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Developing a Fuzzy Multi-Criteria Decision-Making Model for Selecting Design-Build Operational Variations

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Abstract

Many academic researchers have conducted studies on the selection of design-build (DB) delivery method; however, there are few studies on the selection of DB operational variations, which poses challenges to many clients. The selection of DB operational variation is a multi-criteria decision making process that requires clients to objectively evaluate the performance of each DB operational variation with reference to the selection criteria. This evaluation process is often characterized by subjectivity and uncertainty. In order to resolve this deficiency, the current investigation aimed to establish a fuzzy multi-criteria decision-making (FMCDM) model for selecting the most suitable DB operational variation. A three-round Delphi questionnaire survey was conducted to identify the selection criteria and their relative importance. A fuzzy set theory approach, namely the modified horizontal approach with the bisector error method, was applied to establish the fuzzy membership functions, which enables clients to perform quantitative calculations on the performance of each DB operational variation. The FMCDM was developed using the weighted mean method to aggregate the overall performance of DB operational variations with regard to the selection criteria. The proposed FMCDM model enables clients to perform quantitative calculations in a fuzzy decision-making environment and provides a useful tool to cope with different project attributes.

Keywords: design-build, fuzzy set, multi-criteria decision-making, China

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1. Introduction

Design-build (DB) is a procurement method whereby one entity or consortium is contractually responsible for both design and construction (Songer and Molenaar, 1997). In order to meet different sets of construction circumstances, a number of operational variations of the design-build system have been developed including *develop-and-construction, bridging, novation DB, package deals, direct DB,* and *turnkey* method (CIOB, 1988; Janssens, 1991; Akintoye, 1994; Beard et al., 2001; Masterman, 2002; Gransberg et al., 2006). To most of DB clients, it is not an easy task to select an appropriate DB operational variation (Janssens, 1991; Beard *et al*., 2001). Every DB operational variation has its own strengths and weaknesses and clients should take multiple variables or criteria into consideration including project requirements (i.e., cost, time, and quality), their DB experience, project characteristics, and the availability of competent design-builders (Xia and Chan, 2008).

In the selection of DB operational variations, the multi-criteria decision-making model (MCDM) may serve as the most appropriate technique. It is a mathematical tool for evaluating and comparing alternatives, which assist in selecting the optimal choice (Triantaphyllou, 2000). This enables a client to evaluate the performance of each operational variation with regard to the selection criteria. The MCDM also allows the client to assign different weightings to the selection criteria to reflect their relative importance in the decision-making process. Finally, the MCDM can be successfully applied to the context of DB operational variation selections.

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In the process of MCDM however, it is challenging to determine the performance and importance weightings of alternative options. Performance presents the overall suitability of the alternative options against each selection criterion. The importance weightings illustrate a decision maker's preference over the available alternatives. Both the suitability and preference are fuzzy by nature and are typically characterized by subjectivity and uncertainty. Quantifying performance and importance weightings of alternative options should be based on the system's characteristics, impacts, and other relevant attributes. This decision usually requires a group consensus, which may be difficult and time consuming to acquire. As a result, clients are rarely able to determine the performance and importance weighting of the DB operational variations crisply and on a cardinal scale.

Fuzzy set theory can be utilized for dealing with subjectivity and uncertainties. Zadeh (1965) first introduced the fuzzy set theory, which was based on the rational of uncertainty due to imprecision or vagueness. Fuzzy set theory is capable of presenting vague knowledge and allows mathematical operators and programming to be applied to the fuzzy domain. This theory has been applied within the field of decision-making and deals with the vagueness or fuzziness inherent in subjective or imprecise determinations of preferences, constraints, and goals (Yager, 1982). It allows assessments to be made in qualitative and approximate terms, which suits the subjective nature of MCDM. Additionally, Wang and Liang (2004) pointed out that the fuzzy set theory could address the decision-making problem with conflicting goals. Therefore, a fuzzy multi-criteria decision making (FMCDM) model is suitable for the selection of DB operational

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variations.

The primary aim of the current investigation is to develop a FMCDM model in order to select the most appropriate DB operational variation. A three-round Delphi questionnaire survey was conducted to identify DB selection criteria and importance weightings. Following the survey, the researchers adopted a modified horizontal approach with the bisector error method in the fuzzy set theory in order to establish the fuzzy membership functions. Based on these research findings, a FMCDM model was established, which will enable clients to objectively select the most appropriate operational variation of the DB system under different situations.

2. Fuzzy Multi-Criteria Decision-Making (FMCDM) Model

A decision-making problem comprises choosing an optimal decision against goals or objectives from the set of all possible alternative decisions (Klir and Yuan, 1995; Triantapyllou, 2000). In practical decision-making problems, the number of goals or objectives under consideration is often more than one; therefore, such problems are referred to as multiple objective decision-making problems (MOD). Since objectives are established based on set criteria, the multiple objective decision-making problems are also referred to as MCDM problems.

Let U be a set of objects under evaluation, let $\pi = \{c_1, c_2, ..., c_m\}$ be the set of basic criteria in the evaluation system (or process), and let $E = \{e_1, e_2, ..., e_n\}$ be a set of alternatives or objective statements used in the evaluation. For every project, u, the

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objective function, with respect to a selection criterion, c_i, on the alternative, e_j, can be denoted as r_{ij}. This expresses the degree to which the selection criterion, c_i, is satisfied by alternative, e_j. Additionally, there are $m \times n$ values of entries, which can be expressed in the function matrix R as follows:

$$R = \begin{bmatrix} r_{11} & r_{12} & \dots & r_{1n} \\ r_{21} & r_{22} & \dots & r_{2n} \\ \vdots & \vdots & \dots & \vdots \\ r_{m1} & r_{m2} & \dots & r_{mn} \end{bmatrix} \tag{1}$$

The most common approach to solving multiple-criteria problems is to convert these problems into single-criterion decision-making problems (Klir and Yuan, 1995). This conversion can be accomplished by determining the global criterion, $d_j = h(r_{1j}, r_{2j}, \dots r_{mj})$, for each alternative, $e_j \in E$, which is an adequate aggregate of values, r_{1j}, r_{2j}, …, r_{mj}, to which the selection criteria, c_1, c_2, … , c_m, are satisfied. A frequently employed aggregating operator is the weighted, $\sum$, at which point, d_j, takes the following form:

$$d_j = \sum_{i=1}^{m} w_i r_{ij} \qquad (j \in \mathbb{N}_n), \tag{2}$$

Where, $W = (w_1, w_2, \dots, w_m)$, is a constant weighting vector that indicates the relative importance of selection criteria, c_1, c_2, … , c_m. Hence, the following formula is set:

$$D = W \bullet R, \tag{3}$$

Where, D, is the overall performance matrix of alternative options with regard to all selection criteria.

