Winter 12-19-2001

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ABSTRACT

This paper presents an integrated system in which a knowledge-based decision support system (DSS) for selecting planning and design (P&D) tenders in public building construction. The Analytic Hierarchy Process (AHP) method is used to determine the weightings for evaluation criteria among decision makers and Fuzzy Multiple Criteria Decision Making (FMCDM) is dealt with the subjectivity and vagueness in the tender selection process. A case study consisting of nine alternatives, solicited from a public works agency in Taiwan, illustrates the effectiveness of the proposed approach and developed system.

INTRODUCTION

Preliminary planning and design (P&D) is a highly professional engineering service, which involves enormous amount of intellectual devotion. In a project life cycle, this planning and design (P&D) phase is most critical to project success. Yet, when procuring engineering service, most public works owners lack the ability to effectively evaluate tenders. Substandard P&D work is often a direct result of inadequate tender selection. Effective evaluation process/method is an important means of promoting the construction efficiency and quality of public building.

This study uses the Analytic Hierarchy Process (AHP) to determine the criteria weights from subjective judgments of each decision-making group. Since the criteria of building P&D evaluation have diverse connotations and meanings, there is no logical reason to treat them as if they are each of equal importance. Furthermore, the Fuzzy Multiple Criteria Decision Making (FMCDM) was used to evaluate the synthetic performance of building P&D alternatives, in order to handle qualitative criteria that are difficult to describe in crisp values, thus strengthening the comprehensiveness and reasonableness of the decision-making process.

FMCDM analysis has been widely used to deal with decision-making problems involving multiple criteria evaluation/selection of alternatives. The practical applications reported in the literature [9][10][11][12] have shown advantages in handling unquantifiable/qualitative criteria, and obtained quite reliable results. On the other hand, due to advances in computer technologies and current information exchange capabilities, there exists a need to develop a decision support system (DSS) that will assist the government agency in making critical decisions during the phase of building P&D selection process. Thus, this study applied the fuzzy set theory [13] to managerial DM problem of alternative selection, with the intention of establishing and MCDM framework and developing a decision support system in order to help a government entity select the optimum P&D candidate for public building investment.

The aim of this paper is to present a systemic approach of the implementation of DSS in engineering service selection. Initially, the establishment of a hierarchical structure for tackling the problem of building P&D assessment is discussed, and a brief introduction to FMCDM methods (Section 2). Then, introduce the decision support system that we developed (Section 3). In order to demonstrate the usefulness of the system, we then examine an empirical case in Taiwan (Section 4). Finally, concluding remarks are presented (Section 5).

PLANNING AND DESIGN ALTERNATIVES EVALUATION MODEL

Building Hierarchical Structure of Evaluation Criteria

The hierarchical structure adopted in this study to deal with the problems of P&D assessment for public building is shown in Fig. 1. The key dimensions of the criteria for evaluation and selection of building P&D alternatives were derived through comprehensive investigation and consultation with several experts, including one professor in architecture engineering, one professor in civil engineering, one experienced architect and five experienced staffs of Public Work Bureau of Taipei City Government. These individuals were asked to rate the accuracy, adequacy and relevance of the criteria and dimensions and to verify their "content validity" in terms of building P&D assessment. Synthesizing the literature review, the expert and government staff opinions provided the basis for the developing the hierarchical structure used in this study. There are six dimensions including Building Site Layout, Appearance Modeling, Plane Planning, Electrical & Mechanical Systems, Structural Systems and Degree of Requirement Accomplishment. From these, twenty evaluation criteria for the hierarchical structure were used in this study.

