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Fuzzy MCDM framework for locating a nuclear power plant in Turkey

İsmail Erol [a,*], Safiye Sencer [1,b], Aslı Özmen [2,c], Cory Searcy [3,d]

[a] Yıldırım Beyazıt University, School of Management, 06690 Ankara, Turkey
[b] Sakarya University, School of Management, 54187 Sakarya, Turkey
[c] Abant İzzet Baysal University, Department of Business Administration, 14280 Bolu, Turkey
[d] Ryerson University, Mechanical and Industrial Engineering, Toronto, Ont., Canada M5B 2K3

H I G H L I G H T S

- Fuzzy MCDM approach is developed to select nuclear power plant location in Turkey.
- The proposed framework employs fuzzy entropy and fuzzy compromise programming.
- A criterion set was developed using a map by The Turkish Atomic Energy Authority.
- Cilingoz is found to be the best with the index values 0.6584 and 0.0838.
- The proposed tool can be considered a tool to evaluate the alternative sites.

A R T I C L E I N F O

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A B S T R A C T

Turkey has recently initiated a project to revise its nuclear policy. The revised nuclear energy policy considers searching for possible alternative locations for future nuclear power plants in Turkey. At the most basic level, the public cannot accurately evaluate whether it is willing to support nuclear energy unless it has an idea about where the power plants are likely to be located. It is argued that the selection of a facility location is a multi-criteria decision-making problem including both quantitative and qualitative criteria. In this research, given the multi-criteria nature of the nuclear facility location selection problem, a new decision tool is proposed to rank the alternative nuclear power plant sites in Turkey. The proposed tool is based on fuzzy Entropy and *t* norm based fuzzy compromise programming to deal with the vagueness of human judgments. Finally, a discussion and some concluding remarks are provided.

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1. Introduction

With one of the highest economic growth rates among OECD countries, the Turkish economy has been transforming rapidly. In particular, the Customs Union paves the way for streamlining the Turkish economy and its integration into the world trade system. The Customs Union process between Turkey and the European Union (EU) came into effect on January 1, 1996. With the Customs Union, free circulation of industrial goods and processed agricultural products between Turkey and the EU has been guaranteed without being subject to customs duties. Since 1996, Turkey's gross domestic product has increased 4-fold, making it one of the fastest growing economies in the world. Accordingly, the manufacturing industry in Turkey sustained an annual average growth rate of 6% between 1990 and 1998. In 1999 and 2001, the manufacturing industry growth rate declined to −5.7% and −9.9%, respectively. In 2002, the economy recovered, and the manufacturing industry growth rates reached 9.1% in 2002, 7.8% in 2003, 9.4% in 2004, 6.5% in 2005, 5.8% in 2006 and 5.6% in 2007 (IGEME, 2008). In 2008 and 2009, due to the global economic turmoil, the annual manufacturing growth rate declined down to −0.6% and −11.8%, respectively. Finally, in 2010, 2011 and 2012, it improved and the manufacturing growth rate increased by 9.2%, 8.8% and 2.2%, respectively.

Due in large part to the above-mentioned high manufacturing industry growth rates, Turkey is one of the fastest growing energy markets in the world. It is predicted that Turkish industrial electricity demand will be somewhere between 97 and 148 TWh by 2020 (Dilaver and Hunt, 2011). Given the projected high growth rates in electricity consumption, it is likely that Turkey will have to increasingly rely on foreign sources of energy. Meeting this anticipated energy need largely depends on how the country shapes its energy policy. In the new policy, it is essential that Turkey secure a

* Corresponding author:
E-mail address: ierol2001@yahoo.com (İ. Erol).
[1] Tel: +90 264295 7491.
[2] Tel: +90 3742541000.
[3] Tel: +1 416 979 5000x2095.

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safe and diverse energy supply. To this end, nuclear energy projects may be considered particularly due to the following advantages of nuclear energy: (1) it does not lead to carbon emissions, (2) its fuel can be obtained easily, economically, and be stored, (3) as long as appropriate security measures are taken and implemented, the risks to humans or nature are low (Jewell, 2011).

The Turkish Atomic Energy Authority (TAEA) is responsible for determining the basis of national policy and the related plans and programs regarding the peaceful utilization of atomic energy for the benefits of the state. TAEA has recently initiated a project to revise the nuclear policy of the country, including applications in nuclear energy associated with each sector (Kılıç, 2008). Based on the project, the Turkish government plans to begin construction on three nuclear plants by 2015. The first unit will be built at Akkuyu, which is located on the Mediterranean coast, because the site already has a license. Government officials have stated that the locations of the other two plants had not yet been decided.

One of the key issues that must be addressed as a part of the revised Turkish nuclear policy is establishing a framework to guide the selection of locations for future power plants. At the most basic level, the public cannot accurately evaluate whether it is willing to support the nuclear industry unless it has an idea about where the power plants are likely to be located. In the absence of this information, the Turkish Government would be asking the community to make decisions in the abstract without being fully informed.

A location problem, such as locating a nuclear power plant, must deal with the choice of a set of points for establishing certain facilities by taking into account different criteria and verifying a given set of constraints so that the needs of the users are optimally fulfilled (Perez et al., 2004; Gamper and Turcanu, 2007). It is argued that the selection of a facility location among multiple alternatives is a multi-criteria decision-making problem including both quantitative and qualitative criteria. It is also argued that the determination and evaluation of positive and negative characteristics of one location relative to others using miscellaneous criteria is a difficult task (Tuzkaya et al., 2008).

Kirkwood (1982) suggests that the nuclear power plant location problem has a number of challenging features, including: (1) the potential sites may be seismically active or have other natural features that might make them unacceptable for a nuclear power plant, (2) power plants require large quantities of water for cooling purposes, and water may be in short supply in the area, (3) there are significant uncertainties, including uncertainties about geology, water availability and future socioeconomic developments in the area, (4) in addition to system costs, other siting concerns include licensing requirements, public health and safety, environmental and socioeconomic effects and public acceptance, (5) nuclear power plants may have responsibilities to both its shareholders and its rate payers, and a variety of other groups may not be interested in nuclear power, (6) there may be data that could not be collected within a realistic budget and schedule or that may not be available, and (7) regulations of some institutions and other government bodies may impose requirements on the selection of sites for nuclear power plants.

In this research, given the above-mentioned concerns and the multiple criteria nature of the nuclear power plant site selection problem, a new multi-criteria-based framework is proposed in order to select the most appropriate location to build a nuclear power plant in Turkey. In a nuclear power plant problem, exact assessments can be obtained for some criteria, but not others. Since human judgments and preferences are often vague and complex, and decision makers cannot estimate their preferences with an exact scale, linguistic assessments can only be given instead of exact assessments. Therefore, fuzzy set theory is introduced into the proposed multi-criteria decision making (MCDM) framework, which is put forward to solve such uncertainty problems.

The structure of this paper is organized as follows: First, existing research on facility locations based on multi-criteria methods is reviewed. Second, a fuzzy entropy model is developed to identify the weights of the relevant criteria. Next, the fuzzy t norm based compromise programming framework is proposed. The framework is based on obtaining the minimum fuzzy distance to the fuzzy ideal solution of the nuclear power plant location selection problem. Then, Turkey's power plant selection problem is discussed using the proposed model. Finally, a discussion and some concluding remarks are provided.

2. Ranking facility location alternatives using multi-criteria methods

Location analysis has become a very active field of research in the last few decades. In this section, a survey of the most representative multi-criteria location research is provided. First, two studies on nuclear power plant site selection are discussed. Kirkwood (1982) discusses a multi-disciplinary study conducted to select a site for a nuclear power plant. A series of screening steps were carried out to identify candidate sites for the plant, as well as candidate water sources. Then, multi-objective decision analysis methods were used to evaluate and rank these candidate sites and water sources. Ford et al. (1979) present a study to evaluate the appropriateness of alternative methodologies for analyzing a specified problem. This procedure is illustrated by identifying desirable characteristics of nuclear power plant site selection methodologies and evaluating the adequacy of methodologies that have been used to select nuclear power plant sites. The objectives of such siting methodologies are specified and attributes are developed to measure the degree of attainment of each objective. Finally, several siting methodologies are rated on the various attributes, and these ratings are analyzed to determine the adequacy of each methodology.

In addition to the research focused specifically on nuclear power plant site selection, examples of location selection problems in miscellaneous industries are also available. For example, Yang and Lee (1997) present an analytical hierarchy process (AHP) decision model for facility location selection from the view of organizations contemplating the construction of a new facility or relocation of existing facilities. The AHP model provides a framework to assist managers in analyzing various location factors, evaluating location site alternatives, and making final location selections. An example problem is used to illustrate the solution process and address potential managerial implications.

Hokkanen and Salminen (1997) describe an application of a multi-criteria decision aid to the location of a waste treatment facility in eastern Finland. The alternative locations for the facility were considered based on 14 criteria evaluated by 28 decision makers. They make use of the Preference Ranking Organization Method for Enrichment Evaluation (PROMETHEE) decision aid, which was found to fit well with certain constraints in this type of problem with multiple criteria and multiple decision makers.