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In the selection of DB operational variations, fuzziness can be introduced into this MCDM model. A fuzzy set is one whose elements have varying degrees of membership (Cross and Sudkamp, 2002; Niskanen, 2004). The degrees of membership of a single element are expressed by the membership function. Additionally, the grades of membership in fuzzy sets may fall anywhere within the interval [0, 1]. A degree of 0 (zero) means that an element is not a member of the set while a degree of 1 (one) represents full membership. In the selection of DB operational variations, a scale of 0-1 can be used to represent the suitability of each operational variation with regard to each selection criterion (1 means that the DB operational variation is the most suitable for the selection criteria and 0 means that it is the least suitable). Thus the fuzzy sets could be established as the suitability or performance of alternative DB operational variations and degrees of suitability can be expressed by fuzzy membership functions. Therefore, the following formula is set:

$$\underset{\sim}{D} = \underset{\sim}{W} \bullet \underset{\sim}{R} \qquad (4)$$

In this formula, the entries of matrix $\underset{\sim}{R}$ are fuzzy members $\tilde{r}_{ij}$ determined by fuzzy membership functions.

3. Research Methods

The most important steps to establish the FMCDM model include: (1) identifying the selection criteria, (2) measuring their relative importance, and (3) determining the performance of each DB operational variation with regard to the selection criteria.

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Xia and Chan (2008) developed the selection criteria and their relative importance in the construction market of the People's Republic of China (PRC) using a three-round Delphi survey distributed to 20 construction experts. The Delphi technique is a method of obtaining the most reliable agreements of a group of experts by a series of intensive questionnaires interspersed with controlled opinion feedback, and with results of each round being fed into the next round (Linstone and Turoff, 1975). It typically involves the selection of suitable experts, development of appropriate questions to be put to them and analysis of their answers (Cabaniss, 2002; Outhred, 2001). Even if the collective judgments of experts are made up of subjective opinions, it is considered to be more reliable than individual statements, thus, more objective in its outcomes (Johnson and King 1988; Masini, 1993). The Delphi method is best suited in fields where there are no adequate historical data for research purposes (Martino, 1973; Skulmoski et al., 2007). It has proven to be a popular technique in decision-making based on the opinions of experts (Okoli and Pawlowski, 2004; Landeta, 2006). The three features of a typical Delphi survey include (1) anonymous response, (2) iteration and controlled feedback, and (3) statistical group responses (Adnan and Morledge, 2003). The features are designed to minimize biasing effects of dominant individuals, irrelevant communications, and group pressure for conformity.

The Delphi method used in the current study was composed of three rounds with 20 experts with an average of nine years of DB experience in the construction industry. All experts had sufficient DB experience and knowledge and, at the time of this study, held senior management positions in their institutions. During Round 1, all experts were asked

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to list at least five selection criteria for DB operational variations. All Round 1 surveys were returned. During Round 2, the experts were provided with consolidated results from Round 1 and were required to rate the selection criteria on a 5-point Likert scale in order to evaluate the importance of each selection criterion. Seventeen experts completed Round 2 of the Delphi questionnaire survey. During Round 3, the experts were asked to reconsider their ratings of each selection criterion after receiving consolidated results from Round 2. Seventeen experts completed Round 3 of the Delphi questionnaire survey. The consistency of the results for Rounds 2 and 3 were analyzed and compared using Kendall's Concordance Analysis, which indicates the degree of agreement between the experts on the ordered list by mean ranks by taking into account the variations between the rankings (Doke and Swanson, 1995).

While many studies using the Delphi method obtain information from 15-20 survey respondents, with a homogeneous group of experts, reliable results can be obtained with a panel as small as 10-15 respondents (Ludwig, 2001; Ziglio, 1996). Therefore, the opinions solicited from the 17 experts during the third round of the Delphi questionnaire survey are considered adequate to provide reliable results.

After conducting the three rounds of the Delphi questionnaire survey, the top seven selection criteria for DB operational variations were identified. The relative importance of each selection criterion was also obtained. The importance weighting of each selection criterion was calculated by the mean rating of each selection criterion divided by the summation of mean ratings of all seven selection criteria (Yeung *et al*., 2007). Ratings for

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each selection criterion (1 = *not important* to 5 = *extremely important*) during the third round of the Delphi questionnaire survey were believed to be reliable enough to obtain the relative importance of the selection criteria. This was because the Likert scale system has been demonstrated to be effective in measuring the attitudes of respondents (Albaum, 1997), after conducting the three rounds of the Delphi questionnaire survey, experts had reached an agreement on the relative importance of these selection criteria, and the ratings obtained during Round 3 clearly indicated degrees of importance for each selection criterion.

In the current FMCDM model, the performance of each DB operational variation was expressed by fuzzy membership functions. There are four methods for establishing the fuzzy membership functions including (1) the horizontal approach, (2) the vertical approach, (3) the pairwise comparison method, and (4) the membership function estimation approach with the aid of probabilistic characteristics (Ng *et al*., 2002). In addition, Ng *et al*. (2002) proposed a modified horizontal approach to develop a fuzzy membership function to address the fuzziness of the procurement selection criteria. In the current study, the researchers adopted the modified horizontal approach for developing fuzzy membership functions because it is more accurate and allows the final outcome to be derived from simple probability functions (Ng *et al*., 2002; Chow and Ng, 2007).

