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A design-decision support framework for evaluation of design options/proposals using a fuzzy-logic-based composite structure methodology

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With the high cost of construction, operation and maintenance, the offshore industry is seeking ways of reducing both the time and money spent to provide high-quality offshore structures needed to support the oil and gas extraction and production. The successful selection process for choosing a design/procurement proposal is based on a high degree of technical integrity, high safety levels and low costs in construction, maintenance and operation. However, the objectives of maximizing the degree of technical performance, maximizing the safety and minimizing the cost incurred are usually in conflict. The evaluation of the technical performance, safety and cost is always associated with uncertainty, especially for a novel system in the initial concept design stages. In this paper, a decision support framework using a composite structure methodology is suggested for design evaluation of offshore engineering products in the initial stages. It is a multiple criteria decision-making framework, which provides a juxtaposition of safety, cost and technical performance objectives of a system during the evaluation to assist decision-makers in selecting the winning design/procurement proposal that best satisfies the requirement in hand. An example is used to illustrate the proposed framework.

1. Introduction

The report of the Cullen enquiry into the Piper Alpha disaster led to a change of policy in offshore safety, replacing prescriptive rules with a goal-setting approach. In the UK sector there has been a major change in philosophy in recent years, which has opened up ways for innovative thinking. ‘The Industry Guidelines on a Framework for Risk Related Decision Support’ provides a sound basis for evaluating various options in the initial design stages (UK Offshore Operators Association 1999). Based on the guidelines, a design-decision support framework using a fuzzy-logic-based composite structure methodology is proposed for design option/proposal evaluation. The proposed framework could be useful for a wide range of applications under various conditions. Its major purpose is to support risk-based decision-making during the design and operation of offshore products. It provides a solid foundation for evaluating various options that need to be considered in the feasibility and concept selection stages of a project, especially with respect to risks associated with major accident hazards such as fire, explosion, impact and loss of stability.

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In marine and offshore engineering applications, engineers, safety analysts and managers are often asked to make decisions on the basis of widely divergent objectives. For instance, contract proposals may be evaluated on the basis of technical merit, total cost incurred, ability to meet schedule requirements and intangible attributes such as previous performance. In such situations, experts are asked to evaluate the proposals based on their experiences and engineering judgements. Often, especially in early design stages of engineering systems with a high level of innovation, only qualitative or vague statements can be made, such as 'good performance', 'poor cost' and 'quite safe'. Experts then apply numerical ratings to these vague or fuzzy terms to assist in the evaluation. However, each of the scoring criteria may have a different degree of importance depending on the approach of the evaluation. This relative importance must be taken into account so that the best design option is selected.

Fuzzy logic provides a means for evaluating alternatives where the objectives and criteria are vague and where the criteria themselves vary in importance. Fuzzy logic is a subset of conventional logic that has been extended to allow for degrees of truth (i.e. truth values between true and false). Fuzzy logic has been used in safety modelling and design evaluation of marine and offshore engineering systems by many researchers (Sii and Wang 2000, Sii *et al.* 2001a, 2001b, 2001c, 2001d, 2001e, Wang, J. 1997, Q1 Wang and Kieran 2000, Wang and Ruxton 1997, Wang *et al.* 1995, 1996, 2001).

The purpose of this paper is to develop a design-decision support framework for evaluation of marine and offshore engineering design proposals using a fuzzy-logic-based composite structure methodology. It is a multi-criteria decision-making framework using data/information derived from qualitative or quantitative, or the combination of both, sources for design evaluation. The factors such as safety, cost and technical performance of a proposal are described in linguistic terms to address the inherent uncertainty in the data/information sources.

Traditionally, in the marine and offshore industry, the primary objective in selecting a design/procurement option has been to pick up the one with the lowest cost estimate. However, in recent years, selection of the winning design has been complicated by a trade-off among safety, cost and technical performance. Establishing criteria for the quantitative and qualitative selection of design/procurement proposals will enable designers to choose the one that best meets the needs described in the solicitation.

A proposal with a high cost may provide a high degree of technical performance and also safety levels, while a low-cost proposal may not provide adequate technical performance and/or safety levels. In other words, maximizing the degree of technical performance, maximizing safety and minimizing the cost incurred may be in conflict. In addition, there are varying degrees of importance of technical performance, safety and cost. Thus, the ultimate goal of selecting a design/procurement proposal is to determine, under the different importance of objectives, which proposal best satisfies the requirements of technical performance, safety and cost (i.e. a technical performance versus safety versus cost trade-off analysis).

In the design/procurement proposal evaluation process, the assessment of technical performance, safety and cost is subject to uncertainty, especially with a project having a high level of innovation without much previous experience. In this study, the uncertainty in the input variables such as technical performance, safety and costs incurred are characterized by the means of an approximate reasoning approach using fuzzy-logic theory.

The proposed fuzzy-composite evaluation framework may be used as a useful tool to solve decision-making problems where there are conflicting objectives with varying degrees of importance, and values of input variables are uncertain. The specific objectives of this study are twofold. The first objective is to develop a design-decision support framework based on a fuzzy-composite evaluation methodology, and the second one is to apply the proposed framework to technical performance–safety–costs trade-off analysis for design/procurement proposal selection.

2. A framework using a fuzzy-logic-based composite structure methodology for design proposal evaluation

2.1. A design decision support framework

This section proposes a framework based on a fuzzy-logic-based composite structure methodology for design/procurement proposal evaluation of offshore engineering systems. The framework can be used to assist decision-makers in solving design/procurement proposal selection problems where there are conflicting objectives with different preferences (weights) and the value of each input variable is with a certain level of uncertainty. The framework consists of the following steps:

- Step 1: define basic criteria.
- Step 2: group basic criteria into progressively fewer, more general groups.
- Step 3: construct trapezoidal fuzzy sets to represent the uncertainty in the basic criteria.
- Step 4: transform the fuzzy sets into first-level index values.
- Step 5: calculate the second-level index values.
- Step 6: calculate the final composite index values.
- Step 7: rank the alternative options.

Each step is now described in detail.

2.1.1. Step 1: define basic criteria. The first step is to define all the basic criteria used in the design-decision support evaluation process. It is essential to list all the basic criteria, and the salient characteristics of each criterion.

2.1.2. Step 2: group basic criteria into progressively fewer, more general groups. The composite structure procedure involves a step-by-step regrouping of a set of various basic criteria to form a single criterion (Bogardi and Bardossy 1983). The seven basic criteria shown in figure 1 are selected as critical and sensitive ones in accordance with the evaluation criteria specified in the request of the proposal. The set of basic (first-level) criteria is grouped into a smaller subset of second-level criteria. For example, the basic criteria such as capital cost, maintenance cost and inspection cost can be grouped into cost in general, which is an element of the subset of the second-level criteria. The other two second-level criteria are safety and technical performance. The third level is considered the final level for the composite (system) criterion. This can be formed by combining the three second-level criteria (i.e. safety, cost and technical performance).

