Fuzzy Approach to Prequalifying Construction Contractors

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Abstract: Construction contractor prequalification (CCPQ) is a crucial decision making process to select capable potential bidders and ensure the success of construction projects. The purpose of CCPQ is to guarantee a contractor's characteristic to meet the construction project's requirements, which has been established worldwide as a standard practice. However, existing methods, i.e., marking method, subjective judgment method, etc., for contractor prequalification have been inadequate because it is difficult for decision makers to investigate contractor's capabilities against inexact, vagueness, and qualitative criteria. The objective of this paper is to propose a fuzzy framework-based fuzzy number theory to solve construction contractor prequalification issues, which include decision criteria analysis, weights assessment, and decision model development. Finally, a case study for a tunnel construction project was used to demonstrate the feasibility of fuzzy approaches.

DOI: 10.1061/(ASCE)0733-9364(2007)133:1(40)

CE Database subject headings: Fuzzy sets; Construction management; Contractors; Decision making.

Introduction

Contractor selection is a complex process crucial to ensuring the success of construction projects; it is one of the major challenges that owners face in selecting the best contractor. In practice, a contractor selection problem can be divided into two stages: First, a large number of potential contractors are invited and investigated based on a set of predetermined criteria and then a short list of contractors is drawn by the project owner (clients), i.e., prequalification stage. Second, an appropriate contractor is selected from the short list to execute the construction project (contractor selection stage), i.e., bid evaluation stage. Construction contractor prequalification (CCPQ) is a crucial decision making process to select capable potential bidders and ensure the success of construction projects. Normally, as for the project owner, only if interested contractors meet prequalification are their bids considered. Prequalification is a process of investigating and qualifying contractors as available bidders before the award of the contract, by which incompetent and inexperienced contractors are eliminated from consideration. So the owner consequently has a better chance of selecting the best one. As for the contractors, CCPQ can be taken as external auditing of their capabilities (Bubshait and Al-Gobali 1996). Nowadays, CCPQ has become a standard practice in the construction market worldwide.

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Note. Discussion open until June 1, 2007. Separate discussions must be submitted for individual papers. To extend the closing date by one month, a written request must be filed with the ASCE Managing Editor. The manuscript for this paper was submitted for review and possible publication on November 19, 2004; approved on March 24, 2006. This paper is part of the ***Journal of Construction Engineering and Management***, Vol. 133, No. 1, January 1, 2007. ©ASCE, ISSN 0733-9364/2007/1-40–49/$25.00.

CCPQ can be described as the screening of contractors by owners based on a set of criteria (Sönmez et al. 2002). Several construction contractor prequalification models have been discussed in the existed literatures, most of them are based on subjective judgment or qualitative analysis (Russell and Skibniewski 1988, 1990). Sönmez et al. (2002) adopted evidential reasoning theory to prequalify construction contractors, which is based on Dempster and shafter theory (Thierry and Lalla 2001) and the degree of belief was used to elicit decision makers' preferences regarding the prequalification criteria. Hanna and Russell (1997) developed a neural network contractor prequalification model to the solve CCPQ problem, Ng (1996) studied different decision support systems for construction contractor prequalification and developed a case-based reasoning approach to prequalify contractors. The above-mentioned methods have their advantages and disadvantages; they focused on improving various aspects of CCPQ. However, traditional models tend to ignore vagueness, fuzziness, and human behavior inherent in the nature of construction projects. Contractor prequalification, as a multiattributes decision making process, involves much inexact, uncertain, incomplete, or qualitative information that is very difficulty for us to measure, especially, the judgments and preference of decision makers always play an important role in the process. How to deal with this issue in decision making? Fuzzy set theory (Zadeh 1965) provides a useful tool to deal with decisions in which the phenomena are imprecise and vague, it enables us to qualify imprecise information, to reason and make decisions based on vague and incomplete data (Zadeh 1973). This brings hope to incorporate qualitative factors into decision making. Lin and Chen (2004) developed a fuzzy linguistic approach to bid/no-bid decision making, in this approach assessments are described subjectively in linguistic terms, whereas screening criteria are weighted by their relative importance using fuzzy value. Singh and Tiong (2005) propose a fuzzy decision framework for contractor selection where the notion of the Shapely value is used to determine relative importance of each attribute, and linguistic variables based on fuzzy numbers theory is constructed for decision makers to evaluate the contractor's attributes; Li et al. (2005) propose a multiple-layer fuzzy pattern recognition (MFPR) approach to solve construction contractor selection. Integrating judgments, experience, and preferences of decision makers, MFPR uses the paired comparison method (Chen 1994, 1996a) to decide relative membership degrees of qualitative criteria as well as weights of the criteria set. Although much research has been dedicated to improve decision making methodology from the viewpoint of fuzzy concepts, further improvements in CCPQ are still being sought.

