A DECISION-MAKING METHOD ON DESIGN ALTERNATIVES FOR CONSTRUCTION PROJECTS

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This paper introduces a decision-making method on design alternatives to select the best design alternative for construction projects. The new method is developed by combining the Conjunctive and Analytic Hierarchy Process methods with group decision-making methods to eliminate unacceptable alternatives and measure Utility of Designed Quality and Utility of Costs of the acceptable design alternatives for Incremental [Utility of Designed Quality] – [Utility of Costs] Analysis. A case study for the Mekong Bridge in Cambodia done to validate applicability of the developed method is also briefly presented in this paper.

Key Words: *Fuzzy Multiple Attribute Decision-Making, Designed Quality, Analytic Hierarchy Process, Group Decision-Making, Utility of Designed Quality, and Utility of Costs.*

1. INTRODUCTION

Decision-making on design alternatives for construction projects greatly influences projects' output quality and cost that are the most important attributes concerned in investing in construction projects. It is a complex problem of fuzzy multiple attribute decision-making in which attributes may be non-quantifiable, non-obtainable, conflicting, incomplete, incommensurable, and non-traded-off. In addition, it is a mutually exclusive appraisal, requires identification and elimination of unacceptable alternatives, and is usually made by a group rather than an individual.

Several approaches have been proposed to deal with this problem such as Group Decision-Making (Spagon[1)] 1981), Engineering – Economic Analysis (Chon[2)] 1983, Flanan[3)] 1984), SMART (Stuard[4)] 1994), and Multiple Attribute Utility Theory (Shtub, Bard, and Bloberson[5)] 1996), etc., However, the up-to-date approaches are not matured enough in terms of either theoretical basis or practical application, or both. It was found that there are fundamental reasons, why the up-to date approaches are not satisfactory. First, they are weak in establishing a right best-alternative selection criterion for the decision-making. Second, they overemphasize either mathematical algorithm orientation or decision-making process orientation. Third, because they are either ill structured, or too complicated for practitioners, they are very difficult for practical application.

This paper introduces a decision-making method on design alternatives for construction projects. The new method is developed by combining the Conjunctive and Analytic Hierarchy Process (AHP) methods with group decision-making methods. First, the Conjunctive method is applied to identify and eliminate unacceptable design alternatives. Then, the AHP method is employed to measure the Utility of Designed Quality and the Utility of Cost of acceptable design alternatives for the Incremental [Utility of Designed Quality] – [Utility of Cost] Analysis. The group decision-making methods are used to make interventional and final decisions. Due to limit space, this paper will represent the application procedures rather than theoretical bases of the new method. A case study for the Mekong

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Bridge done to validate applicability of the new method will also be briefly described.

2. MATHEMATICAL MODEL OF THE DECISION-MAKING PROBLEM

The decision-making on design alternatives for construction projects can be expressed correctly and concisely in the following mathematical model. There is a set of n design alternatives:

$$A = \{A_1, A_2, ..., A_i, ..., A_n\} \qquad (1)$$

given by the designer *for the owner's decision-making.* Each alternative Ai is attributed by quality Q_i designed for the project, and cost, C_i, required to assure the designed quality. Thus, the set of n design alternatives, A, can be expressed as:

$$A = \{(Q_1, C_1), (Q_2, C_2), ..., (Q_i, C_i), ..., (Q_n, C_n)\} \quad (2)$$

From the owner's perspective, the designed quality includes the several aspects such as fitness for use purpose, durability, reliability, safety, benefits, appearance, effects on environment, construction duration of project, etc. Each of these aspects may include several sub-aspects, and each of the sub-aspects may again include several attributes, and so on. Let us denote a set of m attributes associated with each design alternative by $q = \{q_1, q_2, ..., q_j, ... q_m\}$. Let q_{ij} be attribute q_j of designed quality Q_i (i.e., of design alternative A_i), so a matrix of attributes, Q, for n alternatives is obtained as follows:

$$Q = \| q_{ij} \|, \quad i = 1,2,...,n; \; j = 1,2,...,m \qquad (3)$$

The problem of the decision-making on design alternatives is how to identify and eliminate unacceptable design alternatives, and select the best design alternative among the acceptable design alternatives based on considering and appraising matrix of attributes $Q = \| q_{ij} \|$ versus vector of cost $C=\{C_i\}$, $i=1,2,...,n;\ j=1,2,...,m$.

3. STRUCTURING THE HIERARCHY FOR DESIGNED QUALITY

Hierarchies are divided into two kinds: structural and functional. In structural hierarchies, complex systems are structured into their constituent parts in descending order

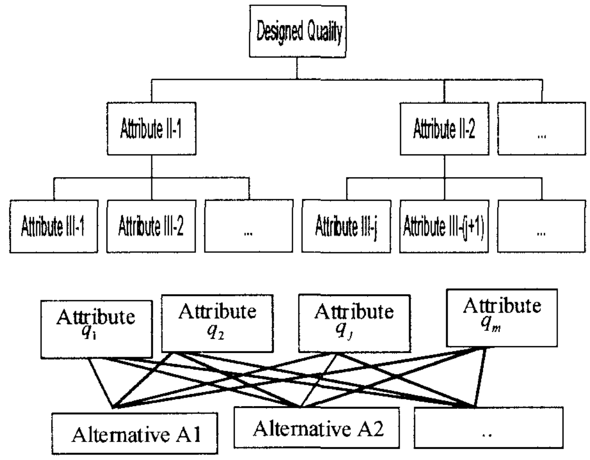

Figure 1 A Typical Hierarchy for Designed Quality

according to structural properties. In contrast, functional hierarchies decompose complex systems into their constituent parts according to their essential relationships. Because the decision-making on design alternatives is considered from owners' perspective only, the hierarchy for designed quality of alternatives should be structured in the structural form.

