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Optimal Selection of Energy System Design Using Fuzzy Framework

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Abstract — The present work proposes the potential fuzzy framework, based on fuzzy set theory, for supporting decision-making problems, especially, selection problems of a best design in the area of nuclear energy system. The framework proposed is composed of the hierarchical structure module, the assignment module, the fuzzification module, and the defuzzification module. In the structure module, the relationship among decision objectives, decision criteria, decision sub-criteria, and decision alternatives is hierarchically structured. In the assignment module, linguistic or rank scoring approach can be used to assign subjective and/or vague values to the decision analyst's judgment on decision variables. In the fuzzification module, fuzzy numbers are assigned to these values of decision variables. Using fuzzy arithmetic operations, for each alternative, fuzzy preference index as a fuzzy synthesis measure is obtained. In the defuzzification module, using one of methods ranking fuzzy numbers, these indices are defuzzified to overall utility values as a cardinality measure determining final scores. According these values, alternatives of interest are ranked and an optimal alternative is chosen. To illustrate the applicability of the framework proposed to selection problem, as a case example, the best option choice of four design options under five decision criteria for primary containment wall thickening around large penetrations in an advanced nuclear energy system is studied.

1. Introduction

Concerning the support of decision-making in the field of energy engineering, the optimal selection problems among suitable design options or the performance evaluation problems using multi-expert opinions appear frequently in the situation of vague, imprecise, and uncertain information. It is important in the design stage of the energy systems for design optimization as one of necessary processes to be taken synthetically into consideration several decision criteria such as safety, economy, maintenance, constructibility, and licensability.

The main purpose of this work is to propose a fuzzy framework applicable to the optimal selection in the area of nuclear energy system design with multiple decision criteria under vague and subjective decision-making condition.

In this study, decision variables stand for the relative importance of each decision criterion under consideration and the degree of appropriateness for each alternative perceived by the decision analyst or the decision-maker (DM). Assigned non-fuzzy (e.g., linguistic or cardinal) values for these variables, based on empirical data and/or engineering judgment, is translated into triangular fuzzy numbers that facilitate the use of fuzzy arithmetic operations.

2. Fuzzy Framework

Fuzzy set theory

Multi-criterion decision-making problems, in general, can be handled using two decision variables such as the importance weights of the decision criteria and the preference ratings of the decision alternatives with respect to each decision criterion. The preference 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 decision criteria. The approaches proposed for supporting decision-making includes commonly the following necessary modules: (1) synthesis of importance weights of criteria and preference ratings of decision alternatives under criteria; (2) rank ordering of the decision alternatives according to a measure such as utility values. In this study, a fuzzy approach based on fuzzy numbers and fuzzy arithmetic operations will be used for the module (1); Pertaining the module (2), the ranking method based on the total integral values coupled with a risk attitude index, as suggested in Ref. [Liou and Wang, 1992].

A fuzzy number M, a triangular fuzzy number denoted by (a, b, c), has its membership function $f_M(x)$ described 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 linguistic variable is a variable whose values are not numbers but words or phrases in a natural or synthetic language.

Let $A = \{A_i \mid i = 1, 2, \ldots, m\}$ be a set of m alternatives under consideration and $C = \{C_t \mid t = 1, 2, \ldots, k\}$ a set of k decision criteria, for each of which the degree of appropriateness for each alternative should be determined. The overall objective is the selection of the best alternative with respect to all decision criteria under consideration. Let S_{it} be the preference rating of alternative A_i for decision criterion C_t, W_t the importance weight for decision criterion C_t, and F_i the fuzzy preference index [Chang and Chen, 1994] for alternative A_i, the degree of appropriateness for the alternative, obtained via fuzzy arithmetic operations of S_{it} and W_t. Based on the arithmetic mean method, F_i can be expressed by

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

Treating 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 approximately written as

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

with for the alternative index $i = 1, 2, \ldots, m$ and the criterion index $t = 1, 2, \ldots, k$

$$Y_i = \left(\frac{1}{k}\right) \cdot \sum_t o_{it} \cdot a_t \qquad Q_i = \left(\frac{1}{k}\right) \cdot \sum_t p_{it} \cdot b_t \qquad Z_i = \left(\frac{1}{k}\right) \cdot \sum_t q_{it} \cdot c_t$$

The total integral value [Liou and Wang, 1992] for triangular fuzzy number $A = (a, b, c)$, can be read as

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

Here α is called the optimism index measuring the degree of optimism of the DM or decision analyst. A larger value of α indicates a higher degree of optimism. In the present work, the total integral value of the fuzzy preference index for each alternative, one of measures ranking the alternatives of interest, is viewed as an overall utility value U_T. In this study, because of the characteristics of the rank score ordering system applied to the importance weight and the preference rating, the alternative with the smallest of overall utility values corresponds to the best selection option.