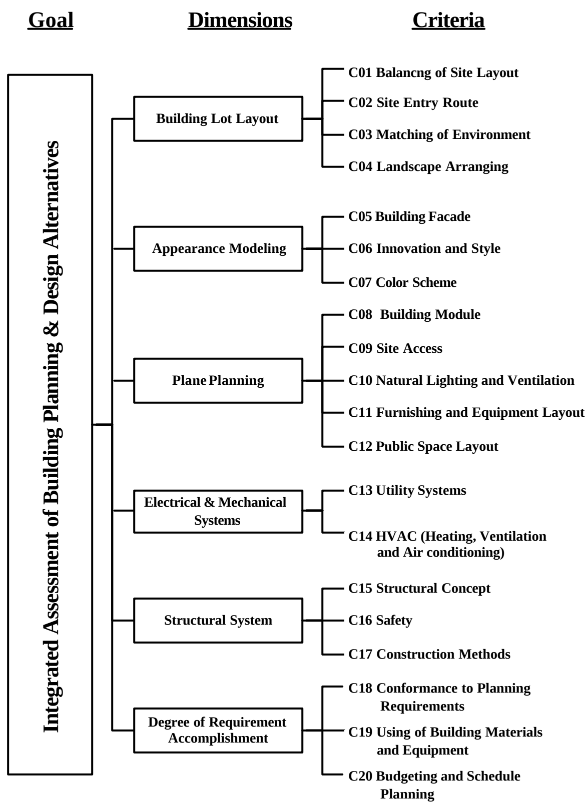

Fig. 1 The Hierarchical Structure for Building Planning & Design Alternatives Assessment

Determining the Evaluation Criteria Weights

Since the criteria of building P&D evaluation have diverse significance and meanings, we cannot assume that each evaluation criteria is of equal importance. There are many methods that can be employed to determine weights such as the eigenvector method, weighted least square method, entropy method, AHP, and LINMAP (linear programming techniques for Multidimensional of Analysis Preference) [4]. The selection of method depends on the nature of the problem. To evaluate building P&D is both a complex and wide-ranging problem, so this problem requires the most inclusive and flexible method. Since the AHP method can systematize complicated problems, is easy to operate, and integrates most of the experts' and evaluators' opinions, this study selected AHP to develop weights.

AHP weighting is mainly determined by evaluators who conduct pairwise comparisons, in order to reveal the relative importance between two criteria [7][8]. If there are n evaluation criteria, then the decision-makers must conduct $C_2^n = n(n-1)/2$ pairwise comparisons. Furthermore, the relative importance derived from these pairwise comparisons allows a certain degree of inconsistency within a domain. Saaty used the principal eigenvector of the pairwise comparison matrix derived from the scaling ratio to find the comparative weight among the criteria of the hierarchy systems.

In engineering service tender selection problem, the group decision-makers should include at least three groups: (a) building owner, (b) building users, (c) invited experts for evaluation. It is important to integrate the weights between the groups in decision-making process.

Getting the Performance Value

In daily life, we often hear people to express their opinion with “not very clear”, “probably so”, or “very likely”, indicating that they have some uncertainty or imprecise judgment. With different daily decision-making problems of diverse intensity, the results can be misleading if the fuzziness (vagueness/uncertainty) of human decision-making is not taken into account. However, since Zadeh put forward fuzzy theory (1965), and Bellman and Zadeh (1970) described the decision-making method in fuzzy environments, an increasing number of studies have dealt with uncertain fuzzy problems by applying fuzzy set theory. This study includes fuzzy decision-making theory, considering the possible fuzzy subjective judgment of the evaluators during their evaluation of the building P&D alternatives. In this way the methodology for engineering service tender selection can be made more objective. The applications of fuzzy theory in this study are elaborated as follows:

a. Fuzzy Numbers

Fuzzy numbers are a fuzzy subset of real numbers, representing the expansion of the idea of the confidence interval. According to the definition of Dubois and Prades, fuzzy numbers should possess the following basic features [3].

Fuzzy number $\tilde{A}$ is of a fuzzy set, and its membership function is $m_{\tilde{A}}(x): R \rightarrow [0,1]$, and it is enshrined with the following characteristics:

(i) $m_{\tilde{A}}(x)$ is a continuous mapping from R to the closed interval [0,1];

(ii) $m_{\tilde{A}}(x)$ is a convex fuzzy subset;

(iii) $m_{\tilde{A}}(x)$ is the normalization of a fuzzy subset, which means that there exists a number x_0 that makes $max\, m_{\tilde{A}}(x_0)=1$.