Figure 1 shows a typical hierarchy for designed quality in the structural form. The hierarchy includes several levels. The last level consists of design alternatives. The branches of the tree structural hierarchy for designed quality do not necessarily descend to the last level but may end at any level. The hierarchy built must be complete and this is easy to fulfill. There exists neither only one right hierarchy for designed quality of a project nor strict rule or procedure for structuring the hierarchy for designed quality of construction projects. Different people often make different hierarchies for the designed quality of the same project. In the decision-making on design alternatives for construction projects, the hierarchy for designed quality should be made by group decision-making. The Interacting Group or Nominal Group method can be applied to structuring the hierarchy for designed quality depending on size and characteristics of project.

Having structured the hierarchy for designed quality, the attributes corresponding to the last elements of each branch of the tree structural hierarchy must be determined either in known scales or in linguistic expression to obtain matrix of attributes $Q = \| q_{ij} \|$, $i = 1,n;\ j = 1,m$, for alternatives. The determination methods of attributes strongly depend on the type, characteristics, and various conditions of project. Group decision-making methods can be applied to determine the non-quantifiable attributes in linguistic expression or in a conventional scale such as 1-10 points or 1-100 points. Some non-quantifiable attributes that are common or well-described in design such as comfort level, beauty, and aesthetic values of project can be judged directly through pair-wise comparisons in the next steps.

4. ELIMINATING UNACCEPTABLE DESIGN ALTERNATIVES

Unacceptable design alternatives are identified and eliminated by applying the Conjunctive method[6] associated with group decision-making methods. Let $[q_i]$ be the minimal acceptable level for attribute q_i. According to the Conjunctive method, alternative A_i is an acceptable alternative only if:

$$q_{ij} \geq \lfloor q_j \rfloor \quad \forall j = 1,2,\ldots,m \qquad (4)$$

However, the relationship between quantity of an attribute and utility of alternatives with respect to that attribute in the decision-making on design alternatives for construction projects are not necessarily in direct ratio to be applied Formula (4). Generally, the attributes of construction projects can be classified into three types named Type I, Type II, and Type III based on the relationship between their quantity and utility of alternatives with respect to them.

Type I includes the attributes whose quantity and utility of alternatives with respect to them are in direct-ratio relation. Examples of the type-I attributes are service life, durability, safety degree, benefits, etc., When quantity of these attributes increases, utility of alternatives with respect to them will increase correspondingly and vice versa. Let $[q_j^I]$ be the minimal acceptable level for type-I attribute q_j^I. Alternative A_i is an acceptable alternative only if its type-I attributes satisfy the following necessary condition:

$$q_{ij}^I \geq \lfloor q_j^I \rfloor \qquad (5)$$

Type II includes the attributes whose quantity and utility of alternatives with respect to them are in inverse-ratio relation. Examples of the type-II attributes are construction duration, negative effects on environment, etc. When quantity of these attributes increases, utility of alternatives with respect to them will decrease correspondingly and vice versa.

Let $[q_j^{II}]$ be the minimal acceptable level for type-II attribute q_{ij}^{II}. Alternative A_i is, therefore, an acceptable alternative only if its type-II attributes satisfy the following necessary condition:

$$q_{ij}^{II} \leq \lfloor q_j^{II} \rfloor \qquad (6)$$

Type III includes the other attributes whose quantity and utility of alternatives with respect to them are in non-linear relation. Examples of type III attributes are temperature in a theater, humidity in a laboratory. Both very high and very low temperatures in a theater are not comfortable for people to watch dramas. The best temperature may be, for example, around 22°C. Similarly, the best humidity in a laboratory is, for example, 60 % for certain tests. Neither the higher humidity nor the lower humidity is good. The minimum acceptable levels for the type-III attributes are set up in range such that $[q_j^{III} + \delta_j]$ where q_j^{III} is the best value and δ_j is the allowable tolerance of type-III attribute, q_{ij}^{III}. Thus, alternative A_i is an acceptable alternative only if its type-III attributes satisfy the following necessary condition:

$$q_{ij}^{III} \subset [q_j^{III} + \delta_j] \qquad (7)$$

Cost of alternatives and utility of alternatives with respect to cost is also in inverse-ratio relation. Let [C] be the minimal acceptable level for cost. Thus, alternative A_i is an acceptable alternative only if its cost, C_i , satisfies the following necessary condition:

$$C_i \leq \lfloor C \rfloor \qquad (8)$$

In synthesis, alternative A_i is an acceptable alternative only if it satisfies the following sufficient condition:

$$\begin{cases} q_{ij}^{I} \geq \left[q_j^{I}\right] \\ q_{ij}^{II} \leq \left[q_j^{II}\right] \\ q_{ij}^{III} \subset \left[q_j^{III} + \delta_j\right] \\ C_i \leq [C] \end{cases} \quad (9)$$

Note that not all of m attributes of matrix of attributes, Q, require to be regulated, or to specify a minimum acceptable level. On the contrary, not all attributes that require to be regulated, or to specify a minimum acceptable level must be present in the matrix of attributes, Q.

To identify and eliminate unacceptable alternatives, the minimal acceptable levels for attributes and cost must first be determined. Some $[q_j]$ are regulated by governmental regulatory agencies. The others and [C] are usually specified by the decision-makers.

If all the design alternatives for a project are unacceptable, a redesign must take place. The next calculations will be done with only the acceptable design alternatives.

5. DETERMINING THE UTILITY OF DESIGNED QUALITY FOR DESIGN ALTERNATIVES

The utility of designed quality of design alternatives is determined through the three following steps:

1. Measuring the relative importance level of attributes with respect to the designed overall quality.
2. Determining the relative performance scores of alternatives with respect to each attribute
3. Aggregating the results of the two steps above

(1) Measuring the Relative Importance Level of Attributes with respect to the Designed Overall Quality

The relative importance level of attributes with respect to the designed overall quality is measured in the following way:

1. It is measured for all attributes of the hierarchy in order from top to down.
2. The relative importance level of attributes at any level with respect to *the designed overall quality* is determined by aggregating their relative importance level with respect to *their mother attribute* at the upper adjacent level and the relative importance level *of their mother attribute* with respect to *the designed overall quality.*
3. The relative importance level of attributes with respect to *their mother attribute* is measured through aggregating subjective judgements of pair-wise comparisons.