Contractor prequalification, in the final analysis, is a typical multiple attribute decision-making process involving fuzzy characteristics and uncertainties. So it needs not only the decision maker having sophisticated engineering, management knowledge, and experience but also an appropriate and efficient decision-making methodology. Based on fuzzy number theory and decision-making analysis for multiobjective systems, this paper proposes a reasonable fuzzy framework to solve construction contractor prequalification issues which include decision criteria analysis, weights assessment, and decision model development. Wherein, relative importance of criteria and evaluation of criteria assigned by decision makers are expressed in linguistic variables based on fuzzy number theory, then a fuzzy arithmetical operation is employed to aggregate the fuzzy numbers into the final decisions, it can aid decision makers in the prequalification process.

Following this instruction, decision criteria structure for construction contractor prequalification is given. Next, fuzzy framework, based on fuzzy number, is established to deal with construction contractor prequalification issues, where four approaches to rank alternatives, i.e., fuzzy number recognition (FNR) method, fuzzy TOPSIS (FT) method, fuzzy number weight center (FNWC) method, and simple defuzzification method are developed. Then, the method for criteria evaluation and weight assessment is presented. After that, construction contractor prequalification for a tunnel construction project in Sinkiang autonomous region (China) is given as a case study. Finally, the conclusions are presented.

Construction Contractor Prequalification Criteria

In general, a two stage contractor selection process (see Fig. 1) includes a prequalification (short listing) stage, as well as a bid evaluation stage. Regarding the prequalification stage, it is normally project specific, and its focus is to identify competent contractors who are interested in submitting bids, after this stage, the prequalified is limited to a short list and the preferred range is between 3 and 5. Before prequalification decision making, decision criteria framework must be established, in practice, these criteria include technical capacity, financial status, past experience, management resource, etc. In this paper, we apply the similar decision criteria set [see Fig. 2 (adapted from Holt et al. 1994)] to that advocated by Holt et al. (1994), they developed a method to evaluate contractor prequalification criteria and give guidelines for practitioners and identified criteria and their weights that are considered in prequalification practice in the literature, for simplicity, the criteria structure is used in this paper for decision making analysis. Generally, the prequalification process involves performing qualification in two steps. Prior to the prequalification decision making process, project-specific benchmarks, such as similar project experience, contractor classification certification, contractor's maximum capability is less than the project or not, etc., for the contractor should be used to filter an incompetent contractor. A contractor will be excluded if he does not meet at least one of the benchmarks. Only a contractor passes the benchmark filtration, can he be evaluated by the next prequalification stage (prequalification decision making process).

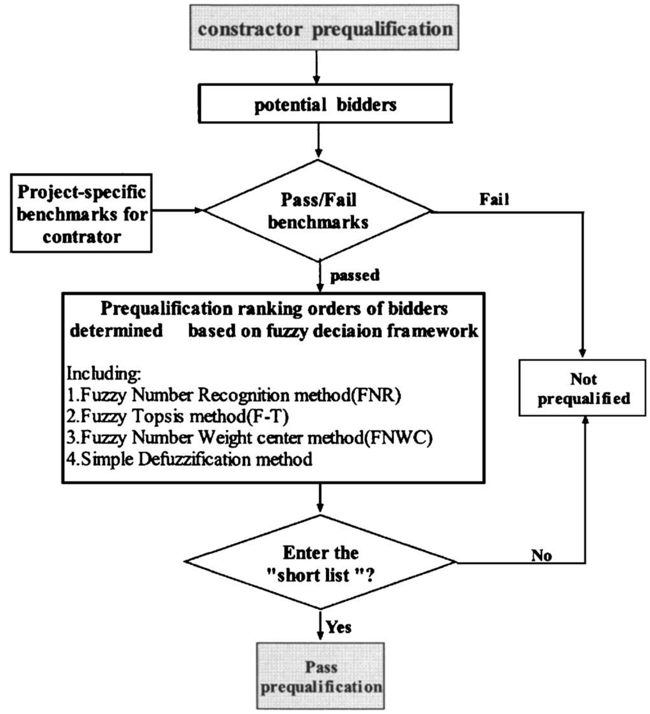

Fig. 1. Structure of contractor prequalification

Fuzzy Approach to Prequalification

Building Linguistic Variable Set

There are several evaluation tools and methods discussed in literature, but most of them are quantitative approaches, they require certain and accurate assessment from the decision maker, this is not the practice under the real world decision making environment, because the majority of the decision making problems are make under uncertainties, vagueness, fuzziness, risk, time pressure, and in the presence of some information that is incomplete or missing (Sönmez et al. 2002). Generally speaking, in the real world prequalification, decision making problems are always ill defined, where objectives and related information are not precise. A decision maker is asked to assess the "quality control policy" of a contractor compared to the others, it is difficult for a decision maker to give an exact numerical value to express his opinion, and the decision maker may feel comfortable to describe it in the fuzzy term of "good," "poor," or "fair," etc. Regarding the criteria weight assessment, a decision maker's opinion will be "very important," "moderate," etc.; these fuzzy terms can be expressed in triangular fuzzy numbers (Cheng and Lin 2002). The fuzziness in the CCPQ issue motivates us to use linguistic variable (fuzzy term) to express decision makers' opinion and develop a fuzzy framework to deal with construction contractor prequalification problem, where the importance weights of various criteria and the ratings of qualitative criteria are considered as linguistic variables in this paper.