Kahraman et al. (2003) solve facility location problems using fuzzy multi-attribute group decision-making. The paper includes four different fuzzy multi-attribute group decision-making approaches. The first one is a fuzzy model of group decisions. The second is fuzzy synthetic evaluation. The third is the weighted goals method, and the last one is fuzzy AHP. These approaches are extended to select the best facility location alternative by taking into account quantitative and qualitative criteria. A short comparative analysis among the approaches is provided, and a numeric example to each approach is given.

Bailey et al. (2003) present an application of a new fuzzy algorithm for finding and exploring potential solutions to group

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site selection problems in a Geographical Information System environment. The paper outlines the fuzzy algorithm and its use in site selection for a recycling facility at the Brisbane Airport site, which is located in Australia. Linguistic assessments from decision-makers are represented as triangular fuzzy numbers. The first aggregation of inputs is a compensatory one based on fuzzy multi-attribute decision making theory. An adjusted aggregation then factors in conflicts, risks and uncertainties to enable a variety of compensatory and non-compensatory outcomes to be generated based on decision-maker preferences.

Norese (2006) describes a phase of the decision process initiated by the District of Turin (in northwest Italy) to evaluate and rank possible plant location sites. Two multi-criteria models—one for the incinerator and the other for the waste-disposal plant—were elaborated and an ELECTRE method used to compare sites and rank them with the aim of selecting the best sites to activate an Environmental Impact Assessment procedure.

Bian and Yu (2006) use AHP in order to evaluate the alternative reverse logistics (RL) operation locations for an international electrical manufacturer. Colebrook and Sicilia (2007) analyze the undesirable center and median models to remove inefficient edges. Finally, they also comment on how this model can be slightly modified to generalize other models presented in the literature.

Queiruga et al. (2008) describe a method for ranking of Spanish municipalities according to their appropriateness for the installation of recycling plants. In order to rank the alternatives, the discrete multi-criteria decision method PROMETHEE, combined with a group of experts, is applied. The method does not present an optimal structure of the future recycling system, but provides a selection of good alternatives for potential locations of recycling plants. Tabari et al. (2008) propose a fuzzy AHP the proposed model considers objective, critical, and subjective factors as the three main common factors in location analysis. Tuzkaya et al. (2008) address the problem of undesirable facility location selection using the analytic network process (ANP). The questions of what criteria are considered and the interdependencies between these criteria and their weights are discussed and determined via interviews with some competent authorities of the Istanbul Municipality and two environmental organizations.

Kannan et al. (2008) investigate the use of AHP and fuzzy AHP for selecting the collection center location in a RL network. Pochampally and Gupta (2008) integrate AHP and fuzzy set theory to determine potential facilities from a set of candidate recovery facilities.

Pochampally and Gupta (2009) employ a four phase approach to evaluate the efficiencies of collection and recovery facilities, namely (1) identification of criteria for evaluation of the facilities of interest, (2) use of fuzzy ratings of existing facilities to construct a neural network that gives the importance value for each criterion, (3) employment of a fuzzy Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) approach to obtain the overall ratings of the facilities of interest, and (4) employment of Borda's choice rule to calculate the maximized consensus ratings of the facilities of interest. Finally, Farahani et al. (2010) provide a review of recent efforts in multi-criteria location problems in three categories, including bi-objective, multi-objective and multi-attribute problems and their solution methods.

Based on the above-mentioned state of the art, in this research, two points are considered: (1) the nuclear power plant selection problem is a multi-criteria decision making problem, and (2) the problem contains several criteria, which are uncertain and vague.

3. Methodology

The proposed fuzzy approach applied to the nuclear facility location selection problem in Turkey is displayed in Fig. 1.

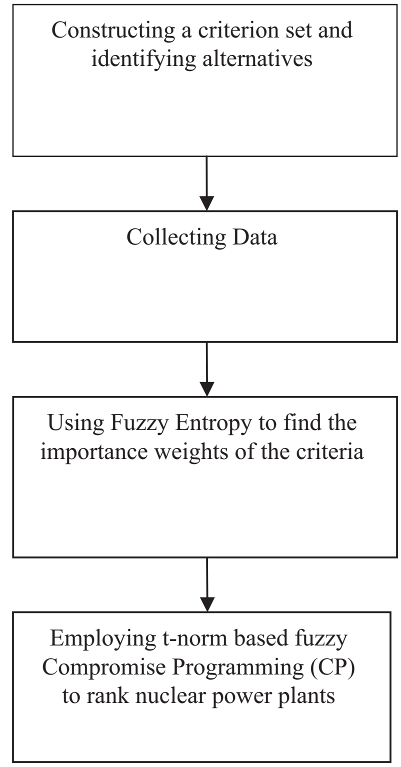

Fig. 1. The proposed model.

In the first step, a criterion set is established and alternative sites are identified. Then, in the second step, data are obtained with respect to criteria established in the first step. In the third step, criteria are weighted using the proposed fuzzy entropy values. In the fourth step, the ranking of the nuclear power plant location alternatives are calculated using t-norm based Fuzzy CP.

3.1. Establishing criteria set, identifying alternatives and collecting data

Criteria enable alternatives to be compared from a specific point of view. Undoubtedly, selecting criteria is a delicate part in formulating the problem facing the decision maker, and thus requires the utmost care. In this process, each possible criterion should be included in the analysis to handle the site evaluation from a wide variety of viewpoints. This would help the decision makers better understand the problem, thus improving their confidence in the final evaluation.

Once criteria have been identified, possible alternatives are generated. However, to make the analysis practical, a screening process could be performed in order to reduce the number of alternatives to be considered. There may still be too many alternatives to analyze in a practical situation. Thus, as a final step before carrying out the complete decision analysis, professionals familiar with the engineering and environmental requirements for a plant site select a relatively small number of specific locations after screening for consideration in the complete decision analysis (Kirkwood, 1982).

Finally, data with respect to alternatives based on criteria are collected using miscellaneous sources. Data can be either quantitative or qualitative in nature. The data collection process is critical since the reliability of the results is based on the accuracy of data.

3.2. Calculating the importance of criteria and ranking alternatives

Data overload is a potentially serious problem with any measurement system. Therefore, once the criteria lists have been

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selected, they should be prioritized for use. Next, the final rankings of the alternatives are calculated. However, since human judgments and preferences are often vague and complex, and decision makers cannot estimate their preferences with an exact scale, linguistic assessments can only be given instead of exact assessments. It is argued that the application of fuzzy reasoning techniques provides an effective tool to handle the uncertainties and subjectivities arising in nuclear plant selection problems. A short introduction to fuzzy numbers is provided in the Appendix.

3.2.1. *Fuzzy entropy*

Several methods can be used to appropriately weigh the criteria. However, no single method can guarantee a more exact result, and the same decision makers may obtain different weights. Therefore, it is argued that there is no method to identify what the true weight is (Chang and Yeh, 2001; Weber and Borcherding, 1993; Yeh et al., 1999).

The entropy method is mainly useful for assigning a weight to each criterion because of the fact that (Chen and Hwang, 1992; Hwang and Yoon, 1981; Zeleny, 1982; Xu et al., 2004; Zou et al., 2006; Sopadang et al., 2002): (1) this method does not require an individual decision maker to rank the criteria, and (2) the relative weight of each criterion can be obtained using straightforward calculations. Briefly, decision makers can use the actual performance values of companies for calculating the weights. It is therefore argued that the Entropy method is an objective weighting technique. Consequently, the inherent subjectivity in calculating weights is in large part addressed.

In the traditional entropy method, the decision variables are deterministic and the utility values are crisp. Therefore, the general entropy method is unable to handle problems with qualitative and uncertain data. To this end, several studies have been done related to fuzzy entropy. For example, Parkash and Sharma (2004a) developed some measures of fuzzy entropy and obtained relationships among these measures. Applications of these measures to coding theory were further provided by Parkash and Sharma (2004b). Guo and Xin (2006) have extended Zadeh's (1965) idea to study some new generalized entropy formulas for fuzzy sets. Parkash et al. (2008) have developed two new measures of weighted fuzzy entropy and applied the results towards optimization principles. Erol et al. (2011) proposed a fuzzy entropy approach based on triangular fuzzy membership functions.

In this study, we propose a fuzzy entropy approach based on trapezoid fuzzy numbers for the fuzzification process since trapezoid fuzzy numbers can provide more sensitive analysis for uncertain data. Since the approach takes into account both subjective and objective factors, it retains the merits of both subjective and objective approaches.