Those numbers that can satisfy these requirements will then be called fuzzy numbers, and the following is an explanation for the characteristics and the operation of a triangular fuzzy number $m_{\tilde{A}}(x)=(L, M, U)$ as shown in equation (1).

$$m_{\tilde{A}}(x)=\begin{cases} (x-L)/(M-L) & L\le x\le M \\ (U-x)/(U-M) & M\le x\le U \\ 0 & otherwis \end{cases} \qquad (1)$$

b. Linguistic Variable

According to Zadeh (1975), it is very difficult for conventional quantification to express reasonably those situations that are overtly complex or hard to define; thus the notion of a linguistic variable is necessary in such situation. A linguistic variable is a variable whose values are words or sentences in a natural or artificial language. For example, the expressions of criteria as “site entry route,” “balancing of site layout,” “landscape arranging,” “building module,” “natural lighting and ventilation,” and so on all represent a linguistic variable in the context of this study. Linguistic variables may take on effect-values such as “very high (very good),” “high (good),” “fair,” “low (bad),” “very low (very bad).” The membership functions of the expression values can be indicated by triangular fuzzy numbers, as shown in Fig. 2. The use of linguistic variables is currently widespread, and the linguistic values found in this study are primarily used to assess the linguistic ratings given by the evaluators. Furthermore, linguistic variables are used as a way to measure the achievement of the performance value for each criterion.

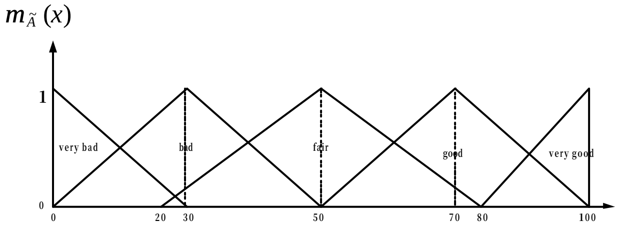

Fig. 2 Membership Function of the Five Levels of Linguistic Variables

c. Fuzzy Multiple Criteria Decision-Making (FMCDM)

Bellman and Zadeh (1970) were the first to probe into the decision-making problem under a fuzzy environment, and they heralded the initiation of FMCDM. This study uses this method to evaluate the engineering service tender of public buildings construction and ranks the P&D alternatives, which submitted by for each tender accordingly. The following will be the method and procedures of the FMCDM theory.

(1) Measurement criteria: Using the measurement of linguistic variables to demonstrate the criteria performance (effect-values) by expressions such as "very good," "good," "fair," "bad," "very bad," the evaluators are asked for conduct their subjective judgments, and each linguistic variable can be indicated by a triangular fuzzy number (TFN) within the scale range of 0-100. In addition, the evaluators can subjectively assign their personal range of the linguistic variable. Take E_{ij}^{k} to indicate the fuzzy performance value of evaluator k towards alternative i under criterion j, and all of the evaluation criteria will be indicated by set S, then,

$$E_{ij}^{k} = (LE_{ij}^{k}, ME_{ij}^{k}, UE_{ij}^{k}), \quad j \in S \tag{2}$$

Since the perception of each evaluator varies according to the evaluator's experience and knowledge, and the definitions of the linguistic variables vary as well, this study uses the notion of average value to integrate the fuzzy judgment values of m evaluators, that is,

$$E_{ij} = (1/m) \otimes (E_{ij}^{1} \oplus E_{ij}^{2} \oplus \ldots \oplus E_{ij}^{m}) \tag{3}$$

The sign $\otimes$ denotes fuzzy multiplication, the sign $\oplus$ denotes fuzzy addition, E_{ij} shows the average fuzzy number of the judgment of the decision-maker, which can be displayed by a triangular fuzzy number as follows:

$$E_{ij} = (LE_{ij}, ME_{ij}, UE_{ij}) \tag{4}$$

The preceding end-point values LE_{ij}, ME_{ij}, and UE_{ij} can be solved by the method put forward by Buckley (1985), that is,

$$LE_{ij} = (\sum_{k=1}^{m} LE_{ij}^{k}) \div m \tag{5}$$

$$ME_{ij} = (\sum_{k=1}^{m} ME_{ij}^{k}) \div m \tag{6}$$

$$UE_{ij} = (\sum_{k=1}^{m} UE_{ij}^{k}) \div m \tag{7}$$

(2) Fuzzy synthetic decision: The weights of the each criterion of building P&D evaluation as well as the fuzzy performance values must be integrated by the calculation of fuzzy numbers so as to be located at the fuzzy performance value (effect-value) of the integral evaluation. According to the weight w_j derived by AHP, the weight vector can be obtained, whereas the fuzzy performance matrix $\boldsymbol{E}$ of each of the alternatives can also be obtained from the fuzzy performance value of each alternative under n criteria, that is,