4. Developing the Fuzzy Multi-criteria Decision-making Model (FMCDM) for the Selection of DB Operational Variations

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4.1 Alternatives of Operational Variations of the DB System

Within the DB system, a variety of operational variations have been developed, each with its own strengths and weaknesses and clients should consider the trade-offs when choosing a DB operational variation. In the construction market of the PRC, the DB operational variations mainly include *develop-and-construction*, novation DB, *enhanced DB*, *traditional DB*, and *turnkey method* (Xia and Chan, 2008). The major difference between these methods is the proportion of design work undertaken by the client. The definitions of the DB operational variations are as follows:

Develop-and-construction. In this operational variation, the client completes most of the design work (typically more than 50% of the design). The successful DB contractor is responsible for the remaining detailed design and construction work.

Novation DB. In this operational variation, the successful contractor is responsible for construction work and detailed design, which may also extend to design development, with the assignment of the design consultant from the DB client.

Enhanced DB. In this operational variation, the client or the employed design consultant undertakes the design work from project definition to schematic design. The DB contractor is responsible for the design development, detailed design, and construction work.

Traditional DB. The successful design-builder takes full responsibility of all the design and construction work. The client may prepare the brief by himself or herself or leave it to the design-builder.

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Turnkey method. The design-builder provides everything, including the commission and handover after construction. All that remains for the client to do is simply to receive the completed facility. This operational variation is traditionally applied in major industry projects.

4.2 Selection Criteria and Their Importance Weightings

In order to facilitate the selection of DB operational variations in the PRC, a specific set of selection criteria was required. The formulation of selection criteria is of great importance to the selection process because an appropriate selection model depends largely on prudent identification of selection criteria to reflect client and project objectives (Luu et al., 2005).

The top seven selection criteria and their importance weightings are shown in Table 1. The Pearson correlation matrix as indicated in Table 2 manifests that the top seven selection criteria are not highly correlated with each other at 5% significance level (most of them are even insignificantly correlated with each other). Although the correlation between the availability of design-builders and clearness of project requirements seem to be significant according to Table 2, these criteria are, by their definition, the condition of DB market and the attribute of a DB project, and they are independent with each other. Kendall's Coefficient of Concordance (W) was also calculated with the aid of the SPSS software to measure the degree of agreement among panel members. The Kendall's Coefficient of Concordance (W) for the rankings of top seven selection criteria was 0.301,

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which was statistically significant at the 0.001 significance level. The null hypothesis was that the respondent's ratings within the group would be unrelated to each other and would have to be rejected. Therefore, it can be concluded that a significant amount of agreement among the respondents of panel experts was achieved.

Please insert Table <1> here

Please insert Table <2> here

The weightings of these selection criteria were calculated as follows (Yeung *et al*., 2007):

$$W_{SCi} = \frac{M_{SCi}}{\sum_{i=1}^{7} M_{SCi}}$$

Where:

W_{SCi} represents the importance weightings of the top seven selection criterion.

M_{SCi} represents the mean rating of the top seven selection criterion.

$\sum M_{SCi}$ represents the summation of mean ratings of the top seven selection criteria.

Therefore, the fuzzy importance weighting vector obtained was:

$$\underset{\sim}{W} = (0.178, 0.156, 0.147, 0.137, 0.132, 0.127, 0.122)$$

4. 3 Establishing Fuzzy Membership Functions

4.3.1 Fuzzy Membership Functions

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A fuzzy set, $\underset{\sim}{A}$, on the given universe, U, is that, for any, u $\in$U, there is a corresponding real number, $\mu_{\underset{\sim}{A}}(u) \in [0,1]$ to u, where, $\mu_{\underset{\sim}{A}}(u)$ is the grade of membership of u belonging to $\underset{\sim}{A}$. This means that there is a mapping,

$$\mu_{\underset{\sim}{A}} : U \rightarrow [0,1], \qquad u \mapsto \mu_{\underset{\sim}{A}}(u)$$

This mapping is called the membership function of $\underset{\sim}{A}$.

4.3.2 Modified horizontal approach with the bisector error method

It is typically difficult to establish proper fuzzy membership functions. In general, the determination of fuzzy membership functions is acquired from human experts using a trial-and-error method (Bagis, 2002). Ng *et al*. (2002) proposed a modified horizontal approach to develop fuzzy membership functions for addressing the fuzziness of the procurement selection criteria. The reason why the modified horizontal approach was adopted for developing fuzzy membership functions is that it is more accurate and allows the final outcome to be derived from simple probability functions (Ng *et al*., 2002; Chow and Ng, 2007). Since the selection process of DB operational variations is similar to the selection of procurement methods, the modified horizontal approach was used to construct fuzzy membership functions of DB operational variations.

The modified horizontal approach is based on an amalgamation of the horizontal approach and the graphical approach (Ng *et al*., 2002). Additionally, this approach consists of four steps in the fuzzy environment of DB operational variations:

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Step 1: Quantifying fuzzy selection criteria based on a 10-point Likert scale

Using a questionnaire survey, the 17 experts who completed the previous three-round Delphi questionnaire survey were asked to provide a numerical figure (f_0) that fits for every DB operational variation pertinent to each selection criterion. For example, in taking the client's DB capability, an expert may believe that the *develop-and-construction* is the most suitable choice when the client's DB capability score is 6.0, while the *turnkey* method is the most suitable with a score of 10 (the highest requirement for a client's DB capability). The reason why these experts were selected to complete the questionnaire survey was that they not only have sufficient DB experience but were also familiar with the research work.

Step 2: Identifying the X value of the membership functions

A membership function of a fuzzy set is formulated using two values, X and A, where X represents the value in the universe of discourse and A represents the value of the membership function of that fuzzy set. X_i values are defined as the means of bands, B_i (i =1, 2, …, k), where, B_i (I = 1, 2,…,k), are the bands of values, f_0, given by the respondents to each operational variation pertinent to the selection criteria. Ng *et al.* (2002) adopted Bharathi-Devi and Sarma's (1995) approach to estimating the number of bands,

$$k = 1.87(N-1)^{2/5},$$

where N is the total number of responses in the questionnaire survey.