First of all, an appropriate standard linguistic variable set should be built to help decision makers to assess the criteria rating and their weights, it includes the following two parts:

1. The membership function of linguistic variables for criteria

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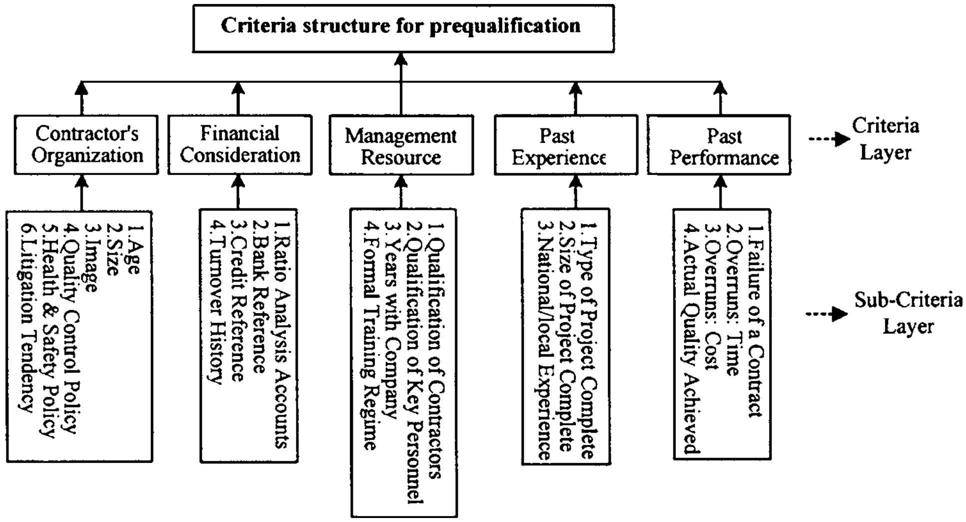

Fig. 2. Criteria structure for prequalification (adapted from Holt et al. 1994)

rating on the fuzzy concept "excellence" (*linguistic scale for criteria ratings*); and

2. Linguistic variables for criteria weight assessment by decision makers (*linguistic scale for criteria weight assessment*).

Definition 1: Let X be a nonempty set. A fuzzy set $\widetilde{A}$ in X is characterized by its membership function (Zadeh 1965)

$$\mu_{\widetilde{A}}: X \rightarrow [0,\ 1]$$

$\mu_{\widetilde{A}}(x)$ is interpreted as the degree of membership of element x in fuzzy set $\widetilde{\mathbf{A}}$ for each $x \in X$.

Definition 2: Let $\widetilde{A}$ be a fuzzy subset of X; the support of $\widetilde{A}$, denoted as $\text{supp}(\widetilde{A})$, is the crisp subset of X whose elements all have nonzero membership degrees in $\widetilde{A}$ (Zadeh 1965)

$$\text{supp}(\widetilde{A}) = \{x \in X | \widetilde{A}(x) > 0\}$$

Definition 3: (Normal fuzzy set) A fuzzy subset $\widetilde{A}$ of a classical set X is called normal (Kaufmann and Gupta 1988; Klir and Yan 1995), if there exists a $x \in X$ such that $\widetilde{A}(x)=1$, otherwise $\widetilde{A}$ is subnormal.

Definition 4: An α-level set of a fuzzy set $\widetilde{A}$ of X is a nonfuzzy set denoted by $\widetilde{A}^{\alpha}$ (see Fig. 3) and is defined by (Mabuchi 1988)

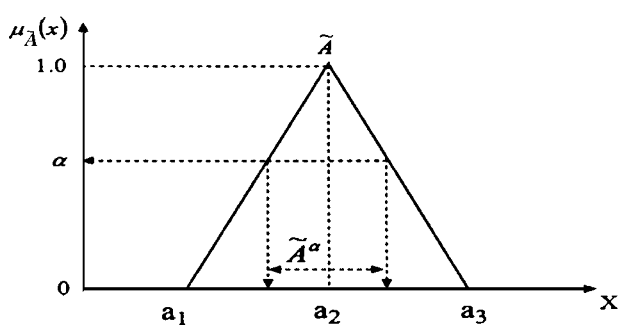

Fig. 3. Illustration of a triangular fuzzy number $\widetilde{A}$

$$\widetilde{A}^{\alpha} = \begin{cases} \{t \in X | \widetilde{A}(t) \geqslant \alpha\} & \text{if } \alpha > 0 \\ \text{cl}(\text{supp}\ \widetilde{A}) & \text{if } \alpha = 0 \end{cases}$$

where $\text{cl}(\text{supp}\widetilde{A})$ denotes the closure of the support of A.