$$\boldsymbol{w} = (w_1, \ldots, w_j, \ldots, w_n)^t \tag{8}$$

$$\boldsymbol{E} = (E_{ij}), \ \forall\ i, j \tag{9}$$

From the weight vector $\boldsymbol{w}$ and fuzzy performance matrix $\boldsymbol{E}$, the final fuzzy synthetic decision can be conducted, and the derived result will be the fuzzy synthetic decision matrix $\boldsymbol{R}$, that is,

$$\boldsymbol{R} = \boldsymbol{E} \circ \boldsymbol{w} \tag{10}$$

The sign "$\circ$" indicates the calculation of the fuzzy numbers, including fuzzy addition and fuzzy multiplication. Since the calculation of fuzzy multiplication is rather complex, it is usually denoted by the approximate multiplied result of the fuzzy multiplication, and the approximate fuzzy number R_i, of the fuzzy synthetic decision of each alternative can be shown as follows:

$$R_i = (LR_i, MR_i, UR_i), \ \forall\ i \tag{11}$$

$$LR_i = \sum_{j=1}^{n} LE_{ij} * w_j \tag{12}$$

$$MR_i = \sum_{j=1}^{n} ME_{ij} * w_j \qquad (13)$$

$$UR_i = \sum_{j=1}^{n} UE_{ij} * w_j \qquad (14)$$

(3) Ranking the fuzzy number: The result of the fuzzy synthetic decision reached by each alternative is a fuzzy number. Therefore, it is necessary that a nonfuzzy ranking method for fuzzy numbers be used for during the building P&D comparison for each alternative. In other words, the procedure of defuzzification is to locate the Best Nonfuzzy Performance value (BNP). Methods of such defuzzified fuzzy ranking generally include mean of maximal (MOM), center of area (COA), and α-cut [10][15]. To utilize the COA method to find out the BNP is a simple and practical method, and there is no need to bring in the preferences of any evaluators, so it is used in this study. The BNP value of the fuzzy number R_i can be found by the following equation:

$$BNP_i=[(UR_i-LR_i)+(MR_i-LR_i)]/3+LR_i,\ \forall I \qquad (15)$$

According to the value of the derived *BNP* for each of the alternatives, the ranking of the building P&D of each of the alternatives can then proceed.

FRAMEWORK OF THE SYSTEM

Following the approach in section 2, we developed an integrated system of AHP and MCDM to perform the selection of P&D tenders for group decision-making by an expert system program-KAPPA PC™. The program is able to consider multi participants perspectives, including owners, experts and the end-users. The main interfaces of the system are showed as Fig.3 to Fig. 12.