2.1.3. Step 3: construct trapezoidal fuzzy sets to represent the uncertainty in the basic criteria. The values of the basic criteria in the design/procurement proposal evaluation process are estimated as fuzzy values. The fuzzy values are numbers that belong to a given set (interval) with a membership degree. To evaluate the various design/procurement options/proposals under uncertainty, let $Z_i(x)$ be a fuzzy value

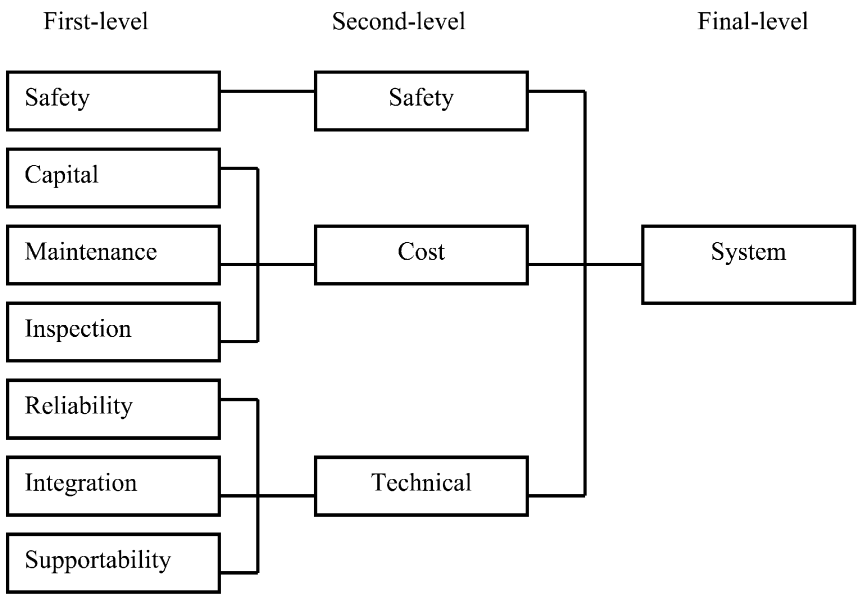

Figure 1. The composite procedure for evaluation and selection of an offshore system.

for the ith basic criterion, and let its membership function $\mu[Z_i(x)]$ be a trapezoid as shown in figure 2, where x is an element (option number or name) of the discrete set of design/procurement proposals. If the trapezoid is reduced to a vertical line, it represents a so-called crisp (non-fuzzy) number. A level-cut concept can be used to define the interval of each basic criterion at various degrees of membership

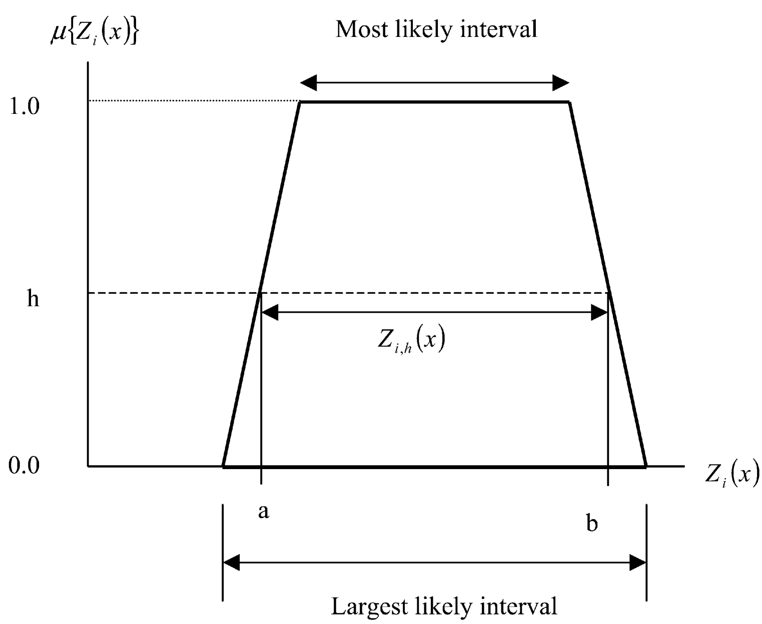

Figure 2. Fuzzy set for a basic criterion.

(Dong and Shah 1987). The membership degree for an uncertain value can be determined using expert judgement based on experience, engineering knowledge and observation variability. As shown in figure 2, $Z_{i,h}(x)$ is the interval value of the ith basic criterion at the membership degree h (i.e. $a \leq Z_{i,h}(x) \leq b$).

2.1.4. Step 4: transform the fuzzy sets into first-level index values. Since the units of the basic criteria are different in nature, it is often difficult to compare them directly. Therefore, the actual value of each basic criterion $Z_{i,h}(x)$ needs to be transformed into an index (first-level index). Using the best value ($BESTZ_i$) and the worst value ($WORSTZ_i$) of Z_i for the ith basic criterion, the actual value $Z_{i,h}(x)$ can be transformed into a first-level index value $A_{i,h}(x)$ denoted by the following expressions:

- If $BESTZ_i > WORSTZ_i$, then:

$$A_{i,h}(x) = \begin{bmatrix} 1, & Z_i(x) \geq BESTZ_i \\ \dfrac{Z_i(x) - WORSTZ_i}{(BESTZ_i - WORSTZ_i)}, & WORSTZ_i < Z_i(x) < BESTZ_i \\ 0, & Z_i(x) \leq WORSTZ_i \end{bmatrix} \tag{1}$$

- If $BESTZ_i < WORSTZ_i$, then:

$$A_{i,h}(x) = \begin{bmatrix} 1, & Z_i(x) \leq BESTZ_i \\ \dfrac{WORSTZ_i - Z_i(x)}{(WORSTZ_i - BESTZ_i)}, & BESTZ_i < Z_i(x) < WORSTZ_i \\ 0, & Z_i(x) \geq WORSTZ_i \end{bmatrix} \tag{2}$$

For example, when selecting a design/procurement proposal for an offshore production platform, the less the construction cost, the better the choice. Because the best value (lowest cost) is less than the worst value (highest cost), equation (2) ($BESTZ_i < WORSTZ_i$) should be used to calculate the index value for the criterion of cost. As for another example, the bigger the area of the net floor, the better the choice. Therefore, in this case, equation (1) ($BESTZ_i > WORSTZ_i$) should be used to obtain the index value for the net floor area. To calculate the index value of the ith basic criterion, one should therefore select either equation (1) or equation (2) according to the characteristics of the criterion.

Two methods can be used to assign the best and worst values (i.e. $BESTZ_i$ and $WORSTZ_i$) of the ith basic criterion. One is to assign the best and worst values of the ith basic criterion according to the overall best and worst values of the ith basic criterion among the design/procurement proposals in hand. The other is to assign the best and worst values of the ith basic criterion according to the opinion of an expert or a panel of experts. These two methods can be combined in certain circumstances to achieve the best results. Since the actual value $Z_{i,h}(x)$ is an interval with lower bound a and upper bound b as shown in figure 2, the first-level index value $A_{i,h}(x)$ resulting from $Z_{i,h}(x)$ is also an interval, as shown in figures 3 and 4.