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Step 3: Identifying the A values of the membership functions

The value of membership function A_i is calculated according to the following formula,

$$A_i = n(B_i)/n_{\max} \ , \ \ i = 1,2,...,k \ .$$

Here, $n(B_i)$ is the number of responses that have values of f_0 and belong to a certain band, B_i, and n_{max} is the maximum value of all the $n\ (B_i)$ with $i = 1,2,...,k$.

Step 4: Formulating the fuzzy membership functions with the bisector error method

Based on X and A values, a scatter diagram for the membership function is plotted, with the horizontal axis representing the X values and the vertical axis representing the A values. After the point-wise grades of membership are determined, the fuzzy membership functions are constructed using constrained best-fit lines with the bisector error method, thus minimizing the residual sum of squares by taking the average of vertical and horizontal distances (Yeung, 2007). The reason why the bisector error method was adopted for the current model is that this method considers the errors created by both the vertical error method (minimizing the residual sum of squares by vertical distance only) and the horizontal error method (minimizing the residual sum of squares by horizontal distance only). Additionally, this method is considered superior to the other two methods (Yeung, 2007).

4.3.3 Fuzzy Membership Functions for DB Operational Variations

Availability of competent design-builders

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Please insert Figure <1> here

As shown in Figure 1, the membership functions of *develop-and-construction*, *novation DB*, *enhanced DB*, *traditional DB*, and the *turnkey method* are triangular shaped according to the best-fit lines. The results indicate that full membership of the five operational variations occurs when the scores of the contractor's competences, or the availability of competent design-builders in the market, are 6, 7.3, 8, 9, and 10, respectively. Generally, the requirements for contractor's competence increase as the DB operational variation moves from *develop-and-construct* to the *turnkey method*. This shift implies that clients can leave more project responsibilities and tasks to the design-builders who are more competent. Additionally, the degree of membership at any level of a contractor's competences can be calculated according to the membership functions for each DB operational variation.

Client's DB capabilities

Please insert Figure <2> here

As shown in Figure 2, the membership functions of develop-and-construction, *novation DB*, *enhanced DB*, *traditional DB*, and *turnkey method* are all triangular shaped according to the best-fit lines. The results indicate that full membership of the five operational variations occurs when the scores of the client's DB capabilities are 6.286, 7, 8, 9, and 10, respectively. According to the fuzzy membership functions, it is appropriate for inexperienced clients to complete more design work using their internal design staff or external design consultants before leaving the project to the design-builder. Otherwise, the clients may lose control of the project.

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Project complexity

Please insert Figure <3> here

As shown in Figure 3, the membership functions *of develop-and-construction, novation DB, enhanced DB, traditional DB,* and the *turnkey method* are triangular shaped. According to the membership functions, *develop-and-construction* and *novation DB* are more suitable for DB projects with a low degree of complexity. In contrast, *enhanced DB*, *traditional DB*, and the *turnkey method* are more appropriate for DB projects with medium to high degrees of complexity. The current results confirm Beard *et al*.'s (2001) research findings that the design-builder should be more involved in those DB projects that have higher degrees of complexity.

The control of the DB projects

Please insert Figure <4> here

As shown in Figure 4, the membership functions of *novation DB*, *enhanced DB*, and the *turnkey method* are triangular shaped according to the best-fit lines, whereas the membership functions of *develop-and-construction* and *traditional DB* are trapezoidal shaped. These results indicate that full membership of the five operational variations occurs when the scores of project control are 9.944-10, 9, 8, 6-7.3, and 6.333, based on a 10-point Likert scale, respectively. According to fuzzy membership functions, *develop-and-construction* and *novation DB* enable clients to have more control of the project compared to *enhanced DB*, *traditional DB*, and the *turnkey method*. In other words, when a client provides more design solutions prior to selecting a DB contractor, the client will

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have more control over the project.

Earlier commencement and shorter duration

Please insert Figure <5> here

As shown in Figure 5, the membership functions of develop-and-construction, *novation DB*, *enhanced DB*, *traditional DB*, and the *turnkey method* are triangular shaped according to the best-fit lines. In order to begin a project as soon as possible and greatly reduced the project schedule, clients should reach out to design-builders as soon as possible. When the design-builder takes on a larger proportion of the design, the project schedule will be greatly reduced due to the overlapping of design and construction, the early input of construction knowledge for the design process, and close communication among project participants (Songer and Molenaar, 1997).

Reduced responsibility and administrative burden

Please insert Figure <6> here

As shown in Figure 6, the membership functions of *develop-and-construction*, *novation DB*, *traditional DB*, and the *turnkey method* are triangular shaped, whereas the membership functions of *enhanced DB* are trapezoidal shaped according to the best-fit lines. According to the membership functions, the client will assume less responsibilities of the DB project when they leave more of the design work to the design-builders. If a client prefers to work with traditional design consultants to complete most of the design work prior to the DB contract, the potential design-builders may feel reluctant to assume all the project responsibilities and they may demand higher contract prices to compensate

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for potential risks.

Clearness of the project definition

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As shown in Figure 7, the membership functions of *develop-and-construction* are triangular shaped, whereas the membership functions of *novation DB*, *enhanced DB*, *traditional DB*, and the *turnkey method* are trapezoidal shaped according to the best-fit lines. In *develop-and-construction*, *novation DB,* and *enhanced DB*, and because clients will undertake comparatively more design work before leaving the projects to the design-builders, the requirements for the clearness of the DB project are comparatively low. However, if the client prefers to leave all project responsibilities to the design-builders as soon as possible, they should have a clear understanding of the perceived DB project at a very early stage. Otherwise, the client may not receive the final project as required.