Fig. 3

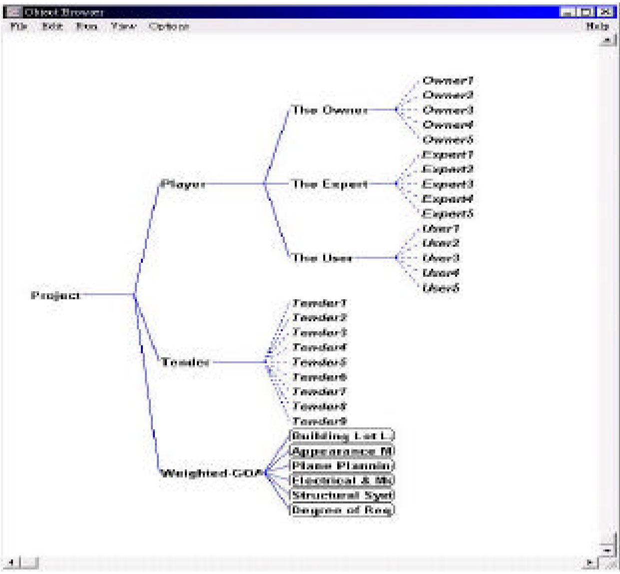

Fig. 4

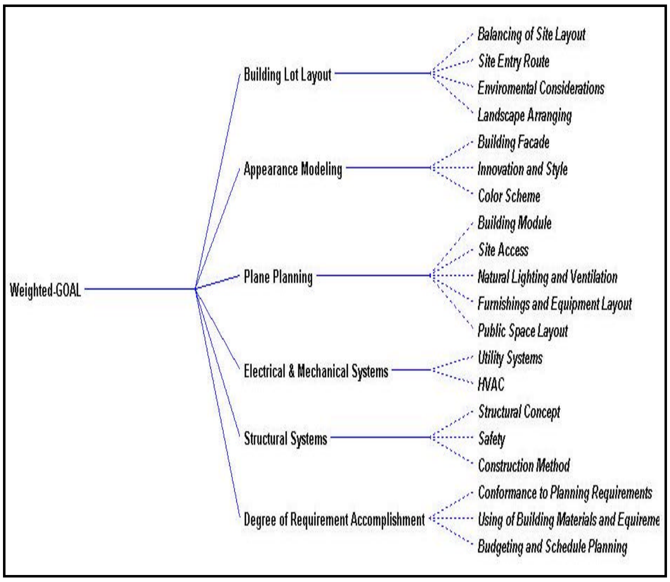

Fig. 5

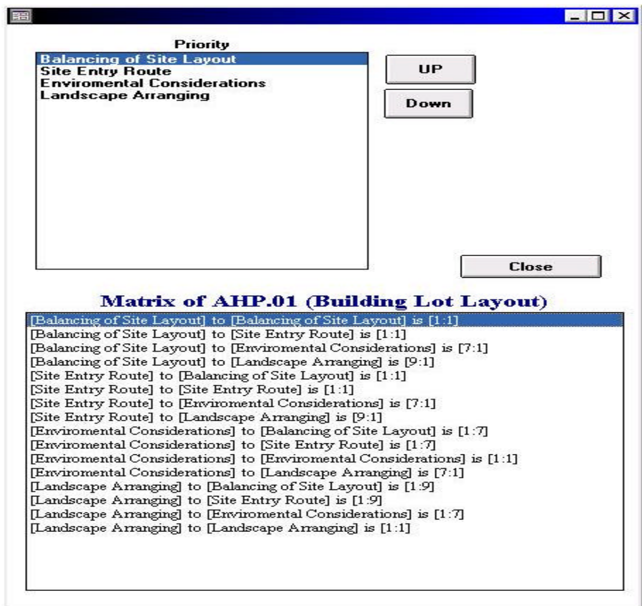

Fig. 6

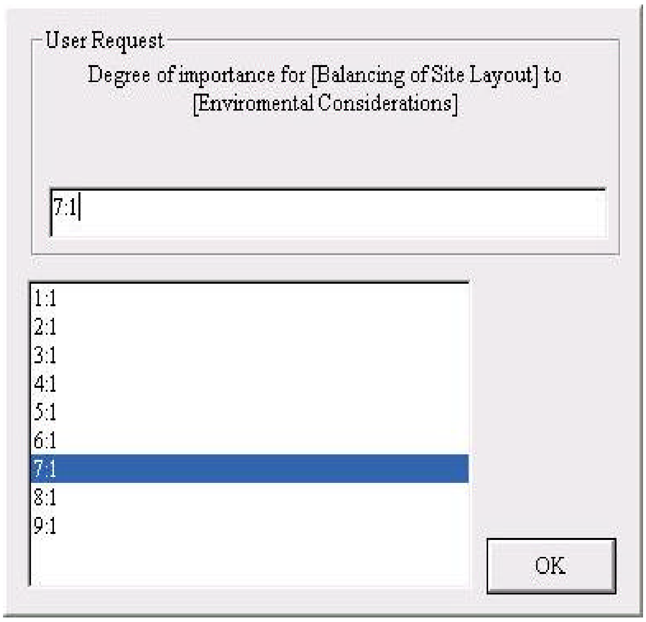

Fig. 7

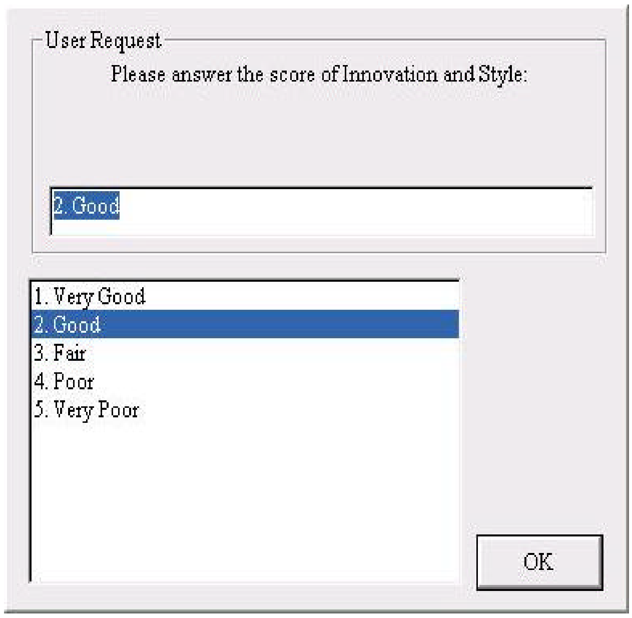

Fig. 10

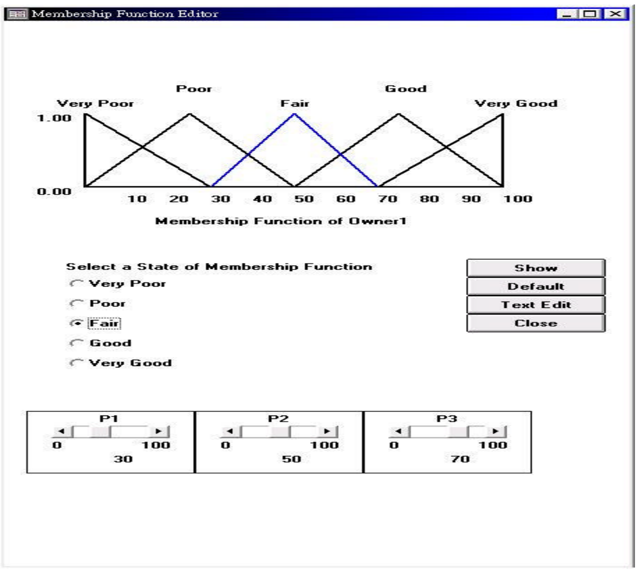

Fig. 8

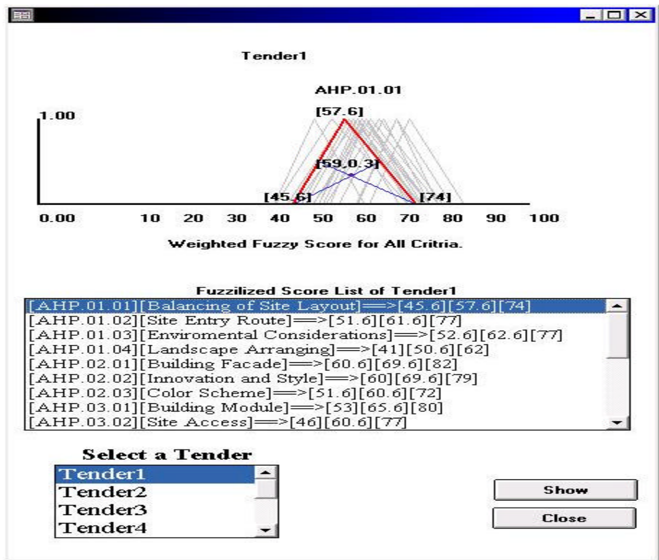

Fig.11

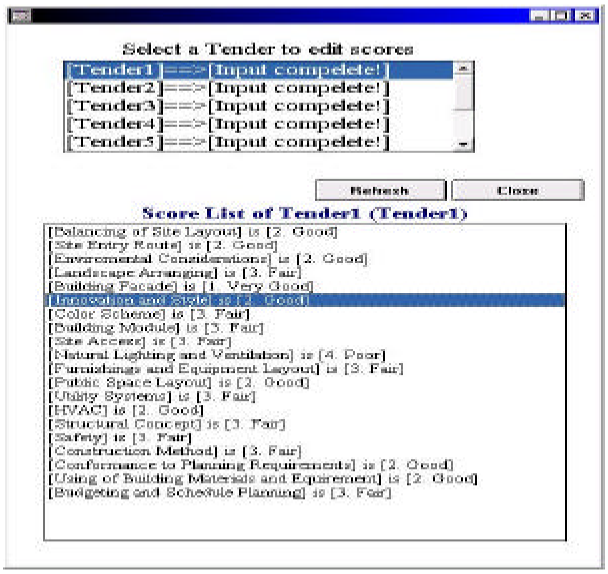

Fig. 9

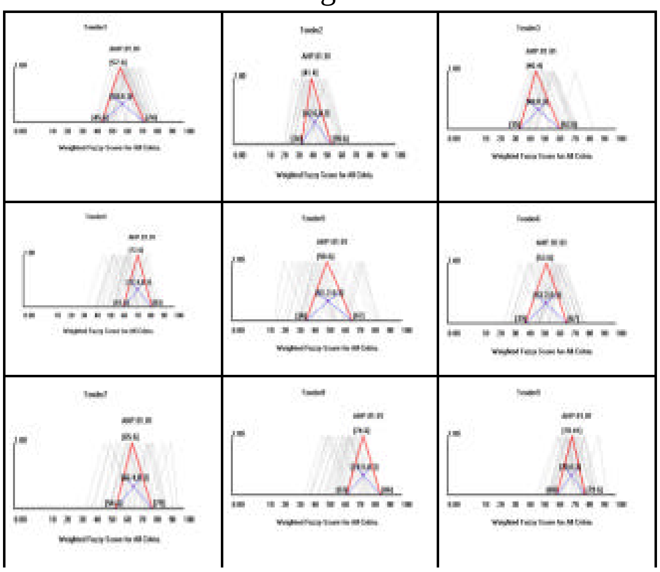

Fig. 12

AN APPLICATION EXAMPLE

This study used the previous case of the Taipei City Police Bureau constructing a branch station building. In this case, nine architects submitted proposals for the new building construction. According to the formulated structure of building P&D alternatives evaluation, the weights of the dimension hierarchy and criterion hierarchy can be analyzed. The simulation process was followed by a series of interviews with three decision-making groups: domain experts (evaluators), superintendents of the Taipei City Police Bureau (owners), and the users of new building in the future (policemen, users). Each DM group contained five representatives. The domain experts included two professors in architecture and design, two professors in civil engineering, and one experienced architect. The owners included one Director General, three Deputy Director Generals