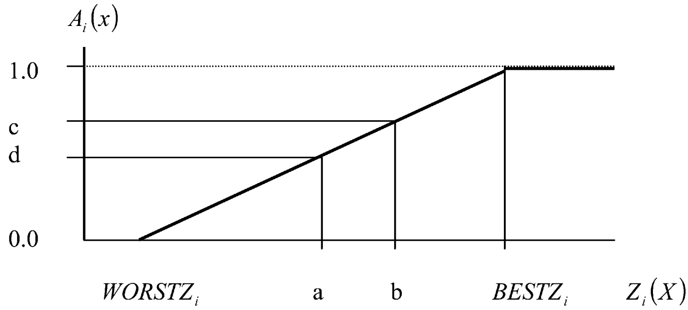

Figure 3. Transferring actual value $Z_i(X)$ into first-level index value $A_i(X)$.

2.1.5. Step 5: calculate the second-level index values. The second-level index values, $B_{i,h}(x)$, for composite criteria can be calculated as follows using the index values of the basic criteria and equation (3):

$$B^{j}_{i,h}(x) = \left(\sum_{i=1}^{n_j} w_{i,j}[A_{i,h,j}(x)p_i] \right)^{1/p_i} \tag{3}$$

where $B^{j}_{i,h}(x)$ is the second-level index value of second-level group *j* (i.e. safety, cost or technical performance), n_j is the number of the elements in group *j*, $A_{i,h,j}(x)$ is the first-level index value for the *i*th basic criterion in group *j*, $w_{i,j}$ is the weight reflecting the importance of the *i*th basic criterion in group *j* ($\sum_{i=1}^{n_j} w_{i,j} = 1$), and p_i is the balancing factor for the *i*th basic criterion in group *j*.

The processes for determining weight and the balancing factor will be described in detail in section 2.2.

2.1.6. Step 6: calculate the final composite index values. The final composite index value $C_h(x)$ can be obtained by combining the index values of the composite or second-level criteria using equation (4a):

$$C_h(x) = \sum_{j=1}^{N} \left\{ w_j \left[B^{j}_{i,h}(x) \right] p_j \right\}^{1/p_j} \tag{4a}$$

where *N* is the number of the second-level criteria and p_j is the balancing factor for second-level group *j*.

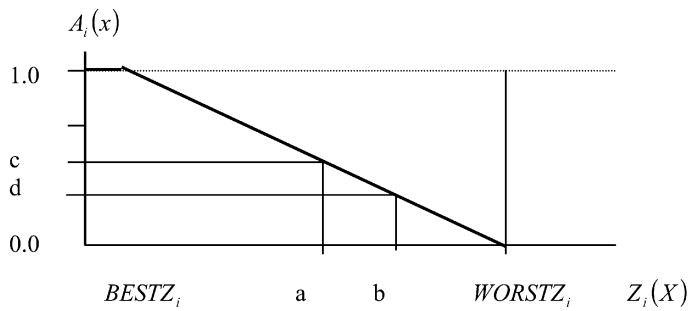

Figure 4. Transferring actual value $Z_i(X)$ into first-level index value $A_i(X)$.

In the hierarchical structure shown in figure 1 where there are only three composite or second-level criteria (i.e. safety, cost and technical performance), if p_j ($j = 1, 2$ or 3) is a constant (p), then equation (4a) can be further elaborated into equation (4b) as follows:

$$C_h(x) = \left(w_C\left[B_i^C(x)\right]p + w_T\left[B_i^T(x)\right]p + w_S\left[B_i^S(x)\right]p\right)^{1/p} \tag{4b}$$

where $B_i^C(x)$ is the index value for the first composite or second-level criterion (cost), $B_i^T(x)$ is the index value for the second composite or second-level criterion (technical performance), $B_i^S(x)$ is the index value for the third composite or second-level criterion (safety), w_C, w_T, and w_S are the weights representing the relative importance of the three composite criteria in the final system evaluation, and p is the balancing factor.

2.1.7. Step 7: rank the alternative options. Let $C(x)$ be the fuzzy number representing the final composite criteria (system) of proposal x. With the help of two index values, $C_{h=1}(x)$ and $C_{h=0}(x)$, the membership function, $\mu[C(x)]$, of fuzzy set $C(x)$ can be approximately calculated from the piecewise linear function as illustrated in figure 5 or directly using equation (5) (Sii *et al.* 2001e).

$$\mu[C(x)] = \begin{bmatrix} 1, & r_{\min} \le C(x) \le r_{\max} \\ \dfrac{C(x) - R_{\min}}{r_{\min} - R_{\min}}, & R_{\min} \le C(x) < r_{\min} \\ \dfrac{C(x) - R_{\max}}{r_{\max} - R_{\max}}, & r_{\max} < C(x) \le R_{\max} \\ 0, & \textit{otherwise} \end{bmatrix} \tag{5}$$

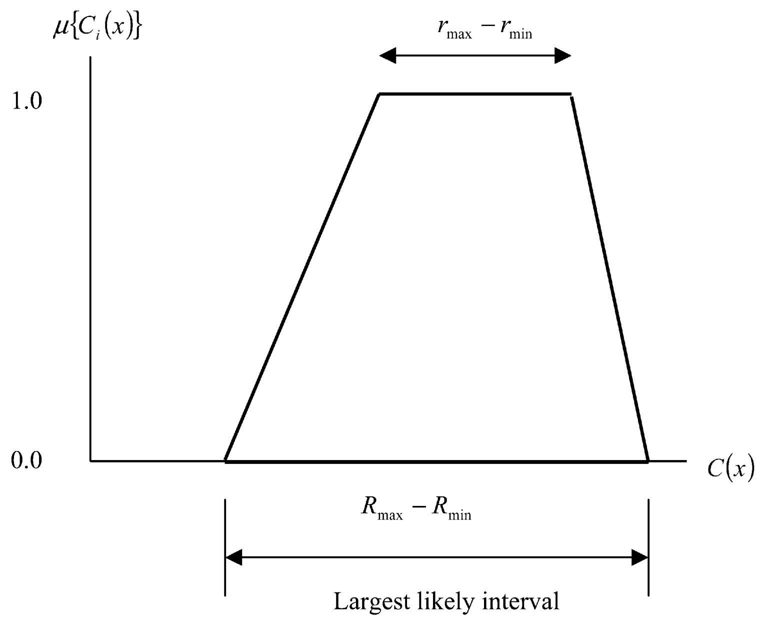

Figure 5. Membership function for $C_i(X)$.

where $r_{\min}$ and $r_{\max}$ are the lower and upper bound values of $C_{h=1}(x)$ while $R_{\min}$ and $r_{\max}$ are the lower and upper bound values of $C_{h=0}(x)$. The ranking of the proposals can be determined using methods such as that developed by Chen (1985). The ranking of the n fuzzy numbers associated with the design proposals can be determined using a maximizing set and a minimizing set.