Let us represent the method of measuring the relative importance level with respect to *the designed overall quality* for attributes at a level y in Figure 2.

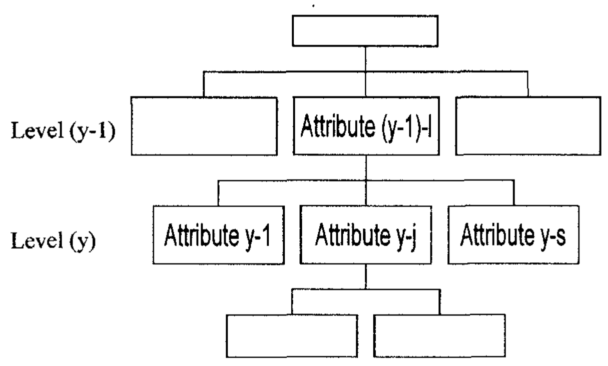

Figure 2 Measuring the Importance Level for Quality Attributes at Level y

The attributes at level y are decomposed from their mother attributes at the upper adjacent level, *(y-1)*. For example, attributes *(y-1),...,(y-s)* are decomposed from their mother attribute *(y-1)-l* at level *(y-1)*. Let us denote attributes *(y-1),...,(y-j),...,(y-s)* by $q_1^y, ..., q_j^y, ..., q_s^y$ respectively, and attribute *(y-1)-l* of the upper adjacent level *(y-1)* by q_l^{y-1}. Thus, the relative importance level of attribute q_j^y with respect to *the designed overall quality* is determined by aggregating the relative importance level of that attribute with respect to *its mother attribute* (attribute q_l^{y-1}) and the relative importance level of *its mother attribute* (q_l^{y-1}) with respect *to the designed overall quality.*

The relative importance level of attributes q_j^y with respect to their *mother attribute* is measured through aggregating judgments of pair-wise comparisons for them with respect to their mother attribute, q_l^{y-1}. This involves a subjective assignment of preference weights to each attribute in the pair-wise comparisons with respect to their mother attribute q_l^{y-1}. In general, when comparing two attributes with respect to their mother attribute, the decision-makers first discern which attribute is more important in terms of contribution to their mother attribute and then ascertain how much the importance level is by selecting a value from the 9-point scale below:

1: equally important

3: weakly more important

5: strongly more important

7: demonstratively more important

9: absolutely more important

2,4,6, and 8 are intermediate values between two adjacent judgements.

Let value I_{ij} be assigned by comparing attribute q_i^y to q_j^y with respect to attribute q_l^{y-1}. Thus, the resulting factor I_{ij} is the preference weight of attribute q_i^y compared to attribute q_j^y with respect to attribute q_l^{y-1}. We have a matrix I, which reflects the preference of the pair-wise comparison, as follows:

$$I = \left\| I_{ij} \right\|, \quad i,j = 1,2,\dots,s \qquad (10)$$

The pair-wise comparison is carried out by the decision-maker group for project and values $I_{ij}, \forall i,j = 1,2,\dots,s$ are determined by group decision-making methods. Having obtained matrix I, a weighting vector w^y pertaining to the attributes can be determined by computing the *Eigenvector* corresponding to the maximum *Eigenvalue* of the matrix.

This vector indicates the set of weights for attributes reflecting the relative importance level of each attribute in comparison with the others with respect to their mother attribute at the upper adjacent level.

$$w^y = \left(w_1^y, w_2^y, \dots, w_s^y\right) \qquad (11)$$

Now, the relative importance level or weight of attributes q_j^y with respect to the designed overall quality, that is the only attribute at the top of the hierarchy, can be determined. Let us denote the relative importance level of the mother attribute q_l^{y-1} with respect to the designed overall quality by w_l (w_l has been determined in previous step), the relative importance level of attributes $q_j^y, j = 1,2,\dots,s$ with respect to the designed overall quality by $w_j, j = 1,2,\dots,s$. w_l are obtained by the following formula:

$$w_j = w_j^y \times w_l \quad \forall j = 1,2,\dots,s. \qquad (12)$$

Perform the presented calculation procedure for the whole hierarchy from top to down, we can obtain a weighting vector indicating the relative importance level for all attributes q_j, which correspond to the last elements of each branch of the tree structural hierarchy, with respect to the designed overall quality.

$$w = \left(w_1, w_2, \dots, w_j \dots, w_m\right) \qquad (13)$$

Checking Consistency of Estimates in Matrix I

Since decision-makers in practice are only estimating the "true" elements by assigning them values from the 9-point scale, it is essential to check the consistency of the estimates in matrix *I* as mentioned above. The consistency of matrix *I* is guaranteed when $\lambda_{\max} \cong s$. $\lambda_{\max}$ and s are the largest Eigenvalue and the size of the square pair-wise comparison matrix I respectively. When $\lambda_{\max}$ is not close to s, we must revise the estimates in matrix I so that the consistency is preserved. The AHP method measures the overall consistency of judgements by means of a consistency ratio, *CR*

$$CR = CI/IR \qquad (14)$$

where *CI* is the consistency index of the pair-wise comparison matrix, determined by

$$CI = \left(\lambda_{\max} - x\right)/(x-1) \qquad (15)$$

RI is the consistency index derived from a completely arbitrary matrix whose entries are randomly chosen. Through simulation, Saaty[7)] obtained the following results for *RI:*

s	4	5	6	7	8	9	10
RI	0.90	1.12	1.24	1.32	1.41	1.45	1.49

Experience suggests that CR should be less than 0.09 for a 4 x 4 matrix and 0.1 for a larger matrix.