and one Secretary General; and the five policemen (users) were selected by random sampling. Weights were obtained by using the AHP method, then the weights of each DM group and average weights were derived in Table 1.

From the weights results, we find the different DM group show different preference for evaluation criteria. For example, the owners group and users group are both very concerned about safety of the building structural system, and its importance ratio is much higher than the experts' group (the weight of owners' group is 0.1776, users' group is 0.1895, experts' group is 0.0277).

In estimating the tender performance, first the evaluators define their own individual range for the linguistic variables employed in this study according to their subjective judgments within a scale of 0-100. This study has employed the method of average value to integrate the fuzzy/vague judgment values of different evaluators regarding the same evaluation criteria. In other words, fuzzy addition and fuzzy multiplication are used to solve for the average fuzzy numbers of the performance values under each evaluation criterion shared by the evaluators for the nine building P&D alternatives.

Table 1 Weights of Dimensions and Criteria for Assessing Building P&D

Dimension	All	Owner	Expert	User	Criteria	All	Owner	Expert	User
Building Lot Layout	0.1527	0.1461	0.1884	0.0918	Balancing of Site Layout	0.0551	0.0547	0.0690	0.0300
					Site Entry Route	0.0541	0.0588	0.0728	0.0250
					Matching of Environment	0.0313	0.0219	0.0347	0.0273
					Landscape Arranging	0.0122	0.0108	0.0119	0.0095
Appearance Modeling	0.1334	0.0734	0.2175	0.1054	Building Facade	0.0584	0.0314	0.0954	0.0470
					Innovation and Style	0.0535	0.0302	0.0914	0.0392
					Color Scheme	0.0215	0.0119	0.0307	0.0192
Plane Planning	0.1737	0.2000	0.2523	0.0737	Building Module	0.0629	0.0737	0.1074	0.0205
					Site Access	0.0384	0.0490	0.0510	0.0149
					Natural Lighting and Ventilation	0.0386	0.0458	0.0576	0.0142
					Furnish Layout	0.0177	0.0132	0.0165	0.0165
					Public Space Layout	0.0162	0.0183	0.0199	0.0077
E&M Systems	0.1566	0.1040	0.0886	0.2957	Utility Systems	0.0926	0.0603	0.0608	0.1479
					HVAC	0.0641	0.0437	0.0278	0.1479
Structure System	0.2441	0.2712	0.1026	0.3710	Structure Configuration Concept	0.0476	0.0369	0.0233	0.0852
					Safety	0.1416	0.1869	0.0551	0.1873
					Construction Methods	0.0550	0.0475	0.0242	0.0985
Degree of Requirement Accomplish-ment	0.1393	0.2049	0.1503	0.0622	Conformance to Planning Requirements	0.0746	0.1235	0.1031	0.0196
					Using of Building Materials and Equipment	0.0418	0.0521	0.0290	0.0291
					Budgeting and Schedule Planning	0.0230	0.0294	0.0183	0.0136