Decision matrix D of m alternatives and n criteria is as follows:

$$D=\begin{array}{c} \\ A_1\\ A_2\\ .\\ .\\ A_i\\ .\\ .\\ A_m\end{array}\begin{array}{c}\begin{array}{cccccc} X_1 & X_2 & & X_j & & X_n\end{array}\\ \begin{bmatrix} X_{11} & X_{12} & \ldots & X_{ij} & \ldots & X_{1n}\\ X_{21} & X_{22} & \ldots & X_{2j} & \ldots & X_{2n}\\ . & . & . & . & . & .\\ . & . & . & . & . & .\\ X_{i1} & X_{i2} & \ldots & X_{ij} & \ldots & X_{in}\\ . & . & . & . & . & .\\ . & . & . & . & . & .\\ X_{m1} & X_{m2} & \ldots & X_{mj} & \ldots & X_{mn}\end{bmatrix}\end{array} \quad (1)$$

where A_i is the ith alternative considered and x_{ij} is the numerical outcome of the ith alternative with respect to the jth criterion.

Step 1: Calculate the normalized fuzzy decision matrix, $\tilde{S}$.

$$\tilde{S}=\lfloor \tilde{s}_{ij}\rfloor_{m\times n}, \quad i=1,\ 2,\ldots,m; \quad j=1,\ 2,\ldots,n. \quad (2)$$

The benefit criteria, normalized value $\tilde{s}_{ij}$ is calculated as

$$\tilde{s}_{ij}=\left(\frac{x_{ij}-\max_i x_{ij}}{\max_i x_{ij}-\min_i x_{ij}}\right) \quad (3)$$

Similarly, the normalized value of $\tilde{s}_{ij}$ for the cost criteria is calculated as

$$\tilde{s}_{ij}=\left(\frac{\max_i x_{ij}-x_{ij}}{\max_i x_{ij}-\min_i x_{ij}}\right) \quad (4)$$

For fuzzy numbers, we would first transform the fuzzy numbers into crisp numbers. Although there are many methods to transform fuzzy numbers, most of these methods do not take into account the decision-maker's preferences for the degree of uncertainties. The following formula can be used to consider these factors:

$$F(s_{ij})=\frac{\int s\ \max_i s_{ij}(s_{ij})dx}{\int s(s_{ij})} \quad (5)$$

where $F(s_{ij})$ represents the value of the jth attribute of the ith alternative.

Step 2: Fuzzy weights by normalization are computed as follows:

$$\tilde{Y}^k=(\tilde{s}^k_{ij})_{m\times n}=\begin{array}{c} \\ s_1\\ s_2\\ .\\ .\\ .\\ s_m\end{array}\begin{array}{c}\begin{array}{cccc} x_1 & x_2 & \ldots & x_n\end{array}\\ \begin{pmatrix} \tilde{s}^k_{11} & \tilde{s}^k_{12} & \ldots & \tilde{s}^k_{1n}\\ \tilde{s}^k_{21} & \tilde{s}^k_{22} & \ldots & \tilde{s}^k_{2n}\\ . & . & . & .\\ . & . & . & .\\ . & . & . & .\\ \tilde{s}^k_{m1} & \tilde{s}^k_{m2} & \ldots & \tilde{s}^k_{mn}\end{pmatrix}\end{array} \quad (k=1,2,\ldots,K) \quad (6)$$

where

$\tilde{s}^k_{ij}=((a^k_{i1j}-\alpha^k_{i1j}),\alpha^k_{i1j},\alpha^k_{i2j},(a^k_{i2j}+\alpha^k_{i2j}))$ represents normalized values

$$f_{ij}=\frac{F(\tilde{S}_{ij})}{\sum_{i=1}^{n}F(\tilde{S}_{ij})} \quad (7)$$

$$\tilde{E}_j=-k\sum_{i=1}^{m}f_{ij}Inf_{ij}=-\frac{1}{Inm}\sum_{i=1}^{m}f_{ij}Inf_{ij} \quad (8)$$

Now, calculate the fuzzy distance entropy weight with the following equation:

$$W^d_j=\frac{1-\tilde{E}_j}{\sum_{j=1}^{n}(1-\tilde{E}_j)} \quad (9)$$

Step 3: Fuzzy weights with the trapezoid approach are calculated below.

$$W_j=(w_j^{a_1-\alpha_1},\ w_j^{\alpha_1},\ w_j^{\alpha_2},\ w_j^{a_2+\alpha_2}), \quad j=1,2,\ldots,n \quad (10)$$

$$w_j^{(a_1-\alpha_1)_{(lowerbound)}}=\frac{(1/f_{ij}^{(a_1-\alpha_1)})-1}{(1/f_{ij}^{(a_1-\alpha_1)})-1+\sum_{k\neq j}((1/f_{ij}^{(a_2+\alpha_2)})-1)},$$
$$k=1,2,\ldots,n, \quad (11)$$

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$$w_j^{a_1} = \frac{(1/f_{ij}^{a_1}) - 1}{\sum_{k=1}^{n}((1/f_{ij}^{a_1}) - 1)}, \quad k = 1, 2, \ldots, n, \tag{12}$$

$$w_j^{a2} = \frac{(1/f_{ij}^{a2}) - 1}{\sum_{k=1}^{n}((1/f_{ij}^{a2}) - 1)}, \quad k = 1, 2, \ldots, n, \tag{13}$$

$$w_j^{(a_2+\alpha_2)_{(upperbound)}} = \frac{(1/f_{ij}^{(a_2+\alpha_2)}) - 1}{(1/f_{ij}^{(a_2+\alpha_2)}) - 1 + \sum_{k\neq j}((1/f_{ij}^{(a_1-\alpha_1)}) - 1)}, \quad k = 1, 2, \ldots, n, \tag{14}$$

In the proposed method, the fuzzy entropy of the criterion is calculated using the hamming distance function as follows:

$$d(x, y) = \sum_{i=1}^{n} |x_i - y_i| \tag{15}$$

We then apply the fuzzified weight values

$$w_d^{(a_1-\alpha_1)} = \sum_{i=1}^{n} |(w_i^{(a_1-\alpha_1)}) - (w_j^{(a_1-\alpha_1)})| \tag{16}$$

$$w_d^{(a_1)} = \sum_{i=1}^{n} |(w_i^{(a_1)}) - (w_j^{(a_1)})| \tag{17}$$

$$w_d^{(a2)} = \sum_{i=1}^{n} |(w_i^{(a2)}) - (w_j^{(a2)})| \tag{18}$$

$$w_d^{(a2+\alpha2)} = \sum_{i=1}^{n} |(w_i^{(a2+\alpha2)}) - (w_j^{(a2+\alpha2)})| \tag{19}$$

$$\tilde{W}_j = \left((w_j^{(a_1-\alpha_1)}) \left(\frac{w_d^{(a_1-\alpha_1)}}{w_j^{(a_1-\alpha_1)}} \right), (w_j^{(a_1)}) \left(\frac{w_d^{(a_1)}}{w_j^{(a_1)}} \right), (w_j^{(a_2)}) \left(\frac{w_d^{(a2)}}{w_j^{(a_2)}} \right), (w_j^{(a_2+\alpha_2)}) \left(\frac{w_d^{(a2+\alpha2)}}{w_j^{(a_2+\alpha_2)}} \right) \right) \tag{20}$$

3.2.2. Fuzzy Compromise Programming

Compromise Programming (CP) is a distance-based Multiple Criteria Decision Making (MCDM) approach introduced by Yu and Zeleny in the 1970s with many theoretical extensions and with applications in several fields (Zeleny, 1982). Its basic idea is to determine a subset of efficient solutions (called a compromise set) that is nearest with respect to an ideal and infeasible point (called the ideal point), for which all the criteria are optimized. The corresponding distance functions are introduced through a family of p-metrics.

In the traditional CP approach, the decision variables are deterministic and the utility values are crisp. For this reason, the general CP method is unable to handle problems with qualitative and uncertain data. In industrial practice, however, practitioners and experts often describe objects or events with uncertain and linguistic information. For instance, decision makers may use a “fuzzy” term such as “very difficult” to describe the degree of effectiveness in a certain performance measurement system. In other cases, they may give a range of a certain parameter for describing an object. In turn, in applying the theory to the selection problem, the decision makers may provide a range of values for a specific indicator level.

To this end, a few studies on fuzzy CP have recently been published. Bender and Simonovic (2000) uses a fuzzy compromise approach to decision analysis within the context of water resource systems planning under uncertainty. The approach allows various sources of uncertainty and is intended to provide a flexible form of group decision support. Li and Lai (2000) present a fuzzy CP approach to multi-objective transportation problems. A characteristic feature of the approach proposed is that various objectives are synthetically considered with marginal evaluation for individual objectives and global evaluation for all objectives. Finally, Alptekin (2012) incorporates fuzzy arithmetic into CP that necessitates the use of fuzzy numbers for the ideal and anti-ideal points, as well as the outcomes of the objective functions. The implementation of fuzzy numbers in the model requires the use of fuzzy ranking approaches.

There are many benefits of adopting fuzzy CP (Bender and Simonovic, 2000). The clearest is the incorporation of subjective uncertainty. Expressing possibility values with fuzzy inputs allows experience to play a significant role in the expression of input information. The shape of a fuzzy set expresses the experience or the interpretation of a decision maker. Conflicting data or preferences can also be easily expressed using multimodal fuzzy sets, making the fuzzy compromise approach a candidate for application to group decision making.