(2) Determining the Relative Performance Scores of Alternatives with respect to each Attribute

a) With respect to Quantifiable Attributes

In general, the quantifiable attributes measured in known scales also include three types classified based on the relationship between their quantity and utility of alternatives with respect to them as described in Section 4 above. To deal with each mentioned-above type of quantifiable attributes, different methods must be employed.

The relative performance scores of alternatives with respect to each type-I attribute are simply determined by normalizing their performance values. No subjective judgement of the decision-makers is needed for this case. Let number of type-I attributes be *b*. We can easily obtain a vector $r_j = \{r_{1j}, r_{2j}, ..., r_{nj}\}$ $j = 1,2,...,b$ indicating a set of weights for alternatives reflecting the relative performance score of each alternative compared to the others with respect to type-I attribute q_j by the following formula:

$$r_{ij} = q_{ij} \Big/ \sum_{i=1}^{n} q_{ij} \qquad (16)$$

where r_{ij} is the relative performance score of alternative A_i compared to the other alternatives with respect to quantifiable type-I attribute q_j; q_{ij} is the performance value of alternative A_i in terms of quantifiable type-I attribute q_j.

To determine the relative performance scores of alternatives with respect to each type-II attribute, the performance values of alternatives in terms of each type II-attribute are first converted into their inverse numbers so that the inverse-ratio relationship between quantity of the type-II attributes and utility of alternatives with respect to them becomes the direct-ratio relationship. Then, the relative performance scores of alternatives with respect to the type II- attributes with converted values will be determined similarly to those with respect to the type-I attributes. Let number of type-II attributes be *c*. We can easily obtain a vector $r_j = \{r_{1j}, r_{2j}, ..., r_{nj}\}$ $j = 1,2,...,c$ indicating a set of weights for alternatives reflecting the relative performance score of each alternative compared to the others with respect to each type-II attribute q_j by the following formula:

$$r_{ij} = \frac{1}{q_{ij}} \Big/ \sum_{i=1}^{n} \frac{1}{q_{ij}} \qquad (17)$$

where r_{ij} is the relative performance score of alternative A_i compared to the other alternatives with respect to type-II attribute q_j; q_{ij} is the performance value of alternative A_i in terms of type-II attribute q_j.

There are two methods to determine the relative performance scores of alternatives with respect to each quantifiable type-III attribute. In the first method, the performances of alternatives in terms of each type-III attribute are converted into a numeric scale (e.g., 1-10 point scale or 1-100 point scale) that is common to everybody. Then, the relative performance scores of alternatives with respect to the quantifiable type III- attributes with the converted performances will be determined similarly to those with respect to the type I / type II attributes. In the second method, the type-III attributes are considered fuzzy attributes. Thus, the relative performance scores of alternatives with respect to the type-III attributes are determined similarly to those with respect to non-quantifiable attributes represented below.

b) With respect to Non-quantifiable Attributes

If attribute q_j is non-quantifiable, the relative performance scores of alternatives with respect to it are determined through aggregating judgements of pair-wise comparisons for all alternatives. The process of aggregating judgements of alternatives with respect to each non-quantifiable attribute q_j is similar to that of aggregating judgements of attributes with respect to their mother attributes presented above.

Let us denote the number of non-quantifiable attributes by *f*, the decision-makers will have to make *f* pair-wise comparison matrices P_j, $j = 1,2,..., f$ as follows:

$$P_j = \| P_{jhk} \|, \quad h,k = 1,2,...,n \qquad (18)$$

P_j is the pair-wise comparison matrix of alternatives with respect to non-quantifiable attribute, q_j, *j=1,2,f.* Element p_{jhk} is the relative performance of alternative *h* compared to alternative *k* with respect to non-quantifiable attribute q_j. The pair-wise comparisons are carried out by the decision-maker group for project and values P_{jhk} $\forall h,k = 1,2,...,n$ & $j = 1,2,..., f$ are determined by group decision-making methods.

Similarly, we can determine vectors $r_j = (r_{1j}, r_{2j}, ..., r_{nj})$ $j = 1,2,..., f$ pertaining to all alternatives with respect to each of the non-quantifiable attributes by computing the *Eigenvectors* corresponding to the maximum *Eigenvalues* of matrices P_j, $j = 1,2,...,f$. r_{ij} is the relative performance score of alternative A_i compared to the other alternatives with respect to non-quantifiable attribute q_j. The consistency of estimates in matrices P_j must be checked by the procedure of checking consistency represented above.

Gathering all vectors r_j obtained, we have matrix R that shows the relative performance scores of alternatives with respect to each attribute:

$$R = \| r_{ij} \|, \quad i = 1,2,...,n; \; j = 1,2,...,m \quad (19)$$

(3) Aggregating the Results

Having measured the relative importance level of attributes with respect to the designed overall quality and determined the relative performance scores of alternatives with respect to each attribute, the aggregation of results to determine the utility of designed quality for alternatives is very simple, just by multiplying matrix R (see (19)), by the transpose of vector *w* (see (13)).

Let denote the vector of utility of designed quality for alternatives by U^Q, we have:

$$\begin{aligned} U^Q &= Rw^T \\ U^Q &= \{U_1^Q, U_2^Q, ..., U_n^Q\} \qquad (20) \\ U_i^Q &= \sum_{j=1}^{m} r_{ij} w_j \qquad i = 1,2,...,n \end{aligned}$$

U_i^Q is the utility of designed quality of design alternative A_i, or the overall performance score of design alternative A_i with respect to the designed overall quality.

6. DETERMINING THE UTILITY OF COST OF DESIGN ALTERNATIVES

Cost in this appraisal context is considered the input to obtain the output that is the quality of project. Therefore, the relationship between the utility of cost of an alternative and the amount cost of that alternative is in direct ratio.