Modules for selecting the best alternative

The modules used for obtaining an optimal option can be described as follows:

Module 1: Construction of hierarchical structure

(1) Identify objective of selection decision-making at the top level; define decision alternatives to be evaluated $A = \{A_i \mid i = 1, 2, \ldots, m\}$ at the bottom level; choose decision criteria $C = \{C_t \mid t = 1, 2, \ldots, k\}$ at the middle level in a hierarchical structure; and furcate criteria into decision attributes as sub-criteria.

Module 2: Assignment of decision matrices

(2) Select importance scale as elements of a set W_t of importance weight of decision criteria; and determine preference scale as elements of a set S_{it} of preference rating of alternatives under each criterion C_t.

(3) Assign values of importance scale to W_t for each criterion C_t of interest; and similarly, give preference values to S_{it} for alternatives A_i under each criterion C_t; then form decision matrix such as importance matrix and preference matrix for each decision criterion.

Module 3: Fuzzification of decision matrices

(4) Form a scale conversion table assigning fuzzy number associated with each scale to the importance weight set and the preference rating set.

(5) Convert scale values of each set into fuzzy numbers using a scale conversion rule and a conversion table for rank score values and linguistic values, respectively.

(6) Obtain fuzzy preference index F_i approximated for each alternative A_i using fuzzy arithmetic operation.

Module 4: Defuzzification of fuzzy preference index

(7) Obtain the utility value of fuzzy preference index F_i for each alternative A_i.

(8) Calculate the overall utility value U_T using the utility values and the total risk attitude index α_T.

Module 5: Selection of best option

(9) Find the ranking of decision alternatives based on overall utility values U_T.

(10) Determine the best option using the magnitude of overall utility values.

3. Application

In the present section, the framework depicted in Section 2 is applied to select the best option for wall thickening around large penetrations in a typical Korean Next Generation Reactor with a dual containment system. This decision problem was qualitatively analyzed in Korea [KOPEC, 1998]. The four options considered in Ref. [KOPEC, 1998] are as follows: A1 = inside wall thickening with a flat surface; A2 = inside wall thickening with a constant thickness; A3 = outside wall thickening with a flat surface; and A4 = outside wall thickening with a constant thickness. In Table 1 is listed the information specified in the above-mentioned qualitative study. The five decision criteria selected are C1 = advancement of constructibility; C2 = safety of structural performance; C3 = inservice inspection (ISI); C4 = licensability; and C5 = economy.

According to the procedure supposed, the treatment of the selection problem in this study is addressed as follows: Four decision alternatives are defined as follows: A = {A1, A2, A3, A4}. Decision criteria are defined as follows: C = {C1, C2, C3, C4, C5}. In the case of importance weight, the term set of scale is T(importance weight) $\equiv W$ = {Zero, One, Two, Three, Four, Five, Six, Seven, Eight, Nine}.

Table 1. Information of criteria attributes assessed for each design option

Attributes	A1	A2	A3	A4
Airlift method applicability	poor	poor	general	general
Combined-thickening applicability	poor	poor	general	general
Effectiveness for vertical tendon deflection	lower	lower	general	general
Effectiveness for liner bulges	lower	lower	general	general
Effectiveness for stress variation	higher	general	general	general
Effectiveness for liner fracture	lower	lower	general	general
Effectiveness for free volume	lower	lower	general	general
Inspection work space in annulus	good	good	poor	general
Welded liner seams requirement	higher	higher	general	general
Experience in operating plants	general	general	general	general
Availability to UPC test	poor	poor	general	good
Opening area liner work effort	general	higher	lower	lower
Transition area liner work effort	general	higher	lower	lower
Concrete inventory	lower	general	higher	general
Span work effort	general	general	lower	lower
Form work effort	general	general	higher	higher
Shear ties work effort	general	lower	higher	lower
Horizontal rebar work effort	general	higher	higher	higher

The term values of scale are assigned to each decision criterion by the decision decision-maker. Table 2 shows the assigned linguistic importance matrix. The linguistic or ordinal values are converted from ten-element linguistic scale into the triangular fuzzy numbers by means of the conversion table given in Table 3, after Ref. [Chen, 1996]. As a result, the fuzzy importance matrix is constructed (See Table 9).

Table 2. Linguistic importance weight matrix for each decision criterion

Criterion	C1	C2	C3	C4	C5
Importance weight	Nine	One	Seven	Three	Five

Table 3. Fuzzy conversion table for linguistic importance weight

Linguistic value	Zero	One	Two	Three	Four
Fuzzy number	(0,0,0)	(0,1,2)	(1,2,3)	(2,3,4)	(3,4,5)
Linguistic value	Five	Six	Seven	Eight	Nine
Fuzzy number	(4,5,6)	(5,6,7)	(6,7,8)	(7,8,9)	(8,9,9)

For the preference rating, based on comparative data stemmed from qualitative and/or quantitative assessment of four alternatives, the linguistic or ordinal information is converted from ten-element linguistic value into the triangular fuzzy numbers. To construct a preference matrix, the rank score, using positive integer numbers, is assigned to each decision attribute furcated from the corresponding decision criteria. The numbers, then, are summarized to obtain total rank score for each criterion. The term set is T(preference rating) $\equiv S$ = {1, 2, 3,..., p, ...}. Here the number p denotes the positive integer. The value of summarized rank score p is converted into the triangular fuzzy number $\underline{N\text{-}p} = (p\text{-}1, p, p+1)$, after Ref. [Chen, 1996]. Tables 4 through 8 show rank scoring assigned to obtain summarized rank score values for the preference ratings.