In this study, we propose a fuzzy CP approach based on the fuzzy entropy weight and fuzzy normalized data using trapezoid fuzzy number structure with Yager's t-norm that focus on the minimization of the distance between fuzzy numbers, the fuzzy ideal solution and the fuzzy objectives. In the proposed fuzzy CP, the distance metric exponent, p, is likely the most imprecise or vague element of distance metric calculation. Fuzziffication of the distance metric exponent, p, can take many forms but in a practical way it might be defined by a trapezoid fuzzy set. Larger or smaller (fuzzy) values of p may also be valid but fuzzy exponential operations for large exponents results in difficult interpretation of the distance metric due to a large degree of fuzziness (range of possible values).

The proposed Yager's t-norm based fuzzy CP considers different values, which can be applied to different cases, such as $p=1$ representing the case of separable and additive utility functions, a linear programming model with compensatory effect, meaning a low performance in one of the objectives could be offset by a higher performance in one or more other objectives (Yager, 1980). $p=2$ corresponds to the Euclidean distance, a typical quadratic programming model case.

The proposed fuzzy CP algorithm to rank alternatives can be summarized as follows:

$$Lp_j = w_k \left[\sum_{k=1}^{(a_1-\alpha_1)_j} \left(\frac{\tilde{f}_k(x) - \tilde{f}_k^*}{\max_{\tilde{f}_k} - \min_{\tilde{f}_k}} \right)^p + \sum_{k=(a_1-\alpha_1)+1}^{(\alpha 1)_j} \left(\frac{\tilde{f}_k(x) - \tilde{f}_k^*}{\max_{\tilde{f}_k} - \min_{\tilde{f}_k}} \right)^p + \sum_{k=a_1+1}^{(a_2)_j} \left(\frac{\tilde{f}_k(x) - \tilde{f}_k^*}{\max_{\tilde{f}_k} - \min_{\tilde{f}_k}} \right)^p + \sum_{k=a_2+1}^{(a_2+\alpha_2)_j} \left(\frac{\tilde{f}_k(x) - \tilde{f}_k^*}{\max_{\tilde{f}_k} - \min_{\tilde{f}_k}} \right)^p \right]^{1/p} \tag{21}$$

where j is the criteria

$\tilde{f}_j^* = (a_1 - \alpha_1)_j^*$ is the ideal value that represents optimal value which is based on criteria's max or min value

$$\begin{aligned} & p = 1 \\ & q \to \infty \quad \text{Lower bound} \\ & T_{lowerbound}(\mu_{\tilde{A}_1}, \mu_{\tilde{A}_2}) = \max\{0; \mu_{\tilde{A}_1}(x_1) + \mu_{\tilde{A}_2}(x_2) - 1\} \end{aligned} \tag{22}$$

$$Lp_j = w_k \otimes \max\left\{ 0, \left[\sum_{k=1}^{(a_1-\alpha_1)_j} \left(\frac{\tilde{f}_k(x) - \tilde{f}_k^*}{\max_{\tilde{f}_k} - \min_{\tilde{f}_k}} \right)^p + \sum_{k=(a_1-\alpha_1)+1}^{(\alpha_1)_j} \left(\frac{\tilde{f}_k(x) - \tilde{f}_k^*}{\max_{\tilde{f}_k} - \min_{\tilde{f}_k}} \right)^p + \sum_{k=a_1+1}^{(a_2)_j} \left(\frac{\tilde{f}_k(x) - \tilde{f}_k^*}{\max_{\tilde{f}_k} - \min_{\tilde{f}_k}} \right)^p + \sum_{k=a_2+1}^{(a_2+\alpha_2)_j} \left(\frac{\tilde{f}_k(x) - \tilde{f}_k^*}{\max_{\tilde{f}_k} - \min_{\tilde{f}_k}} \right)^p \right]^{1/p} \right\} \tag{23}$$

$p \to \infty$

$q = 1$ Upper bound

$Lp_j = w_k \otimes$

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$$\min\left\{1,\left[\sum_{k=1}^{(a_1-\alpha_1)_j}\left(\frac{\tilde{f}_k(x)-\tilde{f}_k^*}{\max_{\tilde{f}_k}-\min_{\tilde{f}_k}}\right)^p+\sum_{k=(a_1-\alpha_1)+1}^{(\alpha_1)_j}\left(\frac{\tilde{f}_k(x)-\tilde{f}_k^*}{\max_{\tilde{f}_k}-\min_{\tilde{f}_k}}\right)^p+\sum_{k=\alpha_1+1}^{(\alpha_2)_j}\left(\frac{\tilde{f}_k(x)-\tilde{f}_k^*}{\max_{\tilde{f}_k}-\min_{\tilde{f}_k}}\right)^p+\sum_{k=\alpha_2+1}^{(a_2+\alpha_2)_j}\left(\frac{\tilde{f}_k(x)-\tilde{f}_k^*}{\max_{\tilde{f}_k}-\min_{\tilde{f}_k}}\right)^p\right]^{1/p}\right\} \tag{24}$$

4. Application

In this research, four potential nuclear power plant sites are considered based on the preliminary screening study conducted by TAEA. Then, the guideline shown in Fig. 1 is followed to rank the alternative sites. The steps of this process are given in the following sections.

4.1. Identifying alternatives

Nuclear power plant construction and operation in Turkey is regulated by TAEA as noted earlier. Therefore, our research team consulted with TAEA management in order to obtain the results of their preliminary studies. They stated that a screening process was conducted, and four alternatives were found to be worthy of further consideration. Therefore, we based our analysis on those alternatives, including Poliçe, Çilingoz, Kefke and İnceburun. Poliçe, Çilingoz and Kefken are located in the Marmara Region, while Inceburun is in the Blacksea Region of Turkey. Poliçe is a small village in Demirköy, district of Kırklareli Province. Çilingoz is a small town located in Çatalca, district of Istanbul. Kefken is situated in Kandıra, which is a district of Kocaeli Province, and the last alternative Inceburun is situated in Sinop Province, which is known as the farthest northern point of Turkey (Fig. 2).

4.2. Establishing a criterion set

A criterion set was developed based on the brief road map suggested by TAEA since any nuclear power plant location study must consider that road map to identify selection criteria in Turkey. (http://www.taek.gov.tr/bilgi/elkitabi_brosur/brosurler/genel/13.html).

Based on that road map, there are three primary criteria for siting nuclear power plants in Turkey: (1) proximity to appropriate existing electricity infrastructure, (2) proximity to transport infrastructure to facilitate the movement of nuclear fuel, and (3) access to large quantities of water for cooling.

There are also a number of potential secondary criteria that are relevant to siting nuclear power plants as follows:

4.2.1. Population density

Nuclear power plants should preferably be located in sparsely populated areas that are distant from large population centers. Distance from densely populated areas is necessary to minimize community opposition and security risks and to reduce the complexity associated with emergency planning.

4.2.2. Geological and seismological issues

Geological and seismological factors have an important bearing on the costs and risks associated with nuclear power plants. They influence how pollution dissipates into the environment, as well as the risk of natural events triggering a substantial release of radioactive material. Siting nuclear power plants in seismically unstable areas increases the costs of construction and operation.

4.2.3. Atmospheric conditions

There are two main atmospheric considerations. The first is whether extreme weather events could affect the safe and efficient operation of the nuclear power plant. Examples of relevant weather events include cyclones and floods. The second consideration is how atmospheric conditions could affect the dispersion of radioactive material and other pollutants from routine releases and accidents. Relevant factors include prevailing winds, topographical factors that influence local climate (for example, hills and valleys), and risk of local fogging or icing due to water vapor discharge.

4.2.4. Cost factors

The construction of nuclear power plants should be evaluated in terms of the cost of construction, the cost of building a power line and the cost of a cooling system. Minimizing these costs is necessary to reduce basic fixed costs, which makes an alternative more desirable.

4.2.5. Risk factors

Two potential environmental risk factors are identified, namely locating a nuclear power plant in major industrial and fresh water areas. Decision makers should consider the fact that when siting a nuclear power plant, putting industrial areas and fresh water resources at risk may cause undesirable results.

Finally, based on the above-mentioned road map, a criterion set was developed, and their measures were identified as displayed in

Fig. 2. Location of alternative sites.

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Table 1. Table 1 indicates that there are 21 criteria, seven of which are qualitative.

4.3. Collecting data

In this step, first, we consulted with TAEA to obtain the data with respect to the alternatives based on the criteria. However, TAEA management informed us that they did not have accurate data and rejected our request. Therefore, the data for each alternative based on the 21 criteria were collected as displayed in Table 2 using various data sources. The linguistic assessment results for qualitative criteria are obtained by guiding the decision makers through a subjective assessment process of comparing the quantitative assessment scale corresponding to the linguistic terms defined in Table 1. Table 2 clarifies how each criterion is improved. Some criteria are improved when their values are maximized while the rest get better when their values are minimized.