4.4 Fuzzy Multi-criteria Decision-making Model and Selection Rule

After the establishment of fuzzy membership functions for each selection criterion, the performance matrix, $\underset{\sim}{R}$, for each DB project can be obtained. Therefore, the final evaluation results can be obtained as follows:

$$\underset{\sim}{D} = \underset{\sim}{W} \bullet \underset{\sim}{R} = \left(d_1, d_2, ..., d_n\right) = (w_1, w_2, ..., w_m) \bullet \begin{pmatrix} r_{11} & r_{12} & \cdots & r_{1n} \\ r_{21} & r_{22} & \cdots & r_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ r_{m1} & r_{m2} & \cdots & r_{mn} \end{pmatrix}$$

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$$d_j = \sum_{i=1}^{m} w_i \bullet r_{ij}$$

Where d_j is the degree of membership of the alternative, e_j, with respect to the selection criteria. This model is called the weighted mean method. The reason why the weighted mean method is used is that this model considers the impact of each selection criterion and is widely used in the decision-making environment (Chan, 2007).

In the selection of DB operational variations, r_{ij} represents the suitability or performance of the alterative, e_j, with regard to the selection criterion, f_i. Therefore, d_j represents the overall suitability or performance of the alterative, e_j, with regard to all selection criteria. As a result, the DB operational variation with the largest value of d could be regarded as the most appropriate operational variation for the DB project.

5. Numerical Example

In the following section, a hypothetical problem for the selection of DB operational variation was developed to demonstrate the computational process of this FMCDM model.

Step 1. Assuming that a DB client has chosen the DB method to deliver his project and now must decide the appropriate DB operational variation for the project. The DB project is of medium complexity and there are not many competent DB candidates in the current

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construction market. Similar to most DB clients in China, the client also does not have much DB experience; however, the client wants to have firm control of the project. At the same time, the client also wants to reduce project responsibility and administrative burden as much as possible. In addition, the client expects the DB project to be completed as soon as possible. Furthermore, the client does not have clear project scope or objectives. According to the project characteristics, the conditions of the selection criteria can be rated based on a 10-point Likert scale as shown in Table 3.

Please insert Table <3> here

Step 2. After defining the ratings of the selection criteria, the fuzzy memberships for five DB operational variations against all selection criteria can be obtained according to the fuzzy membership functions established in section 4.3.3.

The fuzzy memberships of *develop-and-construct*, *novation DB*, *enhanced DB*, *traditional DB*, and the *turnkey method* against the availability of competent design-builders are expressed as,

$$r_{1j} = [0.333, 0.9447, 0.7597, 0.6306, 0]$$

The fuzzy memberships of *develop-and-construct*, *novation DB*, *enhanced DB*, *traditional DB*, and the *turnkey method* against the client's DB capability are expressed as,

$$r_{2j} = [0.762, 0.4508, 0.229, 0, 0]$$

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The fuzzy memberships of *develop-and-construct*, *novation DB*, *enhanced DB*, *traditional DB*, and the *turnkey method* against the project complexity are expressed as,

$$r_{3j} = [0, 0.1526, 0.9826, 1, 0.2224]$$

The fuzzy memberships of *develop-and-construct*, *novation DB*, *enhanced DB*, *traditional DB*, and the *turnkey method* against the client's control are expressed as,

$$r_{4j} = [0.6786, 1, 0, 0, 0]$$

The fuzzy memberships of *develop-and-construct*, *novation DB*, *enhanced DB*, *traditional DB*, and the *turnkey method* against the early commencement and short duration are expressed as,

$$r_{5j} = [0, 0, 0.619, 1, 0.6]$$

The fuzzy memberships of *develop-and-construct*, *novation DB*, *enhanced DB*, *traditional DB*, and the *turnkey method* against the reduced responsibility and project involvement are expressed as,

$$r_{6j} = [0, 0.6, 0.8334, 1, 0.1232]$$

The fuzzy memberships of the *develop-and-construct*, *novation DB*, *enhanced DB*, *traditional DB*, and the *turnkey method* against the clearness of project requirements are expressed as,

$$r_{7j} = [0.9137, 1, 1, 0, 0]$$

Therefore, the fuzzy matrix, $\underset{\sim}{R}$, can be expresses as follows,

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$$\underset{\sim}{R} = \begin{bmatrix} 0.333 & 0.9447 & 0.7597 & 0.6306 & 0 \\ 0.762 & 0.4508 & 0.229 & 0 & 0 \\ 0 & 0.1526 & 0.9826 & 1 & 0.2224 \\ 0.6786 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0.619 & 1 & 0.6 \\ 0 & 0.6 & 0.8334 & 1 & 0.1232 \\ 0.9137 & 1 & 1 & 0 & 0 \end{bmatrix}$$

The fuzzy importance weighting vector that was obtained after Round 3 of the Delphi questionnaire survey is,

$$\underset{\sim}{W} = [0.178, 0.156, 0.147, 0.137, 0.132, 0.127, 0.122]$$

Step 3. After obtaining the fuzzy membership matrix and the weighting vector, the performance for DB operational variations can be calculated according to formula (4),

$$\underset{\sim}{D} = (d_1, d_2, ..., d_n) = \underset{\sim}{W} \bullet \underset{\sim}{R}$$

$$= [0.178, 0.156, 0.147, 0.137, 0.132, 0.127, 0.122] \bullet \begin{bmatrix} 0.333 & 0.9447 & 0.7597 & 0.6306 & 0 \\ 0.762 & 0.4508 & 0.229 & 0 & 0 \\ 0 & 0.1526 & 0.9826 & 1 & 0.2224 \\ 0.6786 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0.619 & 1 & 0.6 \\ 0 & 0.6 & 0.8334 & 1 & 0.1232 \\ 0.9137 & 1 & 1 & 0 & 0 \end{bmatrix}$$

$$= [0.3826, 0.5965, \underline{0.6249}, 0.5182, 0.1275]$$

According to the selection rule, the most appropriate DB operational variation for this project, being in this case is the enhanced DB.