The maximizing set is a fuzzy subset with membership function $\mu M(C)$ given as:

$$\mu_M(C) = \begin{bmatrix} \dfrac{C - C_{\min}}{C_{\max} - C_{\min}}, & C_{\min} \leq C \leq C_{\max} \\ 0, & otherwise \end{bmatrix} \tag{6}$$

where $C_{\min} = \min[\min\ C_{h=0}(x)]$ and $C_{\max} = \max[\max\ C_{h=0}(x)]$ for $x = 1, \ldots, n$. Then, the right utility value, $U_{\mathrm{R}}(x)$, for proposal x is defined as:

$$U_{\mathrm{R}}(x) = \max\big(\min\{\mu_M(C), \mu[C(x)]\}\big) \tag{7}$$

The minimizing set is a fuzzy subset with membership function $\mu_G(C)$ given as:

$$\mu_G(C) = \begin{bmatrix} \dfrac{C - C_{\max}}{C_{\min} - C_{\max}}, & C_{\min} \leq C \leq C_{\max} \\ 0, & otherwise \end{bmatrix} \tag{8}$$

The left utility, $U_{\mathrm{L}}(x)$, for proposal x is then defined as:

$$U_{\mathrm{L}}(x) = \max\big(\min\{\mu_G(C), \mu[C(x)]\}\big) \tag{9}$$

The total utility or ordering value for proposal x is:

$$U(x) = \frac{U_{\mathrm{R}}(x) + 1 - U_{\mathrm{L}}(x)}{2} \tag{10}$$

The proposal that has the highest ordering value in the discrete set of proposals is then selected as the best one.

2.2. *Determination of weights and balancing factors*

In equations (3) and (4), weights and balancing factors are assigned to each criterion. They represent a double-weighting scheme. Thus, the produced result is sensitive to this weighting scheme.

The weighting factors/coefficients that are used to indicate the relative importance of each criterion, are determined using Analytic Hierarchy Processing (AHP) analysis. To calculate the weighting factors/coefficients, the AHP procedure developed by Saaty (1988) is applied. The AHP method can be used to obtain the relative weight of each criterion in a group based on a paired comparison.

Upon completion of the first three steps of the framework, AHP analysis is applied to carry out assessment of priority weights for different basic criteria. Pairwise comparisons are used to determine the relative importance among all basic criteria within groups. The importance is quantified using a scale with which one criterion dominates

Intensity of importance	Definitions
10	Equal importance
30	Weak importance
50	Strong importance
70	Demonstrated importance
90	Absolute importance
20, 40, 60, 80	Intermediate values

Table 1. Linguistic measure of importance, a_{ij}.

another. Comparisons are made within groups to determine the relationship between the criteria indicated by each expert as significant. In the final part of the design-decision evaluation, AHP analysis is also used to carry out the assessment of priority weights for different composite or second-level criteria. The weights in the additive utility function (equation (4a) or equation (4b)) can be evaluated by pairwise comparisons of the composite or second-level criteria. The comparison of two criteria is made at one time by comparing the relative importance. An allocation of a total of 100 points to the two criteria reflects the judgement made of the relative importance of each. For n criteria, $n(n-1)/2$ comparisons are made. The pairs are randomized before being used in the decision-making process. This method is sometimes referred to as the 'constant sum method' (Guilford 1954) because of the allocation of a constant 100 points to the pair in the comparisons. The rating method suggested by Guilford (1954) is utilized for all comparisons where the degree of intensity or preference of the decision maker in the choice for each pairwise comparison is rated on a point scale of 1–100. The quantities are then placed in a matrix of comparison. The use of Guilford's constant sum method also allows the decision-maker's consistency of judgement to be monitored. The normalized average rating, sometimes referred to as priority weight, is used to depict the relative significance of each factor. The steps used in AHP analysis can be found in many references including Saaty (1988). The linguistic measure of importance used in the AHP analysis in this work is displayed in table 1.

The balancing factors ($p \leq 1$) are assigned to groups of criteria and reflect the importance of the maximal deviations, where maximal deviation means the maximum difference between a criterion value and the best value for that criterion. The largest the value of the balancing factor, the greatest the concern with respect to the maximal deviation. When $p = 1$, all deviations are equally weighted. When $p = 2$, each deviation receives its importance in proportion to its magnitude. As the value p becomes larger and larger, the deviation has more and more importance. As a general rule, $p = 3$ or greater should be assigned for limiting criteria (i.e. criteria where undesirable outcome might fatally flaw a proposal); otherwise $p = 1$ or $p = 2$ seems to be a good choice (Torno *et al.* 1988, Paek *et al.* 1992). Q2

3. Case study

3.1. General background

Under most circumstances, assessment of options/alternatives is usually performed on the basis of evaluation inputs that are subjective. Often, however, trade-offs are required when the evaluation criteria have a large degree of uncertainty. In this case, the criteria may be presented as a range of possible values instead of crisp values. The following example is used to illustrate the practicality of the proposed framework for design option evaluation.

The procurement of a support structure for an offshore system must be evaluated on the basis of a number of factors such as safety, cost and technical performance. Assume that four options are being considered for an offshore platform. Option 1 is a conventional support structure for an offshore platform without much innovation involved. Option 2 is a new design with a high safety and reliability level. Its capital and maintenance costs are comparatively more expensive than option 1 as the design is capable of reducing the effect from boat/ship operational or accidental impact via an absorber mechanism. Option 3 is another design associated with some novel design features, which provides improved system integration and supportability. It also provides a high level of safety and reliability. However, these novel design features would inevitably increase the capital, maintenance and inspection costs. Option 4 provides intermediate safety and reliability margins but is associated with a high degree of uncertainty. It also provides intermediate system integration and supportability, but it requires higher costs in both maintenance and inspection throughout its operational life. The proposal, as presented in table 2 consisting of four options submitted for evaluation, is used in this case study to demonstrate the application of the proposed design decision support framework. All the four options are hypothetically prepared for illustration purposes. The engineering design team will perform a technical review for acceptability in meeting the mandatory requirements in terms of safety, cost and technical aspects. The engineering design team may be composed of personnel with various professional expertise in the fields of engineering design, safety analysis, cost estimation, utility engineering, and so on.