To this end, the research team got in touch with several governmental institutions, such as the Turkish Statistical Institute, the Republic of Turkey Ministry of Environment and Forestry, the Turkish State Meteorological Service, and the local municipal bodies. Interviews were conducted with the officers of those institutions, and request letters were also written to each institute. As a result, within 2 months, the data with respect to seven qualitative and 14 quantitative criteria were obtained.

Regarding the qualitative criteria, "topographical features" and "availability of the land" are evaluated based on the scale being extremely high, very high, high, medium, low, very low, and extremely low, respectively as displayed in Fig. 3.

To this end, linguistic values for a certain alternative compared to the rest of the alternatives were obtained. For example, availability of the land for Poliçe was evaluated as linguistics variable "very high" by an expert in Republic of Turkish Ministry of Environment and Forestry. The linguistic values for the criteria "topographical features" and "availability of the land" were obtained similarly. Note that higher linguistics assessments of the scales for the criteria "topographical features" and "availability of the land" indicate that topographical features are getting better, and that more appropriate lands are available for a certain alternative. In another example, maximum probable speed for

Table 1
Selection criteria.

C_{11}	2–10 km between (person) – (C_{11})
C_{12}	10–20 km between (person) – (C_{12})
C_{13}	Distance from population zone (km) – (C_{13})
C_{21}	Seismic position (Magnitude of earthquake) – (C_{21})
C_{22}	Vicinity of earthquakes on faults in the site (distance from active fault) – (C_{22})
C_{31}	Proximity to major highway (km) – (C_{31})
C_{32}	Proximity to major airport (km) – (C_{32})
C_{33}	Topographical features – (C_{33})
C_{41}	Average temperature (°C) – (C_{41})
C_{42}	Maximum probable wind speed (h) – (C_{42})
C_{43}	Maximum probable precipitation/square – (C_{43})
C_{51}	Distance from the closest cooling water source (m) – (C_{51})
C_{52}	Water temperature (°C) – (C_{52})
C_{61}	Availability of the land – (C_{61})
C_{62}	Forest area (ha) – (C_{62})
C_{63}	Farming area (ha) – (C_{63})
C_{64}	Fresh water at risk – (C_{64})
C_{71}	Construction cost – (C_{71})
C_{72}	The cost of constructing a cooling system – (C_{72})
C_{73}	The cost of constructing a power line – (C_{73})
C_{74}	Industry at risk – (C_{74})

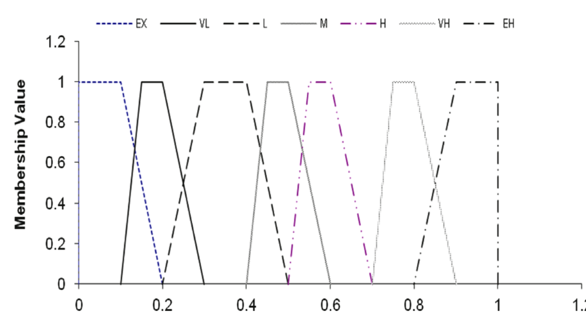

Fig. 3. Membership function values.

Table 2
Each alternative's linguistic and quantitative values.

		POLICE	CILINGOZ	KEFKEN	INCEBURUN	
Population density	Min	2–10 km between (person) – (C_{11})	1411	1387	7757	4697
	Min	10–20 km between (person) – (C_{12})	13,498	16,448	26,795	58,932
	Max	Distance from population zone (km) – (C_{13})	9	9	3	5
Earthquake	Min	Seismic position (Magnitude of earthquake) – (C_{21})	1	2	4	3
	Max	Vicinity of earthquakes on faults in the site (Distance from active fault) – (C_{22})	75	75	45	100
Geographic conditions	Min	Proximity to major highway (km) – (C_{31})	60	35	79	65
	Min	Proximity to major airport (km) – (C_{32})	110	85	140	190
	Max	Topographical features – (C_{33})	EL	EH	EH	EL
Meteorological characteristics	Min	Average temperature (°C) – (C_{41})	33.39	28.76	31.27	26.83
	Min	Maximum probable wind speed (h) – (C_{42})	112.7	98.6	112.7	128.2
	Min	Maximum probable precipitation/square – (C_{43})	75.2	81.3	125.8	133.2
Cooling water features	Min	Distance from the closest cooling water source (m) – (C_{51})	700	1200	500	250
	Min	Water temperature (°C) – (C_{52})	23	23	23	23.5
Land use	Max	Availability of the land – (C_{61})	EH	EH	EL	EL
	Min	Forest area (ha) – (C_{62})	9401.5	574	8154	8185
	Min	Farming area (ha) – (C_{63})	803	21	8425	14,279
	Max	Fresh water at risk – (C_{64})	EL	EL	EH	EH
Economic conditions	Max	Construction cost – (C_{71})	EL	EL	EH	EH
	Max	The cost of constructing a cooling system – (C_{72})	EH	L	L	EL
	Max	The cost of constructing a power line – (C_{73})	EH	EL	EL	EH
	Min	Industry at risk – (C_{74})	M	EL	EL	EH

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Table 3
Linguistic variables for indicators (EH: extremely high; VH: very high; H: high; M: medium; L: low; VL: very low; EL: extremely low).

	Min C_{11}	Min C_{12}	Max C_{13}	Min C_{21}	Max C_{22}	Min C_{31}	Min C_{32}	Max C_{33}	Min C_{41}	Min C_{42}	Min C_{43}	Min C_{51}	Min C_{52}	Max C_{61}	Min C_{62}	Min C_{63}	Max C_{64}	Max C_{71}	Max C_{72}	max C_{73}	Min C_{74}
POLICE	EH	EH	EH	EH	M	L	EL	EL	EL	M	EH	M	EH	EH	EL	VH	EL	EL	EH	EH	M
CILINGOZ	EH	VH	EH	H	L	EH	EH	EH	H	EH	VH	EL	EH	EH	EH	EH	EL	EL	L	EL	EL
KEFKEN	EL	H	EL	EL	EL	EL	L	EH	VL	L	EL	H	EH	EL	EL	VL	EH	EH	L	EL	EL
INCEBURUN	L	EL	VL	VL	EH	VL	EL	EL	EH	EL	EL	EH	EL	EL	EL	EL	EH	EH	EL	EH	EH

Table 4
Fuzzy interval values for each location with respect to criteria.

Alternatives	Fuzzy intervals	Criteria																				
		C_{11}	C_{12}	C_{13}	C_{21}	C_{22}	C_{31}	C_{32}	C_{33}	C_{41}	C_{42}	C_{43}	C_{51}	C_{52}	C_{61}	C_{62}	C_{63}	C_{64}	C_{71}	C_{72}	C_{73}	C_{74}
POLICE	$a_{1-}\ \alpha_1$	0.8	0.8	0.8	0.8	0.4	0.2	0.0	0.0	0.0	0.4	0.8	0.4	0.8	0.8	0.0	0.7	0.0	0.0	0.8	0.8	0.4
	a_1	0.9	0.9	0.9	0.9	0.45	0.3	0.0	0.0	0.0	0.45	0.9	0.45	0.9	0.9	0.0	0.75	0.0	0.0	0.9	0.9	0.45
	a_2	1.0	1.0	1.0	1.0	0.5	0.4	0.1	0.1	0.1	0.5	1.0	0.5	1.0	1.0	0.1	0.8	0.1	0.1	1.0	1.0	0.5
	$a_{2+}\ \alpha_2$	1.0	1.0	1.0	1.0	0.6	0.5	0.2	0.2	0.2	0.6	1.0	0.6	1.0	1.0	0.2	0.9	0.2	0.2	1.0	1.0	0.6
CILINGOZ	$a_{1-}\ \alpha_1$	0.8	0.7	0.8	0.5	0.2	0.8	0.8	0.8	0.5	0.8	0.7	0.0	0.8	0.8	0.8	0.8	0.0	0.0	0.2	0.0	0.0
	a_1	0.9	0.75	0.9	0.55	0.3	0.9	0.9	0.9	0.55	0.9	0.75	0.0	0.9	0.9	0.9	0.9	0.0	0.0	0.3	0.0	0.0
	a_2	1.0	0.8	1.0	0.6	0.4	1.0	1.0	1.0	0.6	1.0	0.8	0.1	1.0	1.0	1.0	1.0	0.1	0.1	0.4	0.1	0.1
	$a_{2+}\ \alpha_2$	1.0	0.9	1.0	0.7	0.5	1.0	1.0	1.0	0.7	1.0	0.9	0.2	1.0	1.0	1.0	1.0	0.2	0.2	0.5	0.2	0.2
KEFKEN	$a_{1-}\ \alpha_1$	0.0	0.5	0.0	0.0	0.0	0.0	0.2	0.8	0.1	0.2	0.0	0.5	0.8	0.0	0.0	0.1	0.8	0.8	0.2	0.0	0.0
	a_1	0.0	0.55	0.0	0.0	0.0	0.0	0.3	0.9	0.15	0.3	0.0	0.55	0.9	0.0	0.0	0.15	0.9	0.9	0.3	0.0	0.0
	a_2	0.1	0.6	0.1	0.1	0.1	0.1	0.4	1.0	0.2	0.4	0.1	0.6	1.0	0.1	0.1	0.2	1.0	1.0	0.4	0.1	0.1,
	$a_{2+}\ \alpha_2$	0.2	0.7	0.2	0.2	0.2	0.2	0.5	1.0	0.3	0.5	0.2	0.7	1.0	0.2	0.2	0.3	1.0	1.0	0.5	0.2	0.2
INCEBURUN	$a_{1-}\ \alpha_1$	0.2	0.0	0.1	0.1	0.8	0.1	0.0	0.0	0.8	0.0	0.0	0.8	0.0	0.0	0.0	0.0	0.8	0.8	0.0	0.8	0.8
	a_1	0.3	0.0	0.15	0.15	0.9	0.15	0.0	0.0	0.9	0.0	0.0	0.9	0.0	0.0	0.0	0.0	0.9	0.9	0.0	0.9	0.9
	a_2	0.4	0.1	0.2	0.2	1.0	0.2	0.1	0.1	1.0	0.1	0.1	1.0,	0.1	0.1	0.1	0.1	1.0	1.0	0.1	1.0	1.0
	$a_{2+}\ \alpha_2$	0.5	0.2	0.3	0.3	1.0	0.3	0.2	0.2	1.0	0.2	0.2	1.0	0.2	0.2	0.2	0.2	1.0	1.0	0.2	1.0	1.0