Since cost is measured in monetary terms, the utility of cost of design alternatives can be determined directly without subjective judgments of the decision-makers. However, on the one hand, the costs of alternatives estimated by the designers are not comparable due to the time value of money. On the other hand, construction duration and, especially, service life of construction projects are very long, and costs expended for a construction project vary from time to time, and from design alternative to design alternative. Thus, it is essential to make all of the costs of alternatives to be comparable for evaluation. In other words, it is essential to transform all of the costs of alternatives from in-equivalence values into comparable equivalent values, before any comparison or evaluation of costs takes place.

(1) Time Value of Money

When money consequences occur in a short time, it is simple to add up the various sums of money and obtain a net result. When the time span is greater, the value of money will be increased because people are willing to pay to have money available for their use. This value is reflected through interest rate of money.

In principle, it is possible to transform the money values of costs to any moment so that the costs become comparable. Let the present time be the time when the decision-making takes place. Let r be the interest rate per interest period *k* of the interval from the present time to the time of project removal (r is in a decimal figure), *N* be the number of the interest periods, C_k^* be the cost expended in interest period *k*, and C_k be the present money value of cost C_k^*,

$$C_k = C_k^* / (1 + r)^k \qquad (21)$$

Let us denote the cost of alternative *Ai* expended in interest period *k* by C_{ik}^*. The money value of the whole cost of alternative A_i, ($A_i = \sum_{k=1}^{N} C_{ik}^*$), at the present time, denoted by C_i, will be determined by the following formula:

$$C_i = \sum_{k=1}^{N} \left(C_{ik}^* / (1 + r)^k \right) \qquad (22)$$

Note that because service life of construction projects is very long, an interest period for calculation should be one year and interest rate, *r*, should be the nominal interest rate. It is believed that the one-year interest period and the nominal interest rate are accurate enough for the decision-making on design alternatives. In addition, the problem of inflation should be considered in the calculation due to long service life of construction projects. Let us denote inflation rate by f and the interest rate without inflation by r', the interest rate r for the computation is determined by the formula below.

$$r = (1 + r')(1 + f) - 1 = r' + f + r'f \quad (23)$$

(2) Determining the Utility of Cost for Alternatives

Having transformed all the costs of alternatives to be comparable equivalent values, the utility of cost of each alternative in comparison with the others can be determined directly by normalizing their transformed costs. Therefore, neither a hierarchy for cost nor subjective judgement of the decision-makers is necessary to be made. Let us denote the transformed cost of alternative A_i by C_i, the utility of cost of alternative A_i by U_i^C. The vector indicating the utility of cost of alternatives can be easily obtained as follows:

$$U^C = \{U_1^C, U_2^C, \ldots, U_n^C\} \quad (24)$$

$$U_i^C = C_i \Big/ \sum_{i=1}^{n} C_i$$

7. ANALYZING [UTILITY OF DESIGNED QUALITY]-[UTILITY OF COST]

The analysis of the [Utility of Designed Quality]-[Utility of Cost] is done based on principle of the Incremental Benefit – Cost Analysis[9] as follows:

1. If either the utilities of designed quality (U_i^Q) or utilities of cost (U_i^C) are the same, choose the alternative with $MAX\,(U^Q/U^C)$.
2. If neither (U_i^Q) nor (U_i^C) are the same:

+ *If there are two alternatives:*

Compute:

$$\frac{\textit{Incremental Utility of Designed Quality}\,(\Delta U^Q)}{\textit{Incremental Utility of Cost}\,(\Delta U^C)}$$

between the two alternatives. If $(\Delta U^Q/\Delta U^C) \geq 1$, choose the higher cost alternative. Otherwise, choose the lower cost alternative.

+ *If there are three or more alternatives:* Repeatedly compare for two alternatives, choose the better and than continuously compare for the chosen alternative and a subsequent alternative and so on. The result of this series comparison shall be the overall best selection.

8. PERFORMING SENSITIVITY ANALYSIS

It is desirable to test the responsiveness or sensitivity of the outcome of a decision to changes in the importance levels (weights) of attributes. This is especially necessary to make the final decision when two or more alternatives appear to be close in U^Q/U^C ratio, (i.e., $\Delta U^Q/\Delta U^C$ between them appears to be close to one). What to do is to change the importance level (weight) of selected major attributes while keeping the proportions of the importance levels (weights) for the other attributes the same so again they all, including the changed attributes, add to one. Decision-makers will then see changes of the outcome to make the final decision. The pessimistic and optimistic situations that may happen to projects and possible reallocations of resources to enhance the best alternative selected are also considered in sensitivity analysis.

9. A CASE STUDY

(1) Introduction

A case study was done for the Mekong Bridge built across the Mekong River in Cambodia to validate applicability of the developed method. Since the Mekong River divides Cambodia into nearly two equal parts without a bridge connecting the two sides and road-based transport modes crossing over the Mekong River completely depend on ferry operations, the Mekong Bridge is expected to play a very important role in the national transportation network. It would improve international road network and accessibility between Phnom Penh and remote areas in the eastern regions of the Mekong River. In addition, it would promote agriculture development and a market-oriented economy, and upgrade living standards in the rural areas.

The feasibility studies and preliminary design for the Mekong Bridge were carried out from April 1995 to July 1996 by a team of the Japan International Cooperation Agency (JICA) that composed of the members from Nippon Koei Co., Ltd. and PADECO Co., Ltd. There were six preliminary design alternatives made for six route alternatives that are A-1 and A-2 in Neak Loeung, B-1 and B-2 in Prek Tamak, and C-1 and C-2 in Kongpong Cham. A multiple-column pile foundation structure was selected for all of the alternative routes with a pile diameter of 2.0m.

Superstructure designed for each alternative is shown in Table 1. The JICA team determined the following engineering-economic criteria for each design alternative: Construction Duration, Effects on Environment, Costs for the Project, and Internal Rate of Return.