These systems are to be evaluated and compared on the basis of safety, three basic cost-related criteria and three technical-related criteria. The safety data for all the options are evaluated by the engineering design team, using the approximate reasoning and evidential reasoning approaches as described in Sii and Wang (2000) and Sii *et al.* (2001e). This is followed by the centre average defuzzification approach suggested by Klir and Yuan (1995) and Wang, L.X. (1997). The values for the three cost-related parameters (i.e. capital cost, maintenance cost and inspection cost) are hypothetically assigned by the engineering design team. The value assignment for the technical performance (reliability, easy system integration and supportability) is carried out in a similar way based on engineering judgement and experiences of the team. The term 'system integration' indicates the ease of installation of other related facilities onto the support structure. The term 'supportability' describes the friendliness of the structure to accommodate external support such as maintenance or inspection support vessel, supply vessels, and so on. As presented in table 2, ranges of these parameters are known in terms of *most likely* values and *largest likely* values on the basis of past experience and expert opinion. In other words, the data of each basic criterion are represented by two intervals; that is, *most likely interval* and *largest likely interval* to reflect the uncertainty in each basic criterion. In this example, the *largest likely interval* of each basic criterion is the interval between the minimum and maximum values estimated by the engineering team. The *most likely interval* is the one between the two values around the average of the total values estimated. These two intervals are then used to construct the fuzzy membership function for each basic criterion as shown in figure 2.

Basic criteria	Option 1		Option 2		Option 3		Option 4	
	Largest likely interval	Most likely interval	Largest likely interval	Most likely interval	Largest likely interval	Most likely interval	Largest likely interval	Most likely interval
Safety	6–9	6.5–8.5	7.5–9	8–8.5	6.5–9.5	7–8.5	5.5–8.5	6–8
Capital (£ million)	1–22	1.5–21	17–20.5	18.5–20	19–23.5	19.5–23	18–22.5	19.5–21
Maintenance (£ million)	13–15	13.5–14.5	12–14.5	13–14	12.5–14.5	13–14	12–14.5	13–14
Inspection (£ million)	7–9.5	8–9	6–9	7–8.5	6–9.5	7–9	7–9.5	8–9
Reliability	0.96–0.995	0.98–0.99	0.96–0.995	0.98–0.99	0.94–0.99	0.96–0.97	0.95–0.995	0.965–0.99
Integration	6–8.5	7–8	6.5–9.5	7–9	7.5–10	8–9.5	5.5–8.5	6–8
Supportability	7–9.5	7.5–9	7–9	8–8.5	7–9.8	8.5–9.5	7–9.5	7.5–9

Table 2. Basic criteria values for the four options/alternatives.

Basic criteria	Best value	Worst value
Safety	10	0
Capital (£ million)	0	25
Maintenance (£ million)	0	15
Inspection (£ million)	0	10
Reliability	1	0
Integration	10	0
Supportability	10	0

Table 3. Best and worst values for each basic criterion.

Table 3 displays the best and worst values for the seven basic criteria. The weight factors for the basic criteria and for the composite criteria are presented in tables 4 and 5, respectively (Sii and Wang 2003). The proposed design decision support framework based on a composite structure methodology is used to determine which of the four options best satisfies the requirements of the project. The evaluation is to be conducted assuming that the reliability is six times as important to the evaluators as the supportability, and twice as important as the easy system integration. The capital cost is 1.5 times as important as inspection cost, and maintenance cost is twice as important as inspection cost and 1.5 times as importance as capital cost. In the final level, safety is 2.5 times as important as technical performance and 1.7 times as important as cost. The cost is 1.5 times as important as technical performance. In addition, the evaluation criteria are only known approximately.

3.2. Design options/proposals evaluation

The proposed design decision support framework is used to perform the evaluation and option selection.

3.2.1. Step 1. The first step is to define all the relevant basic criteria. The seven basic criteria considered in this example are safety, capital cost, maintenance cost, inspection cost, reliability, easy system integration and supportability, as presented in table 2.

3.2.2. Step 2. The second step in the evaluation is to group appropriate basic criteria (first-level) such that they reduce to a single composite criterion (second-level).

Basic criteria	Weight
Safety	1
Capital	0.31
Maintenance	0.48
Inspection	0.21
Reliability	0.6
Integration	0.3
Supportability	0.1

Table 4. Weighting factors for each basic criterion.

Composite criteria	Weighting
Safety	0.5
Cost	0.3
Technical	0.2

Table 5. Weighting factors for each composite or second-level criterion.

The basic criteria are known as the first-level criteria. They include safety, capital cost, maintenance cost, inspection cost, reliability, easy system integration and supportability. The second-level criteria are safety, cost and technical performance. The final composite criterion is the system.

3.2.3. Step 3. This step constructs trapezoidal fuzzy sets to represent the uncertainty in the basic criteria. As shown in figure 2, the most likely values for a particular criterion are assigned a value of 1 for the membership function. The membership function is assumed to be linear for values between the most likely and largest likely values, thus providing the trapezoidal shape.

Each option will be evaluated on a scale of 1–10 for safety, easy system integration and supportability, and 0–1 for reliability. The cost related basic criteria such as capital cost, maintenance cost and inspection cost are evaluated on different monetary scales. For instance, the capital cost is scaled between 0 and 25 million. The adjective ratings and associated scores for safety, reliability, easy system integration and supportability can be seen in table 6.

3.2.4. Step 4. The fourth step is to transform the fuzzy sets for each first-level criterion of each option into first-level index values. The first-level index values can be obtained by normalizing the fuzzy sets in relation to the BEST and WORST values for each criterion using equations (1) and (2).

If the criterion is cost or weight, then lower values are better, and the best value is less than the worst value. If the criterion is safety or reliability, then higher values are better, and the best value is greater than the worst. Because there are four values assigned to a fuzzy set, there will be four first-level index values. Figure 6 illustrates the first-level index values for the system inspection cost of option 1 as an example.

Adjective ratings	Basic criteria scores			
	Safety	Reliability	Easy system integration	Supportability
Outstanding	10	1	10	10
Excellent	9	0.9	9	9
Very good	7	0.7	7	7
Good	5	0.5	5	5
Fair	3	0.3	3	3
Poor	1	0.1	1	1
Worst	0	0	0	0

Table 6. The adjective ratings and associated scores.

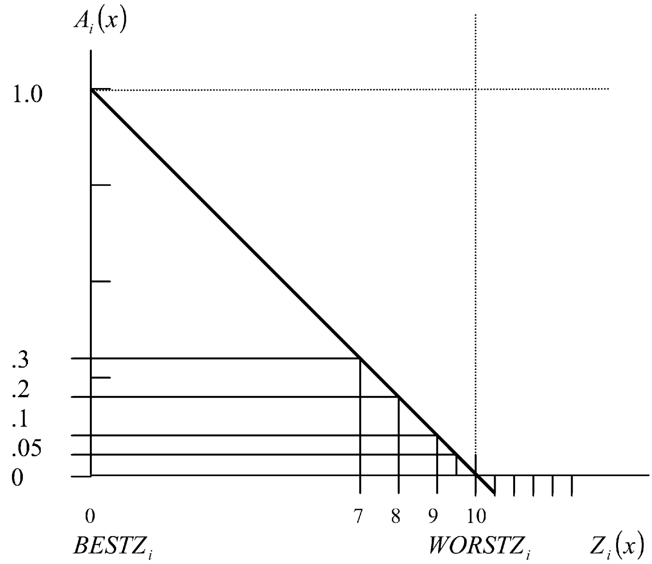

Figure 6. Example of transferring actual value $Z_i(X)$ into first-level index value $A_i(X)$ for inspection cost of option 1.