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The final choice is considered quite reasonable. The hypothetical project is characterized by a high level of complexity and medium to low level of scope clarity and is required to be completed as soon as possible. Meanwhile, the client does not have sufficient DB experience but wants to have a firm control of the project and little project responsibility. The enhanced DB is suitable for projects with medium to high levels of complexity (Love *et al.,* 1998; Chan *et al*., 2001). This method also provides the time saving advantage of the DB system. At the same time, this method offers full conformance to the basic design developed by the original design team, which, in turn, will enable the client to have greater control of design quality (Chan, 2000). Even though there may be a limited number of design-builders with a proven record of both design and construction, the *enhanced DB* is regarded as acceptable because the client could complete the schematic design prior to leaving the project to the winning design-builder.

6. Discussions

When a client decides to employ the DB delivery method, an important next step is to determine which operational variation of the DB system is most appropriate for his needs (Beard *et al.*, 2001). The FMCDM model provides clients with the means to quantitatively measure and compare the performance of each DB operational variation and facilitates selecting the most appropriate one.

In the construction market of the PRC, the main DB operational variations include *develop-and-construction*, *novation DB*, *enhanced DB*, *traditional DB*, and the *turnkey*

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method (Xia and Chan, 2008). Every DB operational variation has its own strengths and weaknesses. *Develop-and-construction,* means to develop the detail from the employer's design and construct the works (Janssens, 1991). The client or his consultants will complete approximately 50% of the design work. This method may preclude the DB team from any significant creativity and innovation since basic solutions and concepts are determined before the design-build team begins and the selection of the design-builders tends to be price-oriented (Quatman and Dhar, 2003). Although *develop-and-construction* is not favored by design-builders (Akintoye, 1994), many clients regard it as a hybrid system taking advantage of the design-build and the traditional DB delivery method. This system is widely used in the PRC construction industry, where many DB contractors and clients remain unfamiliar with the DB system.

In *novation DB*, a successful design-builder is required to engage the employer's consultants to complete the design work during the post-contract stage. The design-builder accepts the novated consultants in order to maintain consistency of the design work. However, the more design work the design-builder takes on, the more likely he will decline such an arrangement because it restricts the design-builder's innovative input. With *enhanced DB*, the design-builder is contractually responsible for the design development, working details, and construction work. This method is an emerging delivery system, which has attracted much enthusiasm in Hong Kong (Chan, 2000). The *enhanced DB* offers the client greater control, while preserving the benefits of time saving.

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The *traditional design-build* represents the original design-build in which the design-builder takes full responsibility for the design and construction. This method offers advantages such as time savings, enhanced financial certainty, improved buildability, reduced disputes, and increased productivity. The main disadvantage of this system is that the owner's interests and requirements may not be fully satisfied. In the *turnkey method*, the contractor provides everything so that all the client has to do is "turn the key" to use his or her building. The term *turnkey* and its concept have been widely accepted in the industry. As one of the basic DB operational variations, the *turnkey method* is traditionally applied to major industrial projects (Janssens, 1991).

In order to select the most appropriate DB operational variation, clients should take various criteria into consideration. In the current investigation, the selection criteria for DB operational variations were identified using a three-round Delphi questionnaire survey. The Delphi method, by its inherent nature, serves as a self-validating mechanism because panel experts are provided the opportunity to re-assess their scores with reference to consolidated mean scores assessed by other experts (Yeung *et al*., 2007). By using the Delphi method, the maximum amount of unbiased and objective information can be obtained from the experts. However, it is worth noting that some of the identified criteria remain broad, vague concepts (e.g., project complexity). It is desirable to identify suitable quantitative interpretations or indicators for each criterion and provide objective evaluation results based on quantitative evidence in the future. In addition, as with any opinion-based study, a weakness of the current study is subjectivity, bias, imprecise definitions, and the difficulty to process complex information. However, the effects of

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these limitations can be further reduced by utilizing a larger sample size in future Delphi questionnaire surveys.

Fuzzy membership functions provide a quantitative calculation method for measuring the performance of each DB operational variation. With the establishment of fuzzy membership functions, clients can closely examine the suitability of every DB operational variation with regard to each selection criterion. Unlike crisp sets that have only one membership, fuzzy membership functions offer different memberships for every DB operational variation under different conditions of project attributes. In these situations, clients are only required to evaluate the characteristics of the project attributes based on a 10-point Likert scale. However, it should be noted that it is not easy to objectively measure project attributes, because most of the selection criteria (such as the client's DB capabilities, project complexity) are qualitative by nature. Additionally, different clients or assessors may have their own interpretation on each criterion and it is often difficult to objectively quantify project attributes using a Likert scale system. Based on this information, subjectivity of the evaluation cannot be eliminated. Thus, it is desirable to provide objective evaluation rules based on quantitative evidence. In addition, the sample size of the current study was not large enough. However, the effects of these limitations could be reduced by conducting a study with a larger sample size once the DB market in China matures.

The final FMCDM model can be extended to the selection of project delivery methods if the selection criteria and the fuzzy membership functions are modified for the specific

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research purpose. The selection process of project delivery methods is similar to that of DB operational variations. It also involves subjectivity and requires project owners to take multiple factors into consideration. The FMCDM framework can be replicated to mitigate the subjectivity and to deal with MCDM problem.

7. Conclusions

The selection of DB operational variation is a complex MCDM problem involving fuzzy characteristics and uncertainties. The researchers proposed a FMCDM model in order to solve this problem. The FMCDM takes full advantage of the experts' knowledge and experiences and makes the decision maker feel more comfortable by providing a quantitative evaluation of different DB operational variations. This model also includes identification of selection criteria, assessment of importance weightings, evaluation of alternative performance, and determination of ranking orders of each DB operational variation. The FMCDM is an efficient and feasible model for industrial practitioners, in particular DB clients.

In developing the FMCDM model, the Delphi method and fuzzy set theory served as suitable techniques for obtaining expert knowledge. The Delphi method was used to identify and develop a practical set of selection criteria for DB operational variations. This method yielded both insight and structure to assessing different DB variations. Additionally, fuzzy set theory was used to deal with the subjectivity and uncertainty during the performance evaluation of the DB operational variations. In particular, the

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fuzzy membership functions represented the degree of suitability for each operational variation with regard to the selection criteria. Therefore, clients can evaluate the performance of DB operational variations based on the established fuzzy membership functions, rather than applying their subjective value judgment.