Cilingoz was evaluated as linguistics variable "extremely high" by an expert in Republic of Turkish Ministry of Environment and Forestry. The value of this criterion should be minimized. Higher linguistic assessments are therefore provided in cases where the maximum probable speed is lower. Table 3 shows all the linguistic assessment results, which are calculated using Eqs. (2)–(5). In another example, please note that Table 3 should be read together with the help of Table 2 because Table 2 clarifies how each criterion is improved. When a certain criterion should be maximized to improve, its linguistic value is higher to reflect the desirability of an increasing value. Accordingly, if improving a criterion requires its value to be minimized, then its qualitative assessment is higher to reflect a decreasing value. In Table 3, quantitative values are also converted into linguistic assessments using Table 2. Finally, fuzzy interval values for each location with respect to criteria are displayed in Table 4.

4.4. Calculating the importance weights of the criteria using fuzzy entropy

Once the data were collected, the weights of the criteria were calculated. To this end, data for the alternatives were plugged into Eqs. (6)–(20), and the weights were computed as displayed in Table 5. An example of calculating weights for C_{11} corresponding to the fuzzy intervals is as follows:

$$Wa_1-\alpha_{1\ (\mathrm{POLICE})} = ((1/0.8)-1)/((1/0.8)-1+(((1/1)-1)+((1/1)-1)+((1/0.2)-1)+((1/0.6)-1))) = 0.050847$$

$$Wa_1-\alpha_{1\ (\mathrm{CILINGOZ})} = ((1/0.8)-1)/((1/0.8)-1+(((1/1)-1)+((1/1)-1)+((1/0.2)-1)+((1/0.6)-1))) = 0.050847$$

$$Wa_1-\alpha_{1\ (\mathrm{KEFKEN})} = ((1/1\mathrm{E}-18)-1)/((1/1\mathrm{E}-18)-1+(((1/1)-1)+((1/1)-1)+((1/0.1)-1)+((1/0.2)-1))) = 1$$

$$Wa_1-\alpha_{1\ (\mathrm{INCEBURUN})} = ((1/0.3)-1)/((1/0.3)-1+(((1/0.4)-1)+((1/0.4)-1)+((1/0.5)-1)+((1/0.6)-1))) = 0.333333$$

The hamming distance based integrated weight value for criterion C_{11} is calculated as follows:

$$w_d^{(a_1-\alpha_1)} = (|0.050847-0.050847|+|0.050847-1|+|0.050847-0.333333|+|0.050847-1|+|0.050847-0.333333|+|1-0.333333|)/6 = 0.5216$$

An example for calculating weights of fuzzy interval a_1 is as follows:

$$Wa_{1\ (\mathrm{POLICE})} = ((1/0.9)-1)/((1/0.9)-1)+(1/0.9)-1)+((1/1\mathrm{E}-18)-1)+((1/0.4)-1)) = 1,11111\mathrm{E}-19$$

$$Wa_{1\ (\mathrm{CILINGOZ})} = ((1/0.9)-1)/(((1/0.9)-1)+((1/0.9)-1)+((1/1\mathrm{E}-18)-1)+((1/0.4)-1)) = 1,11111\mathrm{E}-19$$

$$Wa_{1\ (\mathrm{KEFKEN})} = ((1/1\mathrm{E}-18)-1)/(((1/0.9)-1)+((1/0.9)-1)+((1/1\mathrm{E}-18)-1)+((1/0.4)-1)) = 1$$

$$Wa_{1\ (\mathrm{INCEBURUN})} = ((1/0.4)-1)/(((1/0.9)-1)+((1/0.9)-1)+((1/1\mathrm{E}-18)-1)+((1/0.4)-1)) = 1,5\mathrm{E}-18$$

The hamming distance based integrated weight value is calculated for criterion C_{11} as

$$w_d^{(a_1)} = (|1.11111\mathrm{E}-19-1.11111\mathrm{E}-19|+|1.11111\mathrm{E}-19-1|+|1.11111\mathrm{E}-19-1,5\mathrm{E}-18|+|1.11111\mathrm{E}-19-1|+|1,11111\mathrm{E}-19-1,5\mathrm{E}-18|+|1-1,5\mathrm{E}-18|)/6 = 0.5000$$

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Table 5
The importance weights of the criteria using fuzzy entropy.

C1			C2			C3			C4			C5			C6			C7		
Indicator	Fuzzy Interval	Weights	Indicator	Fuzzy Interval	Weights	Indicator	Fuzzy Interval	Weights	Indicator	Fuzzy Interval	Weights	Indicator	Fuzzy Interval	Weights	Indicator	Fuzzy Interval	Weights	Indicator	Fuzzy Interval	Weights
C_{11}	$a_1-\alpha_1$	0.5216	C_{21}	$a_1-\alpha_1$	0.3571	C_{31}	$a_1-\alpha_1$	0.4500	C_{41}	$a_1-\alpha_1$	0.4700	C_{51}	$a_1-\alpha_1$	0.3000	C_{61}	$a_1-\alpha_1$	0.3500	C_{71}	$a_1-\alpha_1$	0.3500
	a_1	0.5000		a_1	0.4500		a_1	0.3200		a_1	0.5000		a_1	0.5000		a_1	0.5000		a_1	0.3300
	a_2	0.4667		a_2	0.5000		a_2	0.3300		a_2	0.5000		a_2	0.5000		a_2	0.5000		a_2	0.3300
	$a_2+\alpha_2$	2E−18		$a_2+\alpha_2$	0.0700		$a_2+\alpha_2$	0.0500		$a_2+\alpha_2$	0		$a_2+\alpha_2$	0.2000		$a_2+\alpha_2$	0.1500		$a_2+\alpha_2$	0.1200
C_{12}	$a_1-\alpha_1$	0.4818	C_{22}	$a_1-\alpha_1$	0.2500	C_{32}	$a_1-\alpha_1$	0.4900	C_{42}	$a_1-\alpha_1$	0.5200	C_{52}	$a_1-\alpha_1$	0.3500	C_{62}	$a_1-\alpha_1$	0.3500	C_{72}	$a_1-\alpha_1$	0.3100
	a_1	0.5000		a_1	0.3800		a_1	0.5000		a_1	0.5000		a_1	0.5000		a_1	0.3300		a_1	0.3800
	a_2	0.4681		a_2	0.5000		a_2	0.4900		a_2	0.4700		a_2	0.5000		a_2	0.3300		a_2	0.4100
	$a_2+\alpha_2$	2.02E−18		$a_2+\alpha_2$	0.0900		$a_2+\alpha_2$	0		$a_2+\alpha_2$	0		$a_2+\alpha_2$	0.1500		$a_2+\alpha_2$	0.1212		$a_2+\alpha_2$	0.1300
C_{13}	$a_1-\alpha_1$	0.5745				C_{33}	$a_1-\alpha_1$	0.6465	C_{43}	$a_1-\alpha_1$	0.4700				C_{63}	$a_1-\alpha_1$	0.56364	C_{73}	$a_1-\alpha_1$	0.3500
	a_1	0.5000					a_1	0.3300		a_1	0.5000					a_1	0.5000		a_1	0.3300
	a_2	0.4314					a_2	0.3300		a_2	0.4900					a_2	0.4200		a_2	0.3333
	$a_2+\alpha_2$	0					$a_2+\alpha_2$	0		$a_2+\alpha_2$	0					$a_2+\alpha_2$	0		$a_2+\alpha_2$	0.1200
															C_{64}	$a_1-\alpha_1$	0.2222	C_{74}	$a_1-\alpha_1$	0.3200
																a_1	0.3333		a_1	0.2900
																a_2	0.3333		a_2	0.3100
																$a_2+\alpha_2$	0.2222		$a_2+\alpha_2$	0.1100

Table 6
Index values.

