.0000	0.0003	0.0005	0.0008	0.0073	0.0106	0.0157	0.0127	0.0158	0.0206	0.0656	0.1459	0.3172
A36919	0.0000	0.0000	0.0000	0.0019	0.0029	0.0046	0.0026	0.0038	0.0056	0.0014	0.0017	0.0023	0.0726	0.1569	0.3356
A37281	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0024	0.0035	0.0052	0.0017	0.0021	0.0027	0.0617	0.1399	0.3071

Step 4: The positive ideal solution (PIS) and the negative ideal solution (NIS).

	C_1			C_2			C_3			C_4			C_5		
A^+	0.0116	0.0186	0.0321	0.0103	0.0285	0.0764	0.0214	0.0299	0.0443	0.0178	0.0205	0.0252	0.0436	0.0585	0.0768
A^-	0.0029	0.0066	0.0140	0.0000	0.0000	0.0191	0.0117	0.0163	0.0242	0.0044	0.0051	0.0062	0.0002	0.0003	0.0004

	C_6			C_7			C_8			C_9			C_{10}		
A^+	0.0380	0.0548	0.0807	0.0444	0.0669	0.1058	0.0360	0.0522	0.0776	0.0284	0.0354	0.0460	0.0726	0.1569	0.3356
A^-	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0024	0.0035	0.0052	0.0014	0.0017	0.0023	0.0336	0.0961	0.2340

Step 5: Distances d^+ and d^-.

d^+A5879	0.0621	0.0891	0.1337	d^-A5879	0.0486	0.0741	0.1170
d^+A6063	0.0627	0.0886	0.1321	d^-A6063	0.0520	0.0778	0.1201
d^+A13797	0.0774	0.1134	0.1753	d^-A13797	0.0262	0.0378	0.0536
d^+A13952	0.0785	0.1141	0.1737	d^-A13952	0.0371	0.0504	0.0704
d^+A18013	0.0724	0.1051	0.1612	d^-A18013	0.0399	0.0581	0.0865
d^+A20070	0.0797	0.1139	0.1687	d^-A20070	0.0425	0.0657	0.1061
d^+A21039	0.0446	0.0694	0.1137	d^-A21039	0.0738	0.1055	0.1556
d^+A28450	0.0800	0.1140	0.1676	d^-A28450	0.0363	0.0601	0.1040
d^+A36919	0.0850	0.1197	0.1741	d^-A36919	0.0409	0.0677	0.1175
d^+A37281	0.0850	0.1205	0.1767	d^-A37281	0.0317	0.0541	0.0953

Steps 6, 7 and 8: The relative closeness to ideal solution (R_i), defuzzification process ($I_{1/3,1/2}$ (R_i)) and ranking.

	R_i			$I_{1/3,1/2}$ (R_i)	Ranking
A5879	0.1940	0.4542	1.0564	0.5112	3
A6063	0.2060	0.4676	1.0480	0.5207	2
A13797	0.1145	0.2498	0.5177	0.2719	10
A13952	0.1521	0.3066	0.6093	0.3313	9
A18013	0.1612	0.3561	0.7698	0.3926	7
A20070	0.1548	0.3660	0.8675	0.4144	5
A21039	0.2741	0.6032	1.3139	0.6668	1
A28450	0.1337	0.3451	0.8937	0.4013	6
A36919	0.1403	0.3612	0.9332	0.4198	4
A37281	0.1165	0.3098	0.8168	0.3621	8

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