Table 4 Rank scoring of the advancement criteria for four design options

Decision attributes	A1	A2	A3	A4
Airlift method applicability	3	3	2	2
Combined-thickening applicability	3	3	2	2
Total rank	6	6	4	4

Table 5 Rank scoring of safety criteria for four design options

Decision attributes	A1	A2	A3	A4
Effectiveness for tendon deflection	3	3	2	2
Effectiveness for liner bulges	3	3	2	2
Effectiveness for stress variation	1	2	2	2
Effectiveness of liner fracture	3	3	2	2
Effective for free volume	3	3	2	2
Total rank	13	14	10	10

Table 6 Rank scoring of the inservice inspection criteria for four design options

Decision attributes	A1	A2	A3	A4
Inspection work space in annulus	1	1	3	2
Welded liner seams requirement	3	3	2	2
Total rank	4	4	5	4

Table 7 Rank scoring of the licensability criteria for four design options

Decision attributes	A1	A2	A3	A4
Experience in operating plants	2	2	2	2
Availability to UPC test	3	3	2	1
Total rank	5	5	4	3

Table 8 Rank scoring of the economy criteria for four design options

Decision attributes	A1	A2	A3	A4
Opening area liner work effort	2	3	1	1
Transition area liner work effort	2	3	1	1
Concrete inventory	1	2	3	2
Span work effort	2	2	1	1
Form work effort	2	2	3	3
Shear ties work effort	2	1	3	1
Horizontal rebar work effort	2	3	3	3
Total rank	13	16	15	12

The importance weight matrix for each decision criterion and the preference rating matrix for each alternative with respect to each decision criterion are summarized in Table 9. The fuzzy preference indices calculated are shown in Table 9. For various values of α, the overall utility values calculated using total integral value method for fuzzy preference indices are shown in Table 10. According to the magnitude of overall utility values, the ranking order for each alternative can be determined. As shown in Table 10, it is found that the inside-thickening design with a flat surface (i.e., A1) is the optimal option for primary containment wall reinforcement around large penetrations in double containment nuclear power plants. This finding is the same as that obtained by the qualitative evaluation [KOPEC, 1998]. In addition, the optimism index has no effect on the ranking order of alternatives. Namely, the ranking order is independent of the types of DM's attitude towards risk or vagueness.

Table 9. Fuzzy matrix and fuzzy preference index for each alternative

Preference matrix	Decision criteria					Fuzzy preference index
	C1	C2	C3	C4	C5	
Importance matrix	(8,9,9)	(0,1,2)	(6,7,8)	(2,3,4)	(4,5,6)	
A1	*N-6*	*N-13*	*N-4*	*N-5*	*N-13*	(22.8, 35.0, 47.8)
A2	*N-6*	*N-14*	*N-4*	*N-5*	*N-16*	(25.2, 38.2, 51.8)
A3	*N-4*	*N-10*	*N-5*	*N-4*	*N-15*	(22.0, 33.6, 46.2)
A4	*N-4*	*N-10*	*N-4*	*N-3*	*N-12*	(18.0, 28.6, 40.2)

Table 10. Overall utility value (Ranking order) for various values of optimism index α

	Moderate DM (α=0.5)	Pessimistic DM (α=0.0)	Optimistic DM (α=1.0)
A1	35.15 (3)	28.9 (3)	41.4 (3)
A2	38.35 (4)	31.7 (4)	45.0 (4)
A3	33.85 (2)	27.8 (2)	39.9 (2)
A4	28.85 (1)	23.3 (1)	34.4 (1)

4. Conclusions

In the present work, based on fuzzy numbers and fuzzy arithmetic operations, a fuzzy framework composed of five modules is proposed to support the best selection decision-making of decision alternatives under multiple decision criteria in the field of energy system design. In the assignment module, particularly, the rank scoring approach suggested in Ref. [Chen, 1996] is used to facilitate the assignment and conversion with respect to preference rating as well as ten-element scale employed for importance matrix. The rank score summarized for decision attributes that belong to each decision criterion is transformed to fuzzy numbers. With application to a qualitative analysis of the proposed framework, it is found that the present fuzzy framework facilitates treatment of vague and subjective selection decision-making problems handled only by means of qualitative approaches.

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