	CP coefficient=1		CP coefficient=2	
	Lower bound $p=1$ and $q=\infty$	Upper bound $q=1$ and $p=\infty$	Lower bound $p=1$ and $q=$□	Upper bound $q=1$ and $p=\infty$
POLICE	0.7292	1.1798	0.0897	0.4050
CILINGOZ	0.6584	1.1569	0.0838	0.3121
KEFKEN	1.0018	1.1611	0.1538	0.3388
INCEBURUN	0.9288	1.2770	0.1546	0.6945
Results	CI-PO-IN-KE	CI-KE-PO-IN	CI-PO-KE-IN	CI-PO-KE-IN

An example for calculating weights of fuzzy interval a_2 is as follows:

$$Wa_{2\ (\mathrm{POLICE})} = ((1/1)-1)/(((1/1)-1+(((1/1)-1)+((1/0.1)-1)+((1/0.5)-1)) = 0$$

$$Wa_{2\ (\mathrm{CILINGOZ})} = ((1/1)-1)/(((1/1)-1+(((1/1)-1)+((1/0.1)-1)+((1/0.5)-1)) = 0$$

$$Wa_{2\ (\mathrm{KEFKEN})} = ((1/0.1)-1)/(((1/1)-1+(((1/1)-1)+((1/0.1)-1)+((1/0.5)-1)) = 0.9$$

$$Wa_{2\ (\mathrm{INCEBURUN})} = ((1/0.5)-1)/(((1/1)-1+(((1/1)-1)+((1/0.1)-1)+((1/0.5)-1)) = 0.1$$

The hamming distance based integrated weight value is calculated as follows:

$$w_d^{(a2)} = (|0-0|+|0-0.9000|+|0-0.1000|+|0-0.9000|+|0-0.1000|+|0.9000-0.1100|)/6 = 0.4667$$

An example for calculating weights of fuzzy interval $a_2+\alpha_2$ is as follows:

$$Wa_2+\alpha_{2\ (\mathrm{POLICE})} = ((1/1)-1)/((1/1)-1+(((1/0.8)-1)+((1/0.8)-1)+((1/1\mathrm{E}-18)-1)+((1/0.3)-1))) = 0$$

$$Wa_2+\alpha_{2\ (\mathrm{CILINGOZ})} = ((1/1)-1)/((1/1)-1+(((1/0.8)-1)+((1/0.8)-1)+((1/1\mathrm{E}-18)-1)+((1/0.3)-1))) = 0$$

$$Wa_2+\alpha_{2\ (\mathrm{KEFKEN})} = ((1/0.2)-1)/((1/0.2)-1+(((1/0.8)-1)+((1/0.8)-1)+((1/1\mathrm{E}-18)-1)+((1/0.3)-1))) = 4\mathrm{E}-18$$

$$Wa_2+\alpha_{2\ (\mathrm{INCEBURUN})} = ((1/0.6)-1)/((1/0.6)-1+(((1/0.8)-1)+((1/0.8)-1)+((1/1\mathrm{E}-18)-1)+((1/0.3)-1))) = 7\mathrm{E}-19$$

The hamming distance based integrated weight value is calculated as follows:

$$w_d^{(a2+\alpha 2)} = (|0--0|+|0--4\mathrm{E}-18|+|0-7\mathrm{E}-19|+|0-4\mathrm{E}-18|+|0-7\mathrm{E}-19|+|4\mathrm{E}-18-7\mathrm{E}-19|)/6 = 2\mathrm{E}-18$$

4.5. Ranking the alternative nuclear power plant sites

Compromise programming requires calculating a metric, called *Lp*, which is the distance of each alternative from the ideal solution. A rational decision maker is expected to prefer an alternative that is closer to the defined ideal solution than one that is farther. In this research, the compromise programming coefficients are taken as 1 and 2.

The data and the importance weights of the alternatives were plugged into Eqs. (20)–(24), and the index values and the ranking of the alternative sites were determined as demonstrated in Table 6.

The preferred alternative has the minimum *Lp* distance value for each *p* and weight set that may be used. Thus, the alternative

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with the lowest value for the *Lp* metric will be the best compromise solution because it is the nearest solution with respect to the ideal point. Therefore, it is observed from Table 5 that Cilingoz is found to be the best with the index values 0.6584 and 0.0838 when CP coefficients are equal to 1 and 2, respectively. As Inceburun and Kefken have the worst performance with the index values 0.9288–0.1546 and 1.0018–0.1538, Poliçe occupies the second position with 0.7292 and 0.0897.

5. Discussion

This model takes advantage of the fuzzy logic scheme and provides a systematic approach. The result demonstrates that the concept based on fuzzy logic is feasible for decision making in nuclear site selection.

We argue that the proposed methodology has the potential to assist decision makers due to the following reasons: (1) it compares and ranks alternatives, (2) it seeks to take explicit account of multiple criteria in aiding decision making, (3) vagueness in human judgments are considered using the proposed fuzzy Entropy and fuzzy CP, and (4) it serves to complement and to challenge intuition (Belton and Stewart, 2002).

Note that subjectivity is inherent in all decision making. Multi-criteria analysis does not dispel this subjectivity entirely even if fuzzy arithmetic is integrated. It simply seeks to make the need for subjective judgments explicit. Therefore, there is no such thing as the absolute right answer even within the context of the framework proposed in this study. The concept of an optimum does not exist in a multi-criteria framework, and thus multi-criteria analysis cannot be justified within the optimization paradigm. Instead, it should be perceived as an aid to decision-making that facilitates decision makers' learning about the problem, organizational priorities and objectives to guide them in identifying the preferred course of action.

The comprehensiveness of this model and the data requirements with the attendant calculations and analysis make the application of the methodology tedious. With the use of computer-based applications, we cannot only quicken the implementation of this model but also facilitate a clear presentation of the implementation results. However, the fuzzy logic scheme has its own drawback as developing fuzzy rules for the system requires experience from field experts, past results and theoretical derivation. In other words, experts may need to stay put onsite to monitor the system and adjust the fuzzy rules at the beginning of each stage. Furthermore, since a nuclear plant location problem can be extensively affected by numerous dynamic environmental and legislative issues, this can affect one's decision for the selection alternative. These issues should be taken into consideration, but it may require a more complex system to handle these dynamics. Nevertheless, it offers some proof that it is a technique which can improve the performance of the selection process.

In this research, the following points were taken into consideration in line with Roy (1996): (1) a criteria list was generated, (2) how to measure the criteria were identified and demonstrated, (3) an objective method was used to decrease the subjectivity in weighting the criteria, and (4) fuzzy arithmetic was employed to deal with the vagueness of human judgments.

Finally, we suggest that the final rankings of the sites are more like creation than a discovery. The principal aim is not to discover a solution, but to construct or create something which is viewed as liable to help a decision-maker to shape his or her preferences or to make a decision in conformity with his or her goals (Roy, 1990). This is why in the application of multi-criteria decision aids it is often claimed that what is really important is the decision process not the final solution (Roy, 1996). Thus, we argue that each step of the proposed framework is invaluable and should be taken into a careful consideration.

6. Conclusion

In this study, a fuzzy MCDM approach is developed and applied to the problem of nuclear power plant facility location selection in Turkey. Making decisions under uncertainty in a dynamic environment is not easy. Siting a nuclear power plant is a sophisticated problem since the evaluation procedures involve several criteria, and the solution to the problem calls for some compromises to be made among potential conflicting criteria. Fuzzy assessments expressed in linguistic terms are often the most intuitive and effective way for decision makers to deal with challenges such as the one in hand. The proposed framework employs fuzzy entropy with trapezoid numbers and t norm based fuzzy CP to consider the uncertainty such as fuzziness, imprecision, vagueness, incompleteness and ignorance with the linguistic nature of the problem. This paper addresses the problem of nuclear power plant facility location selection in Turkey using a multi-criteria decision framework. Based on the findings, Cilingoz turned out to be the best alternative.

It is suggested that no measure of a complex issue, such as nuclear power plant site selection, is perfect and that rising stakeholder demands require decision makers to make better assessments. Therefore, the proposed tool can be considered one of the means to facilitate the evaluation of the potential of alternative sites.

Appendix A. Fuzzy set theory

A fuzzy set consists of a universe of discourse and a membership function that maps every element in the universe of discourse to a membership value between 0 and 1. In fuzzy set, the class of objects' membership functions is defined as a possibility distribution that the membership grade can be taken as an intermediate value between 0 and 1. For example, letting A denote fuzzy set “old” we can represent its membership function by $\mu_{\tilde{A}}(x)$. People have different views on the same (vague) concept. Fuzzy sets can be used to easily accommodate this reality. Some people might think age 55 is “old” with membership value as high as 0.9, whereas others might consider that 45 is “old” with membership value of merely 0.2. Different membership functions can be used to represent these different versions of “old.”