In this case, the first-level index values are 0.3, 0.2, 0.1 and 0.05, corresponding to the raw values (actual values) of £7 million, £8 million, £9 million and £9.5 million, respectively. Tables 7–10 display the first-level index values of all the four options.

3.2.5. Step 5. In this step, the second-level index values, B_i, are calculated using equation (3) where weighting factors, w, and balancing factors, p, are used.

The weights in the additive utility function in equations (3) and (4) are evaluated using AHP analysis. Pairwise comparisons of the criteria (in this case, three basic criteria for cost and technical performance) are performed respectively. The weighting factors/coefficients for the basic criteria in the groups of technical performance, cost and safety are presented in table 4.

As an illustrative example of the composite or second-level index values, consider the cost criteria for option 1. Values of 0.25, 0.14 and 0.3 were obtained for the

Basic criterion	A_1	A_2	A_3	A_4
Safety	0.6	0.65	0.85	0.9
Capital	0.25	0.225	0.15	0.12
Maintenance	0.14	0.1	0.05	0
Inspection	0.3	0.2	0.1	0.05
Reliability	0.96	0.98	0.99	0.995
Integration	0.6	0.7	0.8	0.85
Supportability	0.7	0.75	0.9	0.95

Table 7. First index values (A_i) for option 1.

Basic criterion	A_1	A_2	A_3	A_4
Safety	0.75	0.8	0.85	0.9
Capital	0.32	0.26	0.2	0.175
Maintenance	0.2	0.14	0.08	0.04
Inspection	0.4	0.3	0.15	0.1
Reliability	0.96	0.98	0.99	0.995
Integration	0.65	0.7	0.9	0.95
Supportability	0.7	0.8	0.85	0.9

Table 8. First index values (A_i) for option 2.

first-level index values for capital cost, maintenance cost and inspection cost, respectively. By using the weighting factors in table 4, the second-level index value is calculated as follows:

$$B_1^C = \{0.31 \times 0.25 \times 1 + 0.48 \times 0.14 \times 1 + 0.21 \times 0.3 \times 1\}^{1/1} = 0.208$$

It is worth noting that the balancing factor (p) is taken as 1 throughout this study. Using the same computation method, the second-level index values for the criteria of each option are obtained as shown in tables 11–13.

Basic criterion	A_1	A_2	A_3	A_4
Safety	0.65	0.7	0.85	0.95
Capital	0.25	0.225	0.08	0.05
Maintenance	0.17	0.14	0.08	0.04
Inspection	0.4	0.3	0.1	0.05
Reliability	0.94	0.96	0.97	0.99
Integration	0.75	0.8	0.95	1
Supportability	0.7	0.85	0.95	0.98

Table 9. First index values (A_i) for option 3.

Basic criterion	A_1	A_2	A_3	A_4
Safety	0.55	0.6	0.8	0.85
Capital	0.28	0.225	0.15	0.1
Maintenance	0.2	0.14	0.08	0.04
Inspection	0.3	0.2	0.1	0.05
Reliability	0.95	0.965	0.99	0.995
Integration	0.55	0.6	0.8	0.85
Supportability	0.7	0.75	0.9	0.95

Table 10. First index values (A_i) for option 4.

Second index values	Option 1	Option 2	Option 3	Option 4
B_1^S	0.6	0.75	0.65	0.55
B_2^S	0.65	0.8	0.7	0.6
B_3^S	0.85	0.85	0.85	0.8
B_4^S	0.9	0.90	0.95	0.85

Table 11. Second-level index values for composite criterion, safety (B_i^S), for options 1–4.

Second index values	Option 1	Option 2	Option 3	Option 4
B_1^C	0.208	0.279	0.243	0.246
B_2^C	0.16	0.229	0.2	0.179
B_3^C	0.092	0.132	0.084	0.106
B_4^C	0.048	0.095	0.045	0.061

Table 12. Second-level index values for composite criterion, cost (B_i^C), for options 1–4.

Second index values	Option 1	Option 2	Option 3	Option 4
B_1^T	0.826	0.841	0.859	0.805
B_2^T	0.873	0.878	0.901	0.834
B_3^T	0.924	0.949	0.962	0.924
B_4^T	0.947	0.972	0.992	0.947

Table 13. Second-level index values for composite criterion, technical performance (B_i^T), for options 1–4.

3.2.6. Step 6. The final composite index values, C_i, are calculated using equation (4):

$$C_i(x) = (w_C[B_i^C(x)]p + w_T[B_i^T(x)]p + w_S[B_i^S(x)]p)^{1/p}$$

The composite index values for each option correspond to a fuzzy set. As an illustrative example, consider option 1 where 0.208, 0.826 and 0.6 were obtained for B_1^C, B_1^T and B_1^S

Final composite index values	Option 1	Option 2	Option 3	Option 4
C_1	0.528	0.627	0.57	0.51
C_2	0.575	0.644	0.59	0.521
C_3	0.637	0.654	0.643	0.617
C_4	0.654	0.673	0.687	0.633

Table 14. Final composite index values for system (C_i) for options 1–4.

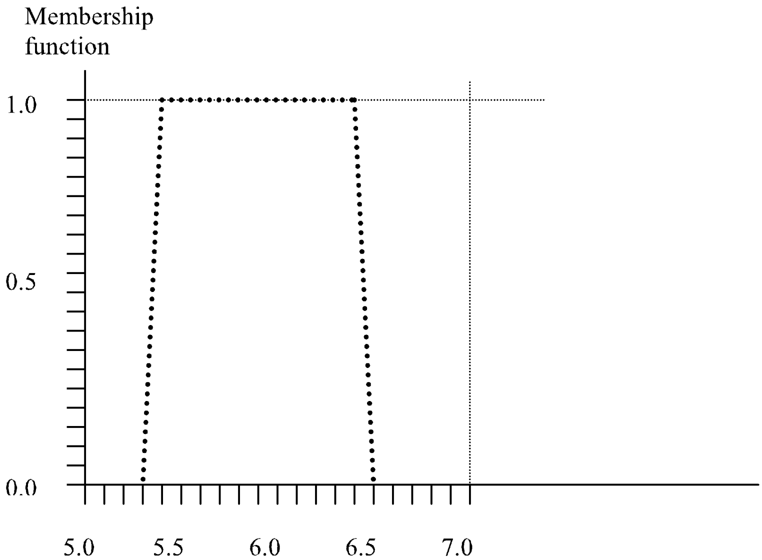

Figure 7. Fuzzy set of final composite index value for option 1.

for cost, technical performance and safety, respectively. By using the weighting factors from table 5, the final composite index value is calculated as follows:

$$C_1(\text{option 1}) = (0.3 \times 0.208 \times 1 + 0.2 \times 0.826 \times 1 + 0.5 \times 0.6 \times 1)^{1/1} = 0.528$$

The final composite index values for the four options are displayed in table 14. The resulting fuzzy sets for the four options are also provided in figures 7–10. As can be seen in table 14, there is overlapping between the fuzzy sets.