Table 1 Superstructure Designed for Alternatives

Route	Type of Superstructure Designed
A-1	Pre-stressed Concrete Cable-Stayed Bridge
A-2	Pre-stressed Concrete Cable-Stayed Bridge
B-1	Pre-stressed Concrete Box-Girder Bridge
B-2	Pre-stressed Concrete Box-Girder Bridge
C-1	Suspension Bridge
C-2	Pre-stressed Concrete Box-Girder Bridge

In this case study, an expert in construction-project development from the Nippon Koei Co., Ltd., and four professors and two Ph.D. candidates of the Department of Civil Engineering, The University of Tokyo, were invited to be involved in the decision- making process as decision-makers. Five experts in bridge engineering were also invited to deal with special technical issues such as estimating some technical parameters, making some pair-wise comparisons for design alternatives with respect to special technical attributes. The software used is the Expert Choice that is software developed based on the Analytic Hierarchy Process method.

(2) Structuring the Hierarchy for the Designed Quality of Alternatives

The hierarchy of the designed quality in this case study was made as follows:

1. First, the authors structured an initial hierarchy for the designed quality.
2. Next, the initial hierarchy was sent to all of the decision-makers for their advance considerations.
3. The decision-makers, then, discussed the initial hierarchy and arrived at a consensus for the final hierarchy.

The hierarchy of designed quality consented by the decision-makers for the decision-making (see Figure 3) was then entered to a model created by the Expert Choice software.

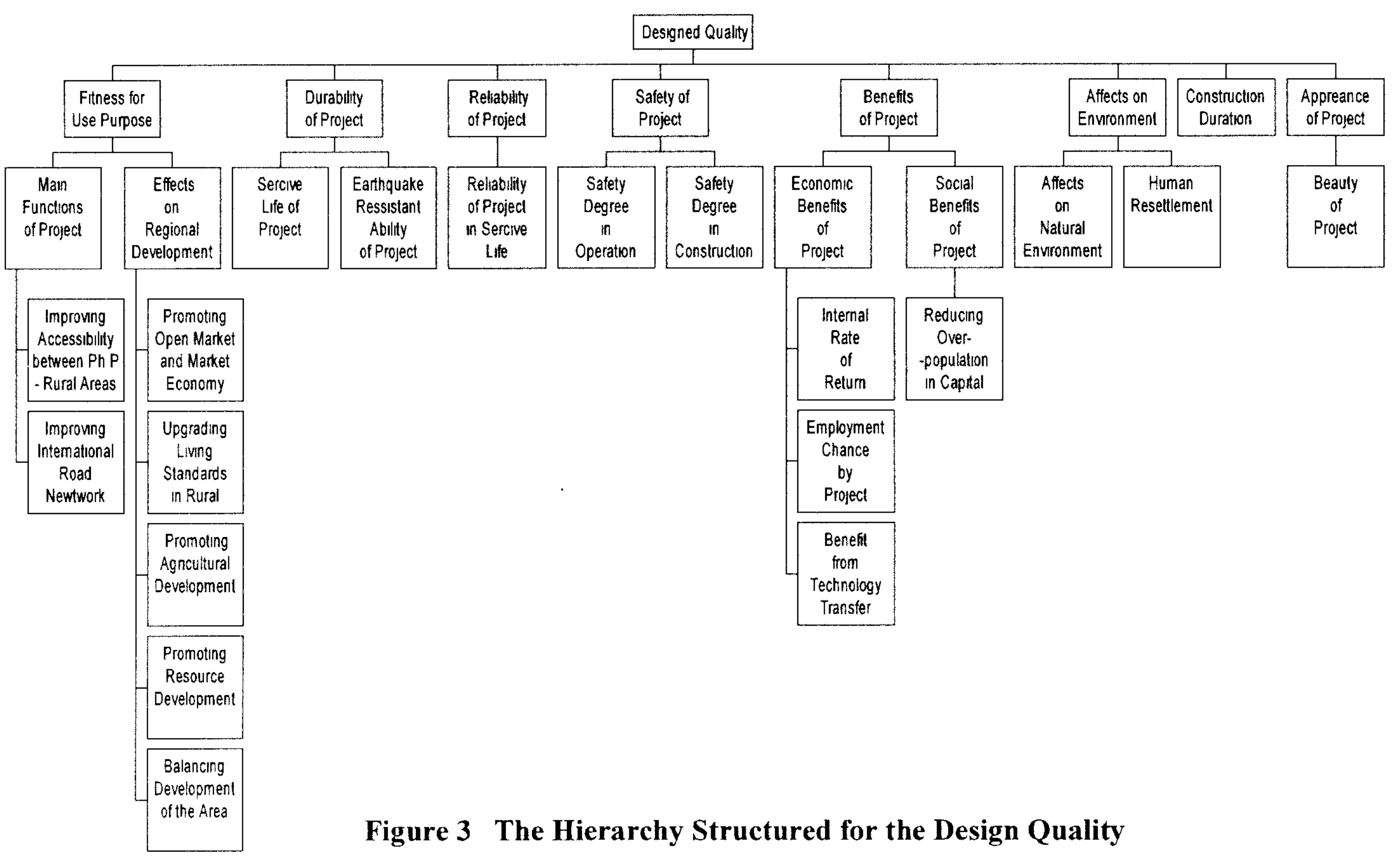

Figure 3 The Hierarchy Structured for the Design Quality

In this case study, the quantifiable attributes such as Construction Duration, Internal Rate of Return, etc., were determined by the JICA Team. Some of the non-quantifiable attributes such as Balancing Development of the Area, Effects on Natural Environment, etc., were also determined by the JICA Team in linguistic scale of very poor, poor, fair, good, very good, and excellent. The other non-quantifiable attributes such as Safety Degree in Operation, Earthquake Resistant Ability, etc., were determined by either the decision-makers or the invited experts in bridge engineering in linguistic scale of very poor, poor, fair, good, very good, and excellent.