Definition 5: A fuzzy number is a fuzzy set $\widetilde{A}$ on R which has the following properties (Cheng and Lin 2002):

- $\widetilde{\mathbf{A}}$ is a normal fuzzy set;
- The $\alpha-cut$ $\widetilde{A}^{\alpha}$ is a closed interval for every $\alpha \in [0,1]$; and
- The support of $\widetilde{A}$ is bounded.

It should be noted that triangular fuzzy numbers are used mostly in practice and a crisp real value is a special case of fuzzy number.

Definition 6: A fuzzy number $\widetilde{A}$ is convex (Kaufmann and Gupta 1988; Zimmermann 1991; Cheng and Lin 2002), if

$$\mu_{\widetilde{A}}(\lambda x_1 + (1-\lambda)x_2) \geqslant \min(\mu_{\widetilde{A}}(x_1),\ \mu_{\widetilde{A}}(x_2)), \quad x_1, x_2 \in X$$

where $\mu_{\widetilde{A}}(x_1)$=membership degree of x_1 belonging to fuzzy set $\widetilde{A}$ and λ=real number, $\lambda \in [0,1]$.

Definition 7: A triangular fuzzy number can be defined as a triplet (a_1, a_2, a_3). Its membership function (Chen 1998; Cheng and Lin 2002) is as follows (see Fig. 3)

$$\mu_{\widetilde{A}} = \begin{cases} 0, & x < a_1 \\ (x-a_1)/(a_2-a_1), & a_1 \leqslant x \leqslant a_2 \\ (a_3-x)/(a_3-a_2), & a_2 \leqslant x \leqslant a_3 \\ 0, & x > a_3 \end{cases} \tag{1}$$

Let $\widetilde{A}$ and $\widetilde{B}$ be two fuzzy numbers parameterized by the triplet (a_1, a_2, a_3) and (b_1, b_2, b_3), respectively. Then the operations of triangular fuzzy number can be expressed as (Chen and Hwang 1992; Cheng and Lin 2002)

$$\widetilde{A}(+)\widetilde{B} = (a_1,a_2,a_3)(+)(b_1,b_2,b_3) = (a_1+b_1, a_2+b_2, a_3+b_3)$$

$$\widetilde{A}(-)\widetilde{B} = (a_1,a_2,a_3)(-)(b_1,b_2,b_3) = (a_1-b_3, a_2-b_2, a_3-b_1)$$

$$\widetilde{A}(\times)\widetilde{B} = (a_1,a_2,a_3)(\times)(b_1,b_2,b_3) = (a_1b_1, a_2b_2, a_3b_3)$$

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Table 1. Linguistic Scale for Criteria Weight Assessment

Linguistic set	Fuzzy ratings	Modal operator
Very low (VL)	(0, 0, 0.1)	Incomparable
Low (L)	(0, 0.15, 0.3)	Extreme
Moderate low (ML)	(0.1, 0.3, 0.5)	Extra
Moderate (M)	(0.3, 0.5, 0.7)	Remarkable
Moderate high (MH)	(0.5, 0.7, 0.9)	Rather
High (H)	(0.7, 0.85, 1.0)	Slight
Very high (VH)	(0.9, 1.0, 1.0)	Same

Table 2. Linguistic Scale for Criteria Ratings

Linguistic set	Fuzzy weight	Modal operator
Very poor (VP)	(0, 0, 0.2)	Incomparable
Poor (P)	(0.1, 0.25, 0.4)	Exceeding
Fair (F)	(0.3, 0.5, 0.7)	Remarkable
Good (G)	(0.6, 0.75, 0.9)	Somewhat
Very good (VG)	(0.8, 1.0, 1.0)	Same

$$\widetilde{A}(/)\widetilde{B}=(a_1,a_2,a_3)(/)(b_1,b_2,b_3)=(a_1/b_3,a_2/b_2,a_3/b_1)$$

$$\widetilde{A}^r=(a_1^r,a_2^r,a_3^r)$$

where $r \in R$.

