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전력연구원, 한국전력공사

Use of Fuzzy Set Theoretical Approach in Radioactive Waste Management

Joo Hyun Moon and Seong Ho Ghyym
Korea Electric Power Research Institute, Korea Electric Power Corporation

Abstract —This paper discusses the potential application of fuzzy set theory to the decision-making in the area of radioactive waste management. The approach proposed in this study is based on the concepts of fuzzy set theory and the hierarchical structure analysis. The linguistic variables and fuzzy numbers are used to aggregate the decision maker's subjective assessments of the decision criteria and of the decision alternatives with respect to these criteria. For each alternative, the fuzzy appropriateness index is evaluated to obtain the final score. Using total integral value method, one of methods for ranking fuzzy numbers, the fuzzy appropriateness indices are ranked. As a case problem, selection of the most suitable option for spent fuel storage is illustrated.

1. Introduction

On the occasion of making an engineering decision, it sometimes has to be made mostly on the basis of vague, imprecise and uncertain information due to the lack of real data. The decision-making for the radioactive waste management is one of the areas that frequently call upon the methods to treat uncertain and ill-defined problems.

The form of uncertainty due to those characteristics is fuzziness rather than randomness, especially when subjective factors are involved. Fuzziness means a lack of precise boundaries for some considered subsets of a given situation. Concerning this aspect, fuzzy set theory [1,2] offers a possibility to handle imprecise data and to do decision-making under subjective considerations that are inherently connected with the way humans think of real-life problems.

The primary aim of this paper is to propose an approach based on the fuzzy set theory applicable to the decision-making in the area of radioactive waste management under the uncertain and ill-defined situation with several criteria to be considered.

In the approach, two main key concepts are employed: linguistic variables and fuzzy numbers. Linguistic variables first represent the relative importance of each decision criterion under consideration and the degree of appropriateness for each alternative perceived by the decision-maker (DM). Then, linguistic values for these variables are translated into triangular fuzzy numbers that facilitate the use of arithmetic operation.

2. Fuzzy set theoretic approach

Fuzzy set theory

The general multi-criteria decision-making (MCDM) problem consists of two decision variables: a set of decision alternatives and a set of decision criteria. The appropriateness of each alternative is judged in terms of these variables. The optimal alternative is viewed as the alternative with the highest degree of appropriateness with respect to all relevant criteria. Similar to most approaches to MCDM, the approach proposed in this section are made up of two tasks: (1) aggregation of the judgements with respect to all criteria and per decision alternative; (2) rank ordering of the decision alternatives according to the aggregated judgments. In the following, we shall describe the definitions and the theoretical backgrounds used in this approach.

First, let's introduce the definitions. A fuzzy number M is a triangular fuzzy number, which is denoted by (a, b, c), if its membership function $f_M(x)$ is given by

$$f_M(x) = \begin{cases} \dfrac{(x-a)}{(b-a)}, & a \le x \le b, \\ \dfrac{(x-c)}{(b-c)}, & b \le x \le c, \\ 0, & otherwise, \end{cases} \tag{1}$$

where a, b, and c are real numbers. And a linguistic variable is a variable whose values are not numbers but words or phrases in a natural or synthetic language. Thus, each word x in a natural language can be viewed as a summarized description of a fuzzy set $A(x)$ of a universe of discourse U, which $A(x)$ represents the meaning of x.

Then, let's describe the decision problem to be considered. Let $A = \{A_i \mid i = 1, 2, \dots, n\}$ be a set of n alternatives under consideration and $C = \{C_t \mid t = 1, 2, \dots, k\}$ a set of k decision criteria, for each of which the degree of appropriateness for each alternative should be determined. And let the overall objective be the selection of the most suitable alternative with all decision criteria being taken into account.

Let S_{it} be the appropriateness rating of alternative A_i for decision criterion C_t, W_t the importance rating (weight) for decision criterion C_t, and F_i the fuzzy appropriateness index [3] for alternative A_i which represents the degree of appropriateness for the alternative which is obtained by aggregating S_{it} and W_t.