(3) Eliminating Unacceptable Design Alternatives

The minimal acceptable levels for the attributes of the Mekong Bridge were specified by the JICA Team with approval of the Cambodian Ministry of Public Works and Transportation as follows.

a) Vertical Clearance of the Bridge.

Vertical clearance of the bridge at Neak Loeung must be equal to or greater than 37 m and that at Prek Tamak and Kongpong Cham must be equal to or greater than 37 m..

b) Service Life of Project

Service Life of the Mekong Bridge must be greater than 50 years.

c) Cross Section

To meet with the Asian Highway codes; the Mekong Bridge must have two traffic lanes (carriageways) for cars and trucks; two lanes for motorcycles; and other two lanes for pedestrian.

Having compared the attributes designed for alternatives with the above-mentioned minimum acceptable levels and other related general regulations by Formulas (9), it was concluded that, all of the alternatives are acceptable.

(4) Determining Utility of Designed Quality for the Design Alternatives

The pair-wise comparisons for the attributes to determine the relative importance level of each attribute were carried out by the Modified Delphi method[10]. First, all of the decision-makers were given in advance necessary documents along with instructions for their considerations. Next, the decision-makers were asked to make pair-wise comparisons for attributes with respect to their mother attributes independently and anonymously. The results of these pair-wise comparisons for attributes were sent back to the authors to compile. Then, the composite results were fed back to the decision-makers. With these composite results in hand, the decision-makers were asked to make further pair-wise comparisons and send them back to the authors. This process was repeated three times and afterwards a meeting of the decision-making was held to freely discuss the different judgements of the pair-wise comparison to arrive at consensus. For dissented judgements, the weighted average value of them was considered the group's decision.

The pair-wise comparisons for the design alternatives to determine the relative performance scores of alternatives with respect to non-quantifiable alternatives were carried out by the Interacting Group method[11]. The decision-makers discussed and judged the pair-wise comparison one pair by one pair. For dissented judgements, the Voting method took place to obtain the final decisions.

By applying formulas represented in Section 5 above, the utility of the designed quality of alternatives were determined as follows:

$$U^Q_{A-1} = 0.185 \qquad U^Q_{A-2} = 0.183$$
$$U^Q_{B-1} = 0.150 \qquad U^Q_{B-2} = 0.160$$
$$U^Q_{C-1} = 0.155 \qquad U^Q_{C-2} = 0.167$$

(5) Determining Utility of Cost of the Design Alternatives

The costs for projects required by the design alternatives were determined by the JICA Team. The annual average interest rate without inflation in Cambodia and the annual inflation rate of US$ were assumed of 8% and 1.7 % respectively. By applying formulas represented in Section 6 above, the utility of the cost of alternatives were determined as follows:

$$U^C_{A-1} = 0.165 \qquad U^C_{A-2} = 0.177$$
$$U^C_{B-1} = 0.146 \qquad U^C_{B-2} = 0.221$$
$$U^C_{C-1} = 0.153 \qquad U^C_{C-2} = 0.138$$

(6) Analyzing [Utility of Quality]- [Utility of Cost]

Since neither $\left(U_i^Q\right)$ nor $\left(U_i^C\right)$ are the same, the analysis of the [Utility of Designed Quality] –[Utility of Cost] for alternatives is done as below.

a) Comparing Alternative A-1 with Alternative A-2

Since

$$U_{A-1}^Q = 0.185 > U_{A-2}^Q = 0.183$$

$$while\ U_{A-1}^C = 0.165 < U_{A-2}^C = 0.177$$

Alternative A-1 is certainly better. Alternative A-2 is eliminated.

b) Comparing Alternative A-1 with Alternative B-1

Compute

$$\frac{\Delta U^Q}{\Delta U^C} = \frac{U_{A-1}^Q - U_{B-1}^Q}{U_{A-1}^C - U_{B-1}^C} = \frac{0.185-0.150}{0.165-0.146} = 1.842 \quad >> 1$$

Alternative A-1 is selected.

c) Comparing Alternative A-1 with Alternative B-2

Because

$$U_{A-1}^Q = 0.185 > U_{B-2}^Q = 0.160$$

$$while\ U_{A-1}^C = 0.165 << U_{B-2}^C = 0.221$$

Alternative A-1 is again selected.

d)Comparing Alternative A-1 with Alternative C-1

Compute

$$\frac{\Delta U^Q}{\Delta U^C} = \frac{U_{A-1}^Q - U_{C-1}^Q}{U_{A-1}^C - U_{C-1}^C} = \frac{0.185-0.155}{0.165-0.153} = 2.5 \quad >> 1$$

Alternative A-1 is continuously selected.

e) Comparing Alternative A-1 with Alternative C-2

$$\frac{\Delta U^Q}{\Delta U^C} = \frac{U_{A-1}^Q - U_{C-2}^Q}{U_{A-1}^C - U_{C-2}^C} = \frac{0.185-0.167}{0.165-0.138} = 0.666 \quad << 1$$

Alternative C-2 is better than alternative A-1 and is the best alternative among available alternatives

(7) Performing Sensitivity Analysis

Because the best alternative, C-2, is much better than the second-best alternative, A-1, $\left(\left(U_{A-1}^Q - U_{C-2}^Q\right)/\left(U_{A-1}^C - U_{C-2}^C\right) = 0.666 \ << 1\right)$ the sensitivity analysis in this case study is not necessary. Nevertheless, several sensitivity analyses were performed. The following are some examples

a) Appraising Alternatives with respect to only Main Attributes.