Definition 8: As for fuzzy triangular numbers $\widetilde{A}$ (a_1,a_2,a_3) and $\widetilde{B}$ (b_1,b_2,b_3), the distance between them can be calculated as (Heilpern 1997)

$$d_g(\widetilde{A},\widetilde{B})=\begin{cases}\left(\dfrac{1}{3}\displaystyle\sum_{i=1}^{3}|a_i-b_i|^p\right)^{1/p}, & 1\leqslant p<\infty\\ \max\limits_i(|a_i-b_i|), & p=\infty\end{cases} \tag{2}$$

In general, real number a can be considered as the special case of triangular fuzzy numbers $\widetilde{A}$ (a,a,a). Eq. (2) meets the concept of the classical geometrical distance for any $p(1\leqslant p<\infty)$, when $p=2$; it is similar to Euclidean distance measurement and it is most commonly used, reasonable, and practicable for practitioners. Further, it is easy to see that the distance measure satisfies the properties $d_g(\widetilde{A},\widetilde{B})=d_g(\widetilde{B},\widetilde{A})$ and $d_g(\widetilde{C},\widetilde{C})=0$.

We use seven linguistic variables to express decision maker's opinion on the importance degree of criteria, i.e., "very low (VL)," "low (L)," "moderate low (ML)," "moderate (M)," "moderate high (MH)," "high (H)," and "very high (VH)" corresponding to seven fuzzy level scales (see Table 1, Fig. 4).

Further, five linguistic variables are constructed to measure the performance of each contractor regarding certain criteria (see Table 2 and Fig. 5).

Fuzzy Decision Making Models Development

A linguistic variable set has been built in the previous section. In this section, a fuzzy approach to CCPQ, by using the concepts of fuzzy number theory and multiple-criteria decision analysis, is presented. This method is very suitable for making decisions under a fuzzy environment.

Assuming that a set of construction contractors who were invited to present prequalification material are

$$D=(d_1,d_2,d_3,\ldots,d_n) \tag{3}$$

where d_j=jth contractor, $j=1,2,\ldots,n$. Each bidder can be valued by m prequalification related criteria, and then factor set is

$$O=(o_1,o_2,o_3,\ldots,o_m) \tag{4}$$

where o_i=ith criteria, $i=1,2,3,\ldots,m$.

According to Tables 1 and 2, the importance of the criteria and the rating of alternatives with respect to each criterion are assessed by decision makers, and the rating of the criteria and its weight can be denoted as $\tilde{\mathbf{r}}_{ij}$ (fuzzy number) and $\tilde{\mathbf{w}}_i$ (fuzzy number). Therefore, the fuzzy evaluation value of each contractor can be calculated (Chen 2001) as

$$\mathrm{FLD}_j^*=\sum_{i=1}^{m}(\widetilde{w}_i\otimes\widetilde{r}_{ij})$$

where $\widetilde{w}_i$=weight of criteria i and $\widetilde{r}_{ij}$=fuzzy linguistic assessment of contractor j regarding criteria i.

Then FLD_j^* can be expressed as $\mathrm{FLD}_j^*=(a_1^j,a_2^j,a_3^j)$. In order to preserve the property that the range of fuzzy number FLD_j^* belong to [0, 1], normalization should be used here, the formula is as follows, it is a final fuzzy evaluation value of each contractor (FLD_j):

$$\mathrm{FLD}_j=\left(\frac{a_1^j}{a_3^*},\frac{a_2^j}{a_3^*},\frac{a_3^j}{a_3^*}\right)=\frac{\mathrm{FLD}_j^*}{a_3^*} \tag{5}$$

where $a_3^*=\max_j a_3^j$ is the maximum value of a_3^j among all ratings of contractors.

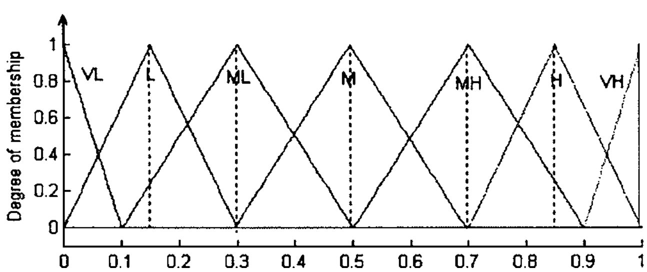

Fig. 4. Membership function of linguistic variables for criteria comparison on fuzzy concept "importance"

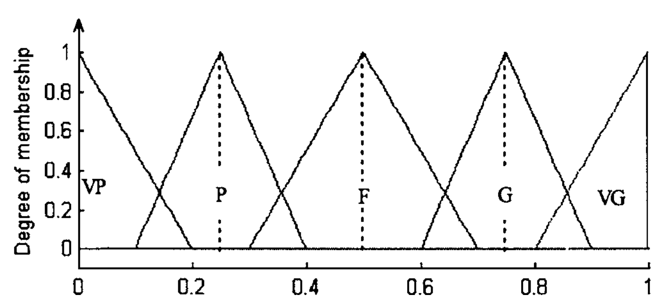

Fig. 5. Membership function of linguistic variables for criteria rating on fuzzy concept "excellence"

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Determination of Fuzzy Weight and Contractor Rating

The weight of each criterion can be obtained by either direct assignment or indirectly using pair-wise comparisons (Hsu and Chen 1994). Here, it is suggested that the decision maker easily uses a complementary paired comparison method (Chen 1994) to evaluate the importance of the criteria and the ratings of alternatives with respect to various subjective criteria.