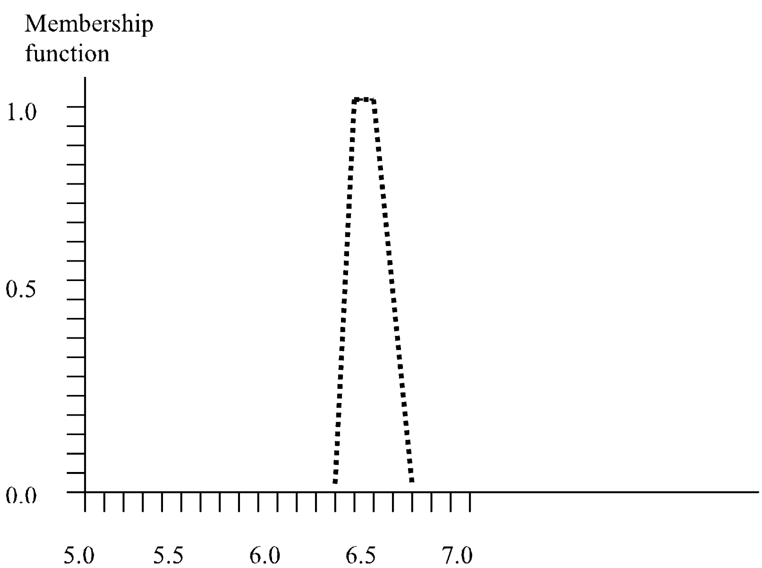

Figure 8. Fuzzy set of final composite index value for option 2.

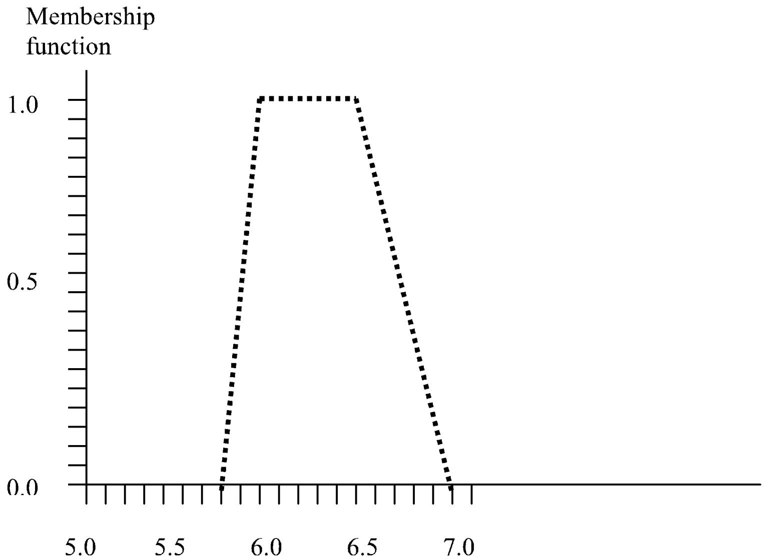

Figure 9. Fuzzy set of final composite index value for option 3.

3.2.7. Step 7. To rank the options, the maximizing and minimizing set concepts of fuzzy logic are used. The ranking method is illustrated in figures 11–14.

As depicted in figures 11–14, the maximizing set intersects each trapezoidal fuzzy set in two places. A right utility value, U_R, for each fuzzy set is the larger of these two intersection values. Similarly, the value for the left utility value, U_L, is the maximum of the two intersection values of the minimizing set and the

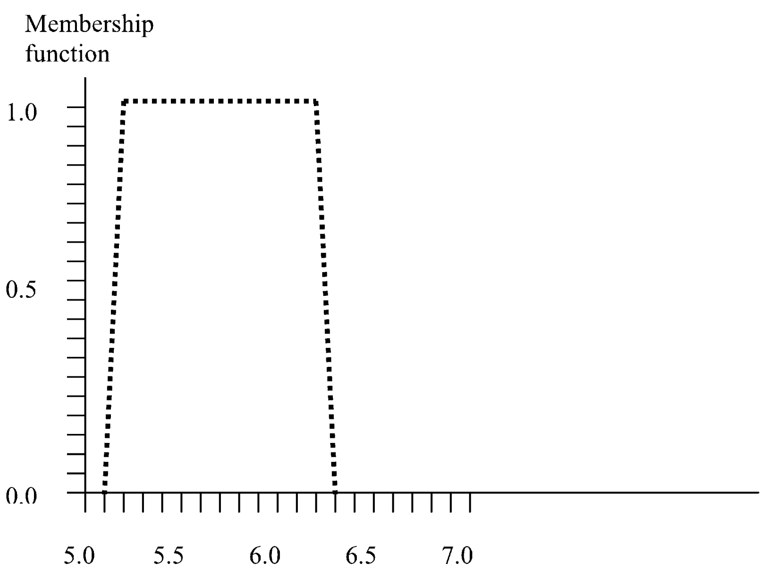

Figure 10. Fuzzy set of final composite index value for option 4.

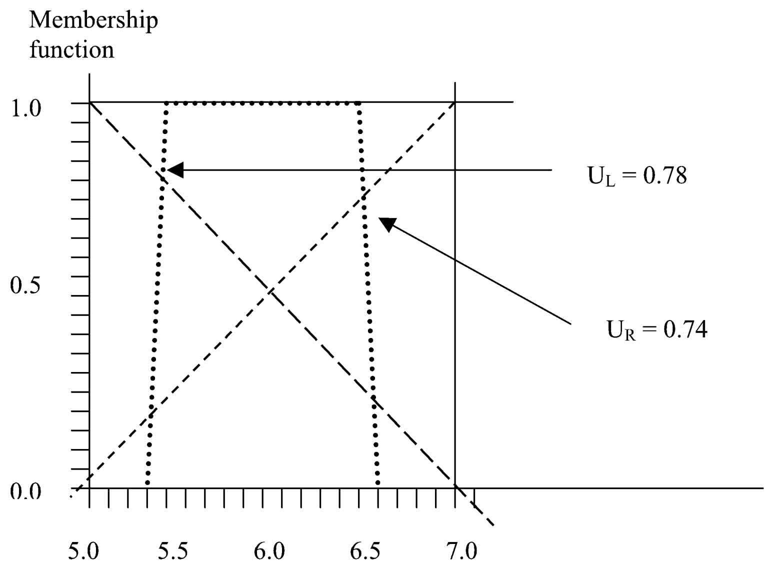

Figure 11. Calculating the left and right utility values (U_L and U_R) for option 1.