The main attributes that have the highest importance level scores in this case study are Fitness for Use Purpose, Durability of Project, Benefits of Project, and Reliability of Project. The utility of the designed quality of alternatives with respect to only main attributes were as follows:

$U_{A-1}^Q =$ 0.190 $\quad$ $U_{A-2}^Q =$ 0.180

$U_{B-1}^Q =$ 0.144 $\quad$ $U_{B-2}^Q =$ 0.154

$U_{C-1}^Q =$ 0.155 $\quad$ $U_{C-2}^Q =$ 0.169

Analyzing the [Utility of Designed Quality] –[Utility of Cost] for alternatives as represented above, (for example, compare alternative A-1 with alternative C-2:

$$\frac{\Delta U^Q}{\Delta U^C} = \frac{U_{A-1}^Q - U_{C-2}^Q}{U_{A-1}^C - U_{C-2}^C} = \frac{0.190-0.169}{0.165-0.138} = 0.77 \quad << 1)$$

it was concluded that with respect to only main attributes, alternative C-2 is much better than the other alternatives.

b) Appraising Alternatives with Changes in Importance Level of Main Attributes.

There are many scenarios of changes in importance levels of the main attributes to examine. The following is an example.

Increase 10% importance level of Fitness for Use Purpose, Durability of Project and reduce 10% importance level of Benefits of Project, the utilities of designed quality of alternatives in this scenario were determined as below.

$U_{A-1}^Q =$ 0.187 $\quad$ $U_{A-2}^Q =$ 0.185

$U_{B-1}^Q =$ 0.146 $\quad$ $U_{B-2}^Q =$ 0.157

$U_{C-1}^Q =$ 0.156 $\quad$ $U_{C-2}^Q =$ 0.169

Analyzing the [Utility of Designed Quality] –[Utility of Cost] for alternatives as presented above, it was concluded that in this context alternative C-2 is again much better than the other alternatives.

(8) Remarks through the Case Study

a) Remark 1

In this case study, the best alternative, C-2, is also the one with $Max\left(U_i^Q/U_i^C\right)$: $U_{C-2}^Q/U_{C-2}^C = 1.21$

However, this is a random since in principle of the Incremental Benefit-Cost Analysis, the alternative with $Max\left(U_i^Q/U_i^C\right)$ is not necessarily the best alternative. Indeed, assuming that the utility of designed quality of alternative A-1, $U^Q_{A-1} = 0.196$ but not 0.185. Compare the two alternatives, A-1 and C-2, we have:

$$\frac{\Delta U^Q}{\Delta U^C} = \frac{U^Q_{A-1} - U^Q_{C-2}}{U^C_{A-1} - U^C_{C-2}} = \frac{0.196 - 0.167}{0.165 - 0.138} = 1.074 > 1$$

Alternative A-1 would, therefore, be better than alternative C-2 and be the best alternative although

$$\frac{U^Q_{C-2}}{U^C_{C-2}} = \frac{0.167}{0.138} = 1.21 > \frac{U^Q_{A-1}}{U^C_{A-1}} = \frac{0.196}{0.165} = 1.18$$

b) Remark 2

The design alternatives for the Mekong Bridge are ranked by the developed method in the following order:

C-2, A-1, B-1, C-1, A-2, B-2

In addition, design alternatives A-2 and B-2 are too poor because comparing with even the second-best alternative, A-1, they require more cost but produce less quality:

$$U^Q_{A-1} = 0.185 > U^Q_{A-2} = 0.183; \; but$$
$$U^C_{A-1} = 0.165 < U^C_{A-2} = 0.177; \quad and$$
$$U^Q_{A-1} = 0.185 > U^Q_{B-2} = 0.160; \; but$$
$$U^C_{A-1} = 0.165 << U^C_{B-2} = 0.221$$

c) Remark 3

The case study demonstrated that the proposed method is applicable for the decision-making on design alternatives for construction projects. It is very well structured but very flexible, and is easy to apply in practice. The measurement of performance scores of alternatives with respect to each attribute appears easy and explicit to the decision-makers.

The most critical work in applying the proposed method is the problem of making subjective judgements of pair-wise comparison for attributes with respect to their mother attribute. It was found that the judgements of the decision-makers in the first round were very different each other in many cases. This weak point of the method is also the most critical limitation of the AHP method. However, the case study proved that this weak point could be overcome very much by the employment of the Delphi Method. In addition, an essential condition for the successful applicability of the method depends highly on the fact that the decision-makers must be very well informed of design alternatives and backgrounds of project before they make subjective judgements for the decision-making.

10. CONCLUSION

The new decision-making method on design alternatives for construction projects comprises quantitative methods, Conjunctive and AHP methods, associated with group decision-making methods. The quantitative methods play a role as the backbone for the decision-making to eliminate unacceptable alternatives and quantify and integrate attributes associated with design alternatives so that design alternatives become comparable for evaluation. Group decision-making methods are employed to make interventional and final decisions. The best design alternative is selected based on the Incremental [Utility of Designed Quality]/ [Utility of Cost] Ratio Analysis. The case study proved that the new method is applicable, and it is very well structured but flexible, and easy to apply in practice.

The developed method does not assume that decisions made by decision-makers in the past were completely unsatisfactory. Rather, it assists decision-makers in understanding their problems to make better decisions by organizing their thinking, quantifying and integrating their separate evaluations. The developed method is both mathematical algorithm orientated and decision-making process oriented. It is able to handle fuzzy attributes and group references in an explicit manner as well as to solve inter-group conflicts among decision-makers. In addition, it has a clear procedure to identify and eliminate unacceptable alternatives and can be applicable to any project regardless of type, size, and other characteristics of project.

The developed method can also deal with risk in the decision-making though it does not ask lottery questions like the Multiple Attribute Utility Theory method. Indeed, the developed method in fact has a very rich context for risk developed through scenarios and through cost factors whose effect is captured by the [Utility of Designed Quality] to [Utility of Cost] ratio. Moreover, the concern with risk can be represented in the hierarchy through scenarios expressing risk and uncertainty to be faced, through criteria indicating both uncertain and risky outcomes and through the performance of attributes and costs. In addition, sensitivity analysis is used to test the effect of risky factors on the utility of designed quality and cost.

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