Furthermore, from the criteria weights of three DM groups obtained by AHP (Table 1) and the average fuzzy performance values of each criterion of experts for each alternative, the final fuzzy synthetic decision can then be conducted (R_i). After the fuzzy synthetic decision is processed, the nonfuzzy ranking method is then employed and finally the fuzzy numbers are changed into nonfuzzy values. This study has employed COA to determine the BNP value, which is used to rank the evaluation results of each P&D alternative. The ranking results produced from the system automatically, and details of it are presented in Fig. 13.

As can be seen from the alternative evaluation results in Fig. 13, the Tender-9 is the best alternative given the weights of owners' group, users' group and the average of the three. However, the Tender-7 is the best alternative by the weights of the experts' group, clearly different from the other two groups. One interesting point that can be observed from Fig. 13 is that the ranking order of owners group is the same as the average of the three. The results in Fig. 13 reflect the common perception that changes in criteria weights may affect the evaluation outcome to a certain degree. It is evident that most alternatives maintain similar relative rankings under different criteria weights.

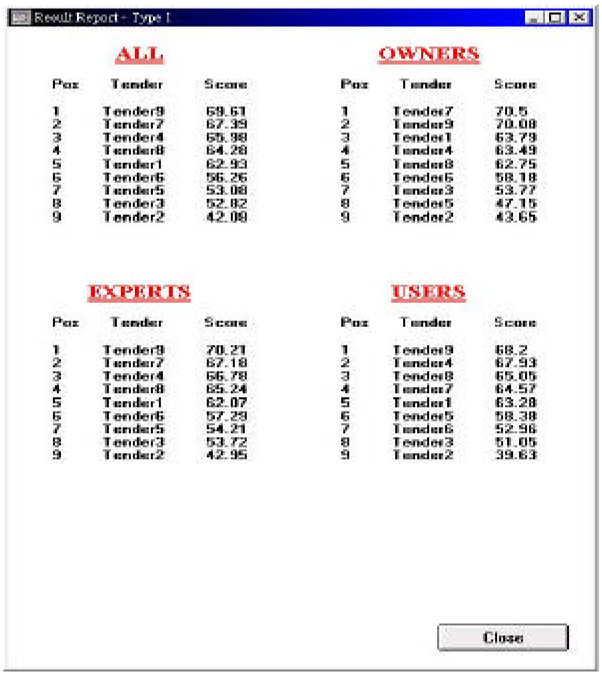

Fig. 13

CONCLUSION

The purpose of this study was to develop a scientific framework and computer-based decision support system for the evaluation of engineering service tender for public building construction. In current methods of building P&D tender selection, government agencies rely only on a panel of experts to perform the evaluation, neglecting the fuzziness of subjective judgment and other relative interest groups' perception in this process. Thus, an effective evaluation procedure is essential to promote the decision quality. This work examines this group decision-making process and proposes a multi-criteria framework for building P&D tender selection. To deal with the qualitative attributes in subjective judgment, this work employs Analytic Hierarchy Process (AHP) to determine the weights of decision criteria for each relative interest group, including the owners', users' and experts' representatives. Then, the Fuzzy Multiple Criteria Decision Making (FMCDM) approach is adopted to synthesize the group decision. This process enables decision makers to formalize and effectively solve the complicated, multicriteria and fuzzy/vague perception problem of optimal building P&D selection, decreasing erroneous decisions and the risky significant design changes. An integrated intelligent decision support system that combines the AHP method and FMCDM approach to be effective and convenient for evaluating P&D alternatives. It will assist the government agencies in making critical decisions during the phase of building P&D selection process.

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