Using the mean operator, F_i is given by

$$F_i = \left(\tfrac{1}{k}\right)\left[(S_{i1} \otimes W_1) \oplus (S_{i2} \otimes W_2) \oplus \cdots \oplus (S_{ik} \otimes W_k)\right] \tag{2}$$

Substituting S_{it} and W_t with triangular fuzzy numbers, that is, $S_{it} = (o_{it}, p_{it}, q_{it})$ and $W_t = (a_t, b_t, c_t)$, F_i is approximated as

$$F_i \cong (Y_i, Q_i, Z_i) \tag{3}$$

with

$$Y_i = \left(\tfrac{1}{k}\right) \cdot \sum_t o_{it} \cdot a_t$$

$$Q_i = \left(\tfrac{1}{k}\right) \cdot \sum_t p_{it} \cdot b_t$$

$$Z_i = \left(\tfrac{1}{k}\right) \cdot \sum_t q_{it} \cdot c_t$$

for $i = 1, 2, \cdots, n$ and $t = 1, 2, \cdots, k$.

Let the total integral value [4] for triangular fuzzy number $A = (a, b, c)$, be defined as

$$I_T^{\alpha}(A) = \left(\tfrac{1}{2}\right)\left[\alpha c + b + (1-\alpha) a\right]. \tag{4}$$

Here α is called an index of optimism which represents the degree of optimism of the DM.

A larger value of α indicates a higher degree of optimism. For any fuzzy numbers A_i and A_j, if $I_T^\alpha(A_i) < I_T^\alpha(A_j)$, then $A_i < A_j$; if $I_T^\alpha(A_i) = I_T^\alpha(A_j)$, then $A_i = A_j$; if $I_T^\alpha(A_i) > I_T^\alpha(A_j)$, then $A_i > A_j$. Hence, in the present paper, the total integral value of the fuzzy appropriateness index for each alternative is viewed as a measure to rank the alternatives.

Steps to select the most suitable alternative

In order to select the most suitable alternative, the specific steps used in this study are summarized as follows:

Step 1. Problem definition

(1) Identify n alternatives and k relevant decision criteria, that is, $A = \{A_i \mid i = 1, 2, \ldots, n\}$ and $C = \{C_t \mid t = 1, 2, \ldots, k\}$

(2) Define the importance rating and the appropriateness rating for the alternatives and the decision criteria, which consist of linguistic variable x, term set $T(x)$ which represents the ratings of linguistic variables, and their corresponding membership functions.

Step 2. Determination of degree of appropriateness for each alternative

(3) Assign W_t to each criterion C_t under consideration and S_{it} to each alternative A_i for each criterion C_t, which are then substituted with triangular fuzzy numbers for arithmetic operation.

(4) Compute the fuzzy appropriateness index F_i.

Step 3. Selection of the most suitable alternative

(5) Compute the total integral value of the fuzzy appropriateness index F_i for each alternative.

(6) Rank decision alternatives using the total integral values and select the option with the largest total integral value as the most suitable option.

3. Application

In the present section, the approach depicted in Section 2 is applied to select the most suitable option for spent fuel interim storage in Korea. This decision problem was analyzed using the analytic hierarchy process (AHP) [5] several years ago in Korea [6]. The four options considered in Ref. [6] are as follows: A1 = wet storage; A2 = dry horizontal modular storage; A3 = dry vault storage; and A4 = dry vertical concrete cask storage.