Among the criteria set in contractor prequalification, they are all qualitative, such as the bidder's contractor's organization, financial consideration, management resource, etc. Chen (1994) developed a complementary paired comparison method to decide subjective weights of criteria, where linguistic variables, fuzzy rating, fuzzy weight, as well as modal operators, are constructed in Tables 1 and 2.

Assuming that o_i ($o_i \in O$) is a qualitative factor, bidder k (d_k) is compared with bidder l (d_l)($d_l, d_k \in D$) regarding factor o_i on the fuzzy characteristic of excellence, the scales can be denoted as

1. When d_k is better than d_l, $e_{kl}=1$, $e_{lk}=0$;
2. When d_k is as same as d_l, $e_{kl}=e_{lk}=0.5$; and
3. When d_k is worse than d_l, $e_{kl}=0$, $e_{lk}=1$.

So, the sorting scale matrix of the bidder set regarding qualitative factor o_i on fuzzy characteristic excellence can be denoted as

$$
{}_iE = \begin{pmatrix} {}_ie_{11} & {}_ie_{12} & \cdots & {}_ie_{1n} \\ {}_ie_{21} & {}_ie_{22} & \cdots & {}_ie_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ {}_ie_{n1} & {}_ie_{n1} & \cdots & {}_ie_{n\times n} \end{pmatrix} = ({}_ie_{kl})_{n\times n}
$$

$$
\text{subject to} \begin{cases} e_{kl} \in \{0, 0, 5, 1\} \\ e_{kl} + e_{lk} = 1 \\ e_{kk} = e_{ll} = 0.5 \end{cases}
$$

where $l, k = 1, 2, \ldots, n$.

The necessary and sufficient conditions for sorting consistency scale matrix ${}_iE$ are as follows (Chen 1998):

1. If $e_{pk} > e_{pl}$ then $e_{kl}=0$;
2. If $e_{pk} < e_{pl}$ then $e_{kl}=1$; and
3. If $e_{pk}=e_{pl}=0.5$ then $e_{lk}=e_{kl}=0.5$,

where $p=1, 2, \ldots, n$.

Approaches to Ranking Contractors

According to Eq. (5), the fuzzy rating (FLD_j) of contractor j has been obtained, it is also denoted as a fuzzy number, so we must rank these fuzzy numbers, i.e., $\text{FLD}_1, \text{FLD}_2, \ldots, \text{FLD}_n$, to achieve the ranking order of contractors. Several methods for ranking fuzzy numbers have been proposed (Sengupta 1998; Gonzalez 1990; Yager 1981), in this paper, we provide four approaches, i.e., weight center, fuzzy number recognition, fuzzy TOPSIS, and simple defuzzification methods; they are detailed presented as follows.

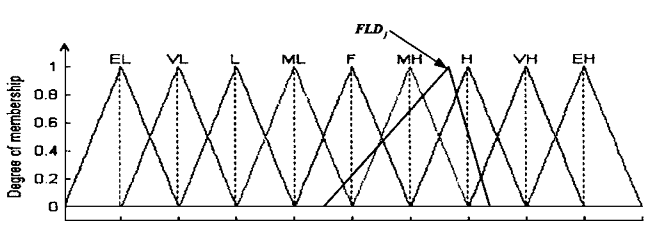

Fig. 6. Illustration of fuzzy number ranking recognition methodology

Table 3. Standard Linguistic Scale for Matching Fuzzy Rating

Extremely low (EL)	(0, 0.1, 0.2)
Very low (VL)	(0.1, 0.2, 0.3)
Low (L)	(0.2, 0.3, 0.4)
Moderate low (ML)	(0.3, 0.4, 0.5)
Fair (F)	(0.4, 0.5, 0.6)
Moderate high (MH)	(0.5, 0.6, 0.7)
High (H)	(0.6, 0.7, 0.8)
Very high (VH)	(0.7, 0.8, 0.9)
Extremely high (EH)	(0.8, 0.9, 1.0)

Approach A: Fuzzy Number Recognition Method

Once final fuzzy assessment of contractors (FLD_j) has been obtained according to Eq. (5) by decision makers, one can further approximate a linguistic label whose meaning is the same as the meaning of FLD_j from the nature language expression set of the fuzzy assessment level (see Fig. 6, i.e., EL, VL, L, …, EL), several methods for matching a membership function (FLD_j, fuzzy triangular number) with linguistic terms has been developed (Schmucker 1985; Lin and Chen 2004), The Euclidean distance is the most intuitive form of human perception of proximity and the most commonly used method (Kaufmann and Gupta 1991; Chaudhuri and Rosenfeld 1996; Groenen and Jajuga 2001), so we use a Euclidean distance to recognize the fuzzy number (FLD_j) against the standard linguistic variables set (see Fig. 6 and Table 3) for an alternative rating on the fuzzy concept excellence. A contractor (fuzzy number FLD_j) belongs to a fuzzy level (i.e., VL, ML, etc.) if the distance between the contractor and the fuzzy level is shortest among all the levels. The explanation is detailed in Fig. 6.