fuzzy set. The total utility or ordering value, U, for each option is found as follows using equation (10):

$$\text{Option 1: } U(\text{option 1}) = \frac{0.74 + 1 - 0.78}{2} = 0.48$$

$$\text{Option 2: } U(\text{option 2}) = \frac{0.78 + 1 - 0.33}{2} = 0.725$$

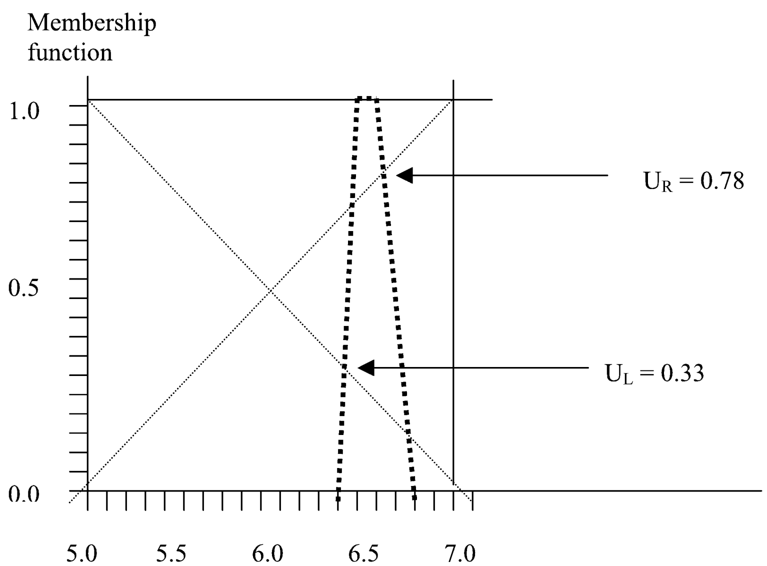

Figure 12. Calculating the left and right utility values (U_L and U_R) for option 2.

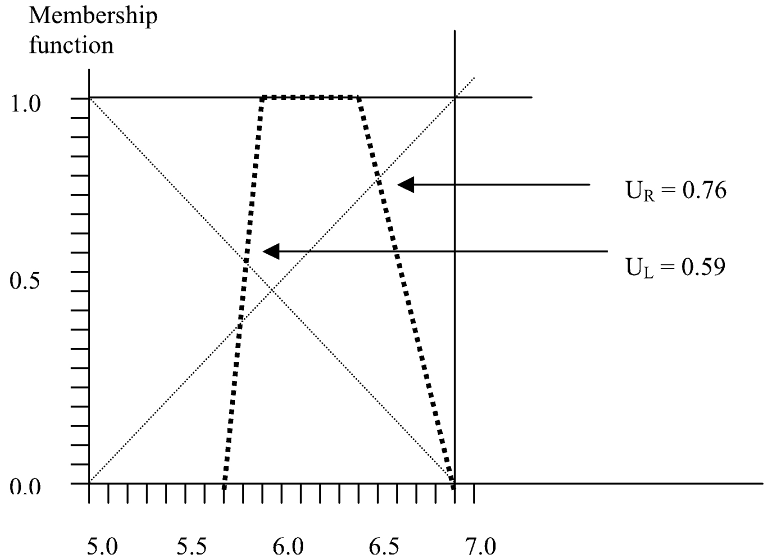

Figure 13. Calculating the left and right utility values (U_L and U_R) for option 3.

$$\text{Option 3: } U(\text{option 3}) = \frac{0.76 + 1 - 0.59}{2} = 0.585$$

$$\text{Option 4: } U(\text{option 4}) = \frac{0.62 + 1 - 0.9}{2} = 0.36$$

In this case study, option 2 has lower technical performance than the others. However, due to the combination of its low cost and high safety, option 2 is ranked the best of the

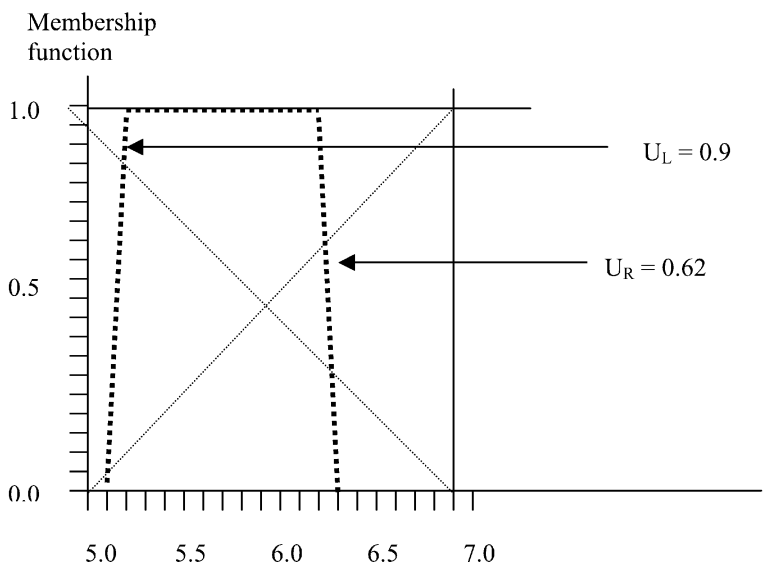

Figure 14. Calculating the left and right utility values (U_L and U_R) for option 4.

four options proposed because it has the highest ordering/utility value. The final result (ranking of the design/procurement proposals) may vary with the weights and balancing factors assigned to each criterion at different levels. If all the second-level criteria are assumed to be of equal importance, even though the ranking order of the four design options remains unchanged, the difference of the total utility values between options 2 and 3 becomes smaller. It may be difficult to identify the difference between the ranking values 0.66 and 0.57 for options 2 and 3 because the two values are too close. Thus, it may be reasonable to consider a combined use of options 2 and 3. Because the selection of different basic criteria may also lead to different results, care must be taken to select the critical requirement criteria so that the result of the analysis will be consistent. In this example, only seven criteria were used to compare the four alternative options; this process can easily be extended to include more criteria and design alternatives.

4. Conclusions

The proposed framework can be used to assist decision-makers in selecting the best design/procurement proposal under uncertainty. In the framework, the basic criteria values are transferred into fuzzy numbers to represent their uncertainty. Fuzzy logic allows for quantifying vague or qualitative ideas, which are common in multi-objective problems. In the evaluation process, the evaluating criteria or objectives are rated against each other, forcing the decision-maker to decide the most important. Most importantly, the process provides a result based on the degree to which each alternative meets each objective, thereby allowing for a decision based on factors that may have been overlooked in conventional procedures. The following conclusions can be made:

- The uncertainty in the values of the basic criteria selected for evaluating the design/procurement proposals can be represented using the fuzzy-set approach.
- The multiple criteria decision-making methodology presented in this study can be a useful tool for solving design/procurement proposal selection problems where there are conflicting objectives, the objectives are of varying degrees of importance, or the values of the basic criteria variables are uncertain.

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