Fuzzy set theory and Yager's t norm approach are given below with some definitions (Yager, 1980; Hauke, 1999; Rommenfange and Keresztfalvi, 1995).

Definition 1. Let X be a set with $x \in X$. A fuzzy set $\tilde{A}$ in X is a set of tuple $\tilde{A} = \{(x, \mu(x)) : x \in X\}$, where $\mu_{\tilde{A}} : X \to [0, 1]$ is called membership function as displayed in Fig. 2. $\mu_{\tilde{A}}(x)$ could be interpreted as

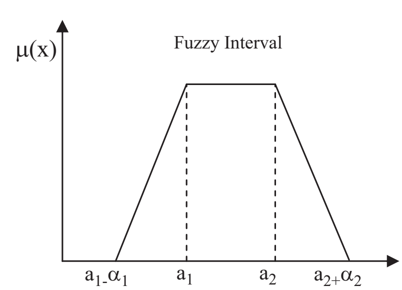

Fig. 4. Trapezoid fuzzy interval.

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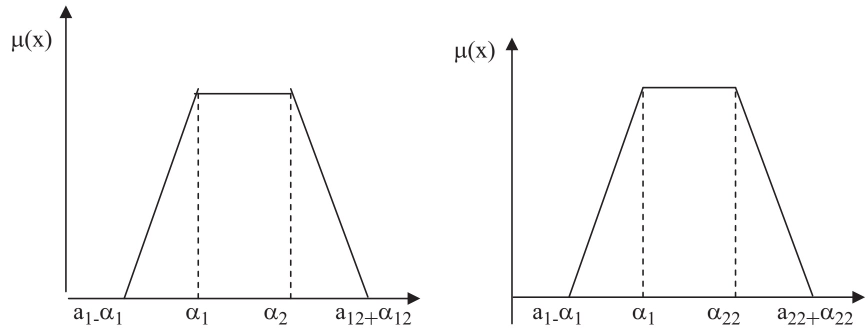

Fig. 5. $\tilde{A}_1$ and $\tilde{A}_2$'s trapezoid fuzzy interval

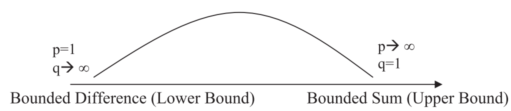

Fig. 6. Yager's t-norms with parameter $p>1$.

the degree of membership of x in $\tilde{A}$. The closer this value is to 1, the more x belongs to $\tilde{A}$ (Fig. 4).

Definition 2. Numerous applications have shown that only four types of membership functions are needed in most circumstances: trapezoidal, triangular (a special case of trapezoidal), Gaussian, and bell-shaped. All these fuzzy sets are continuous, normal, and convex. Among the four, the first two are more widely used. In this study, we use trapezoidal membership functions to make the illustration more general. A fuzzy number $\tilde{m}$ is a special fuzzy subset on the set R of real numbers, which satisfy the following conditions.

(1) There exists a $x_0 \in R$ at least so that the degree of its membership $u_{\tilde{m}}(x_0)=1$;
(2) Membership function $u_{\tilde{m}}(x)$ is left and right continuous.

Let $\tilde{m}=((a_1-\alpha_1),\alpha_1,\alpha_2,(a_2+\alpha_2))$ be a trapezoid fuzzy number, where the membership function of $\mu\tilde{m}$ is given by

$$\mu_{\tilde{m}}x)=\begin{cases}\frac{x-(a_1-\alpha_1)}{a_1-(a_1-\alpha_1)} & ((a_1-\alpha_1)\le x\le a_1)\\ 1 & (a_1\le x\le a_2)\\ \frac{(a_2+\alpha_2)-x}{(a_2+\alpha_2)-a_2} & (a_2\le x\le (a_2+\alpha_2))\end{cases} \quad (A.1)$$

where $[b,c]$ is called a mode interval of $\tilde{m}$, and a and d are called the lower and upper limits of $\tilde{m}$, respectively.

Zimmermann defines the mth power, and algebraic operations are defined as follows (Zimmermann, 2001): The mth power of a fuzzy set $\tilde{A}$ is a fuzzy set with the membership function (Fig. 5)

$$\mu_{\tilde{R}^m(x)}=[\mu\tilde{A}(x)]^m, \quad x\in X \quad (A.2)$$

Zadeh's widely used connectives are given in originally

$$A_1(x)\cup A_2(x)=Max[A_1(x),A_2(x)] \quad (A.3)$$

$$A_1(x)\cap A_2(x)=Min[A_1(x),A_2(x)] \quad (A.4)$$

Definition 3. The bounded sum $\tilde{A}=\tilde{A}_1\oplus\tilde{A}_2$ is defined as

$$\tilde{A}=\{(x,\mu_{\tilde{A}_1\oplus\tilde{A}_2}(x))x\in X\}$$

where

$$\mu_{\tilde{A}_1\oplus\tilde{A}_2}(x)=\min\{1,\mu_{\tilde{A}_1}(x)+\mu_{\tilde{A}_2}(x)\} \quad (A.5)$$

Definition 4. The bounded difference $\tilde{A}=\tilde{A}_1\Theta\tilde{A}_2$ is defined as

$$\tilde{C}=\{(x,\mu_{\tilde{A}_1\Theta\tilde{A}_2}(x))x\in X\} \quad (A.6)$$

where (Keresztfalvi, 1993)

$$\mu_{\tilde{A}_1\Theta\tilde{A}_2}(x)=\max\{0,\mu_{\tilde{A}_1}(x)+\mu_{\tilde{A}_2}(x)-1\} \quad (A.7)$$

Definition 5. The extended addition formula is defined as follows:

$$\tilde{A}_1\oplus\tilde{A}_2=[a_{11}+a_{21},a_{12}+a_{22},(\alpha_{11}^q+\alpha_{21}^q)^{1/q},(\alpha_{12}^q+\alpha_{22}^q)^{1/q}] \quad (A.8)$$

where $(1/p)+(1/q)=1$. The extreme cases for the parameter p in Yager's t-norms as displayed in Fig. 6 yield the same results as the classical min-bounded difference and bounded sum (Rommenfanger, 1995)

- $q=1$ resp. $p\to\infty$ (min-operator):
$$\tilde{A}_1\oplus\tilde{A}_2=[a_{11}+a_{12},a_{12}+a_{22},\alpha_{11}+\alpha_{21},\alpha_{12}+\alpha_{22}] \quad (A.9)$$

- $p=1$ resp. $q\to\infty$ (bounded difference):
$$\tilde{A}_1\oplus\tilde{A}_2=[a_{11}+a_{12},a_{12}+a_{22},\max\{\alpha_{11},\alpha_{12}\},\max\{\alpha_{12},\alpha_{22}\}] \quad (A.10)$$

Definition 6. The extended multiplication approximation formula is given below:

$$\tilde{A}_1\otimes\tilde{A}_2\approx[a_{11}a_{21},a_{12}a_{22},((a_{11}\alpha_{21})^q+(a_{21}\alpha_{11})^q)^{1/q},((a_{12}\alpha_{22})^q+(a_{22}\alpha_{12})^q)^{1/q}] \quad (A.11)$$

where $(1/p)+(1/q)=1$.

This approximation holds for α_{11} and α_{21} compared with a_{11} and a_{21} (Dubois and Prade, 1980). The extended extreme cases yield the same results as the bounded difference and bounded sum.

- $q=1$ resp. $p\to\infty$ (bounded sum):
$$\tilde{A}_1\otimes\tilde{A}_2\approx[a_{11}.a_{21},a_{12}.a_{22},a_{11}.\alpha_{21}+a_{21}.\alpha_{11},a_{12}.\alpha_{22},a_{22}.\alpha_{12}] \quad (A.12)$$

- $p=1$ resp. $q\to\infty$ (bounded difference):
$$\tilde{A}_1\otimes\tilde{A}_2\approx[a_{11}a_{21},a_{12}a_{22},a_{11}\alpha_{21}+\max\{a_{11}\alpha_{21},a_{21}\alpha_{11}\},\max\{a_{12}\alpha_{22},a_{22}\alpha_{12}\}] \quad (A.13)$$

A special case of extended multiplication is that of multiplying a non-negative real number $k\ge 0$ and a fuzzy interval $\tilde{A}=[a_1,a_2,\alpha_1,\alpha_2]$. The result is

$$k\otimes\tilde{A}=[ka_1,ka_2,k\alpha_1,k\alpha_2] \quad (A.14)$$

and

$$\frac{\tilde{A}}{k}=\frac{1}{k}\otimes\tilde{A}=\left[\frac{a_1}{k},\frac{a_2}{k},\frac{\alpha_1}{k},\frac{\alpha_2}{k}\right] \quad (A.15)$$

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