It has to be noted that all linguistic values of the importance and appropriateness ratings assigned in this section are simply for illustrative purpose. The actual steps to tackle the problem in this study are summarized as follows:

(1) Four alternatives are defined as follows: A = {A1, A2, A3, A4}. Then, decision criteria are defined as follows: C = {SA, EI, SI, CO, SR, FL, EN}, where SA = safety, EI = environmental impact, SI = socioeconomic impact, CO = cost, SR = site requirements, FL = flexibility, and EN = engineering;

(2) With the linguistic variables defined as 'importance' and 'appropriateness' to represent the relative importance of each decision criterion under consideration and the degree of appropriateness for each alternative for each decision criterion, respectively, the term sets are: T(importance) $\equiv W$ = {VL, L, M, H, VH}, where VL = very low, L =

low, M = medium, H = high, VH = very high as well as T(appropriateness) $\equiv S$ = {VP, P, F, G, VG}. Here VP = very poor, P = poor, F = fair, G = good, VG = very good; The membership function corresponding to each element of each term set is represented by the approximate reasoning using each triangular fuzzy number, as shown in Table 1.

(3) The importance rating for each decision criterion and the appropriateness rating for each alternative with respect to each decision criterion are assigned and summarized in Tables 2 and 3, respectively.

(4) The fuzzy appropriateness indices are calculated and summarized in Table 3.

Table 1. Triangular Fuzzy Number Corresponding to Each Linguistic Value

Linguistic variable	VL VP	L P	M F	H G	VH VG
Fuzzy number	(0,0,0.25)	(0,0.25,0.5)	(0.25,0.5,0.75)	(0.5,0.75,1)	(0.75,1,1)

Table 2. Importance Rating for Each Decision Criterion

Criterion	SA	EI	SI	CO	SR	FL	EN
Importance Rating	VH	M	M	M	L	L	H

Table 3. Appropriateness Rating and Fuzzy Appropriateness Index for Each Alternative

	Appropriateness Rating							Fuzzy Appropriateness Index
	SA	EI	SI	CO	SR	FL	EN	
A1	G	F	G	VG	G	F	G	(0.1429, 0.3929, 0.7054)
A2	G	F	F	F	F	G	F	(0.0982, 0.3125, 0.6161)
A3	G	G	F	VP	F	G	F	(0.0982, 0.2946, 0.5893)
A4	F	F	P	G	F	F	P	(0.0536, 0.2411, 0.5268)

Table 4. Total Integral Value and Rank for Various Values of Optimism Index α

	Moderate DM (α=0.5)	Pessimistic DM (α=0.0)	Optimistic DM (α=1.0)
A1	0.4085 (1)	0.2679 (1)	0.5491 (1)
A2	0.3348 (2)	0.2054 (2)	0.4643 (2)
A3	0.3192 (3)	0.1964 (3)	0.4420 (3)
A4	0.2656 (4)	0.1473 (4)	0.3839 (4)

(5) For various values of α, the total integral values for fuzzy confidence indices are calculated and summarized in Table 4.

(6) With the total integral values calculated in the above, their ranks are derived and summarized in Table 4. The wet storage (i.e., A1) is identified as the most suitable option for spent fuel interim storage. Also, it is found that the rank of alternatives is independent of values of the optimism index, in other words, of DM's risk attitudes.

4. Summary and conclusions

In this paper, a simple and easy-to-use approach using fuzzy set theory is proposed to aid the evaluation of the degree of appropriateness for each alternative in decision-making under uncertain environment in radioactive waste management. Although the case problem is relatively straightforward, practical application needs additional effort to resolve the issues as follows:

- How to assign the membership grades of a fuzzy set to represent a linguistic variable: Since this is the starting point for any fuzzy set analysis, it is important for the membership grades to be as realistic as possible. It is advisable for user to perform a sensitivity study on selected fuzzy sets to determine the impact of varying the membership grades.
- How to perform arithmetic operations in the fuzzy set analysis: Although extensive research has been done to develop the basic concept of fuzzy set theory, it often happens that individual practitioners have their own intuitive notions about how concepts of arithmetic operation should be applied. There is a need to standardize arithmetic operations.

Once these issues are studied further for facilitating generally acceptable use of fuzzy sets, decision-making problems with respect to the radioactive waste management would more easily be handled using this technique.

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