The FMCDM model provides clients with a quantitative approach to examine and compare different DB operational variations. In general, when DB operational variations move from the *develop-and-construction* to the *turnkey method*, the requirements for a design-builder's competence, a client's DB capabilities, and the clearness of the project's definition increase. Clients tend to experience less control of these projects and may assume less project responsibility. In addition, when project complexity increases, it is appropriate to leave more design work to the design-builders.

Given that the selection of DB operational variations is a problem not only in China but internationally, further research should be conducted in other countries to seek similarities and differences by adopting the same research methods for international comparisons. It is expected that the selection model will deepen the understanding of DB operational variations in general and promote the application of the DB system in the PRC construction market in particular.

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Table 1 The results of Round 3 of the Delphi survey

Criteria for DB variations selection	Weightings (w)
1. *Availability of competent design-builders* Are there many competent design-builders in the local construction market?	0.178
2. *Client's design-build capability* Does the client have DB capabilities, particularly the similar DB experience?	0.156
3. *Project complexity* Does the project have high requirements for construction method, project management, etc?	0.147
4. Client's control of project Does it enable clients to have more control of the project?	0.137
5. *Early commencement and short duration* Does it enable clients to start projects as soon as possible? Is the short duration first priority?	0.132
6. *Reduced responsibility or involvement for clients* Does it reduce the client's project responsibility or involvement as much as possible?	0.127
7. *Clear end user's requirements* Does the client have clear project definition or project requirement?	0.122

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Table 2 Pearson correlation matrix among the top seven selection criteria

	Competent design-builders	Client's DB capability	Project complexity	Project control	Short duration	Reduced responsibility	Clear requirements
Competent design-builders	1	-.142	.316	-.275	-.149	-.026	-.516*
Client's DB capability		1	.384	.468	.143	-.445	-.335
Project complexity			1	.227	-.057	.202	-.505*
Client's project control				1	-.182	-.428	-.074
Short duration					1	-.027	.093
Reduced responsibility						1	.197
Clear end user's requirements							1

Notes: * Correlation is significant at the 0.05 level (2-tailed).

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Table 3 Conditions of the selection criteria

Criteria for DB variations selection	Ratings
1. Availability of competent design-builders	6
2. Client's DB capability	5
3. Project complexity	8
4. Client's control of project	9
5. Early commencement and short duration	9
6. Reduced responsibility or involvement for clients	8
7. Clear end user's requirements	6

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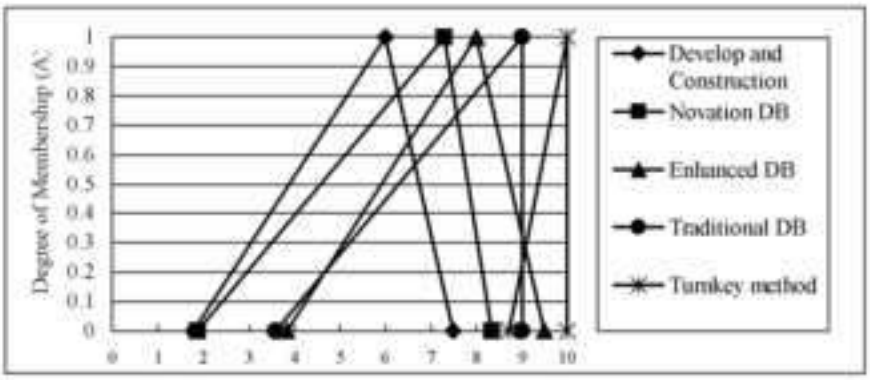

Fig 1 Fuzzy Membership Functions for DB Operational Variations with Respect to Contractor's Competences in the Construction Market of the PRC

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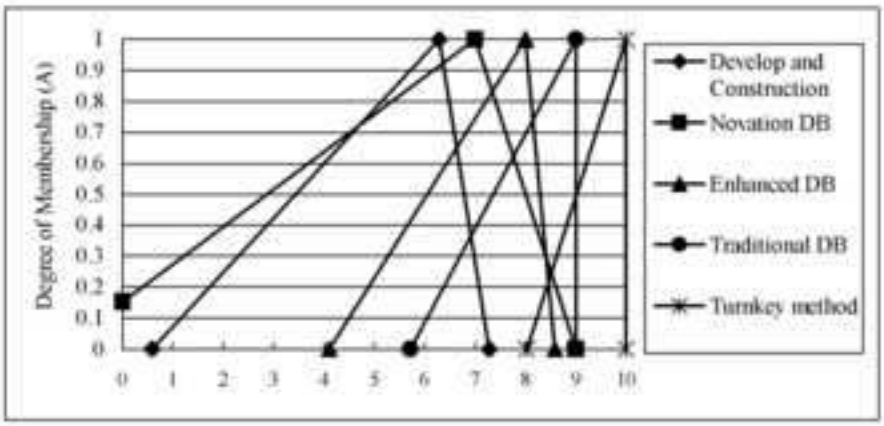

Fig 2 Fuzzy Membership Functions for DB Operational Variations with Respect to Client's DB Capabilities in the Construction Market of the PRC

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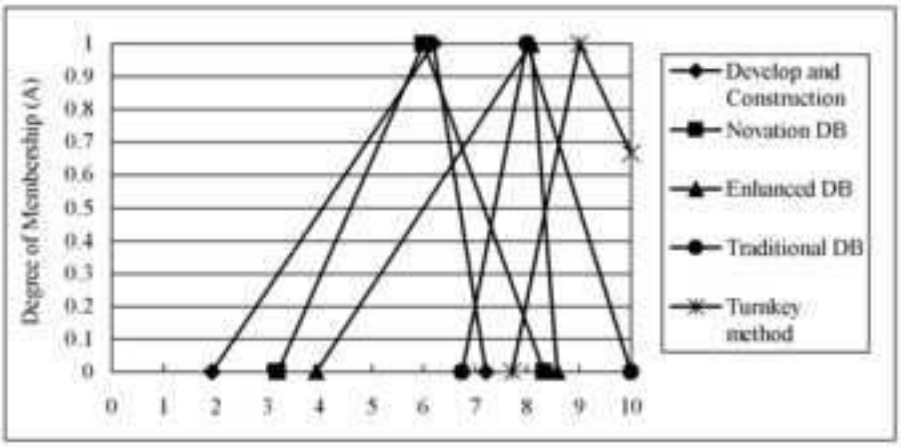