Suppose the nature language expression set $\text{NLES}=(\text{EL}, \text{VL}, \text{L}, \text{MLF}, \text{MH}, \text{H}, \text{VH}, \text{EH})$ (fuzzy numbers, see Table 3), then the distance between fuzzy number FLD_j and NLES_k (k=number of elements in NLES, $k=1, 2\ldots, 9$) can be calculated as $d_g(\text{FLD}_j, \text{NLES}_k)$ according to Eq. (2), then the closest nature expression with a minimum distance can be identified.

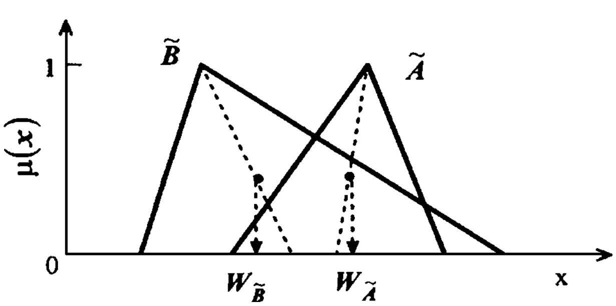

Fig. 7. Comparison of two triplet fuzzy number

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Approach B: Weight Center Method

As for two fuzzy numbers, $\tilde{A}$ and $\tilde{B}$, their weight center ($W_{\tilde{A}}$ and $W_{\tilde{B}}$, see Fig. 7) can be defined as

$$W_{\tilde{A}} = \frac{\int_X \mu_{\tilde{A}}(x)xdx}{\int_X \mu_{\tilde{A}}(x)dx}, \quad W_{\tilde{B}} = \frac{\int_X \mu_{\tilde{B}}(x)xdx}{\int_X \mu_{\tilde{B}}(x)dx}$$

Especially, regarding the fuzzy triangular number, the weight center can be simply calculated as

$$W_{\tilde{A}} = \frac{\int_X \mu_{\tilde{A}}(x)xdx}{\int_X \mu_{\tilde{A}}(x)dx} = \frac{a_1 + a_2 + a_3}{3} \tag{6}$$

$$W_{\tilde{B}} = \frac{\int_X \mu_{\tilde{B}}(x)xdx}{\int_X \mu_{\tilde{B}}(x)dx} = \frac{b_1 + b_2 + b_3}{3} \tag{7}$$

We calculate the equation $\mathrm{Comp}(\tilde{A},\tilde{B}) = W_{\tilde{A}} - W_{\tilde{B}}$.

If $\mathrm{Comp}(\tilde{A},\tilde{B}) > 0$, then $\tilde{A}$ is superior to $\tilde{B}$;

If $\mathrm{Comp}(\tilde{A},\tilde{B}) < 0$, then $\tilde{B}$ is superior to $\tilde{A}$; and

If $\mathrm{Comp}(\tilde{A},\tilde{B}) = 0$, then the ranking orders of $\tilde{A}$ and $\tilde{B}$ are equal.

Based on the weight center of FLD_j, we can obtain the ranking order of the contractors. This approach is easily operated and suitable for practitioners.

Approach C: Fuzzy TOPSIS Method

Besides the weight center method and FNR methods mentioned previously, we propose to use the FT method (Tsao 2003) that combines TOPSIS decision-making and fuzzy number theory, TOPSIS is a "crisp" multicriteria decision-making methodology based on the assumption that the best alternative should be as close as possible to the ideal solution and the farthest from the negative-ideal solution (Triantaphyllou and Lin 1996). Here, it is developed into a fuzzy TOPSIS decision-making method based on fuzzy number theory.