Fig 3 Fuzzy Membership Functions for DB Operational Variations with Respect to Project Complexity in the Construction Market of the PRC

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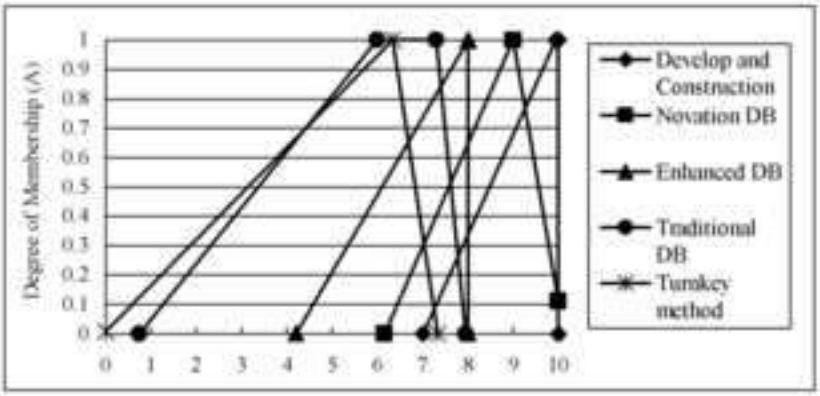

Fig 4 Fuzzy Membership Functions for DB Operational Variations with Respect to Project Control in the Construction Market of the PR

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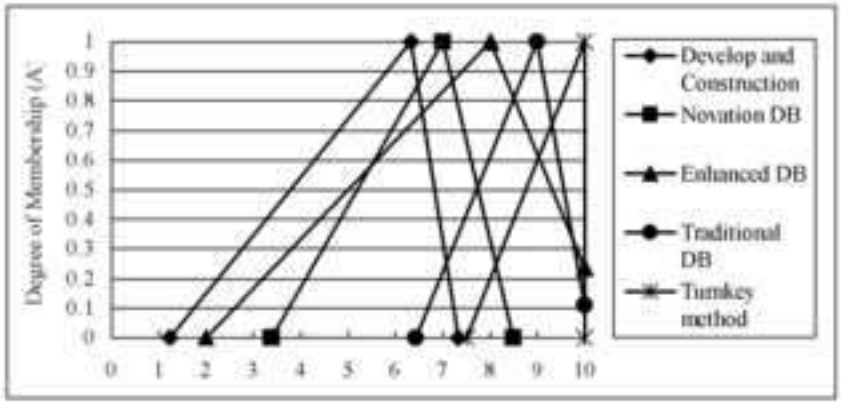

Fig 5 Fuzzy Membership Functions for DB Operational Variations with Respect to Early commencement and short duration in the Construction Market of the PRC

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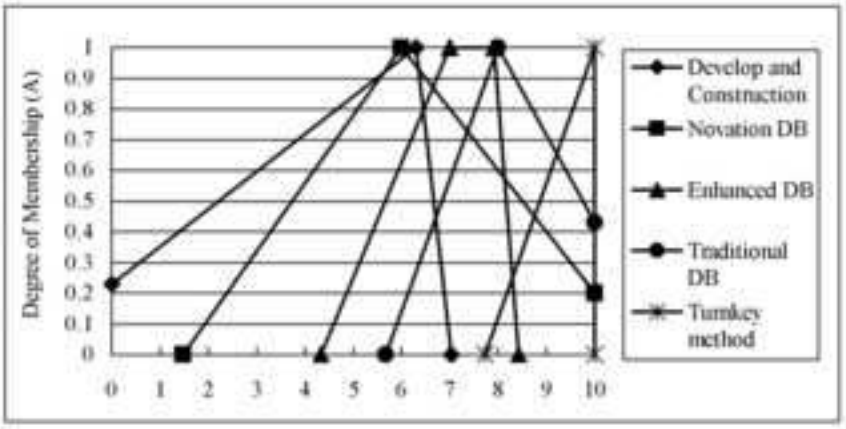

Fig 6 Fuzzy Membership Functions of DB Operational Variations with Respect to Reduced Responsibilities in the Construction Market of the PRC

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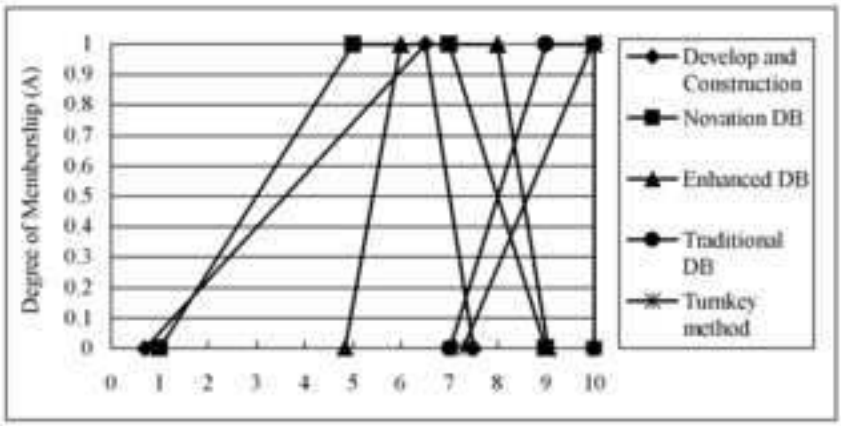

Fig 7 Fuzzy Membership Functions for DB Operational Variations with Respect to Clear Definition in the Construction Market of the PRC