Assume that the final evaluation of contractor j (FLD_j) is expressed as a fuzzy triangular number ${}^j\tilde{A}:({}^ja_1, {}^ja_2, {}^ja_3)$, where $j = 1, 2, \ldots, n$, the ideal solution (fuzzy number) can be defined as

$$\begin{aligned} {}^G\tilde{A} = [&\mathrm{Max}({}^1a_1, {}^2a_1, \ldots, {}^na_1), \mathrm{Max}({}^1a_2, {}^2a_2, \ldots, {}^na_2),\\ &\mathrm{Max}({}^1a_3, {}^2a_3, \ldots, {}^na_3)] \end{aligned} \tag{8}$$

The negative-ideal solution (fuzzy number) is

$$\begin{aligned} {}^B\tilde{A} = [&\mathrm{Min}({}^1a_1, {}^2a_1, \ldots, {}^na_1), \mathrm{Min}({}^1a_2, {}^2a_2, \ldots, {}^na_2),\\ &\mathrm{Min}({}^1a_3, {}^2a_3, \ldots, {}^na_3)] \end{aligned} \tag{9}$$

The final ranking of alternatives is obtained by referring to the value of the relative closeness to the ideal solution, defined as follows:

$$\mathrm{FT}_j = \frac{D_j^+}{D_j^- + D_j^+} \tag{10}$$

where $D_j^+ = d({}^j\tilde{A}, {}^G\tilde{A})$ and $D_j^- = d({}^j\tilde{A}, {}^B\tilde{A})$ = Euclidean distances between contractor j (FLD_j) and the ideal solution and negative-ideal solution, respectively. According to Eq. (10) the best alternative is the one that has the shortest distance to the ideal solution. If an alternative has the minimum value of FT_j, it is assured to be the best among all contractors.

For simplification, the ideal solution and negative-ideal solution (fuzzy number) can also be defined as

$${}^G\tilde{A} = [1,1,1], \quad {}^B\tilde{A} = [0,0,0]$$

According to FT_j, the ranking orders of contractors (fuzzy number FLD_j) can be obtained.

Approach D: Simple Defuzzification Method

Defuzzification is an operation that produces a nonfuzzy or crisp value that adequately represents the degree of satisfaction of the aggregated fuzzy number, It is such an inverse transformation that maps the output from the fuzzy domain back into the crisp domain. After fuzzy judgment we have a linguistic output variable which needs to be translated into a crisp value. The objective is to derive a single crisp numeric value that best represents the fuzzy values of the linguistic output variable. The defuzzification formula of a triangular fuzzy number can be expressed as follows (Kaufmann and Gupta 1991; Cheng and Lin 2002; Singh and Tiong 2005):

$$e = (a_1 + 2a_2 + a_3)/4 \tag{11}$$

where e = defuzzification (crisp value) of triangular fuzzy number (a_1, a_2, a_3), based on Eq. (11) we can rank the fuzzy triangular numbers FLD_j, thereby, ranking orders of contractors can be obtained.

Case Study

A tunnel construction project in the Sinkiang autonomous region, China, is taken as an example to illustrate the fuzzy prequalifying construction contractors methodology. This is a project with a large monetary value, the investment is near \$100 million, after benchmarks filtration (contractor classification certification, similar project experience), five contractors anonymously named *A*, *B*, *C*, *D*, and *E*, had been subjected to a detailed prequalification by investigating their financial stability and status, credit rating, past performance, safety record, etc. (prequalification criteria are detailed in Fig. 2). The prequalification committee assessed the weight of criteria and the performance of the contractors regarding criteria set, and their judgments are listed in Table 4.

We propose to use four fuzzy approaches, i.e., the FNR method, the FT method, FNWC method, and the simple defuzzification method to determine five contractors' ranking orders.

First of all, we should determine the relative importance of the criteria. Regarding the main criteria, we use a complementary paired comparison method (Chen 1994) to obtain the fuzzy weights of the main criteria set (i.e., contractor's organization o_1, financial consideration o_2, management resource o_3, past experience o_4, and past performance o_5). Five main criteria are compared with each other on the fuzzy characteristic of excellence, the sorting consistency scale matrix is obtained as follows:

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Table 4. Criteria Weights and the Performance of the Contractors Regarding Criteria Assessed by Prequalification Committee

			Contractor				
Criteria	Subcriteria	Weight	A	B	C	D	E
Contractor's organization	Age	(0.3, 0.5, 0.7)	(0.8, 1.0, 1.0)	(0.6, 0.75, 0.9)	(0.3, 0.5, 0.7)	(0.1, 0.25, 0.4)	(0.3, 0.5, 0.7)
(0.3, 0.5, 0.7)	Size	(0.5, 0.7, 0.9)	(0, 0, 0.2)	(0.3, 0.5, 0.7)	(0.1, 0.25, 0.4)	(0.6, 0.75, 0.9)	(0.8, 1.0, 1.0)
	Image	(0.7, 0.85, 1)	(0.3, 0.5, 0.7)	(0.6, 0.75, 0.9)	(0.3, 0.5, 0.7)	(0.8, 1.0, 1.0)	(0.1, 0.25, 0.4)
	Quality control policy	(0.9, 1, 1)	(0.3, 0.5, 0.7)	(0.3, 0.5, 0.7)	(0.8, 1.0, 1.0)	(0.8, 1.0, 1.0)	(0.3, 0.5, 0.7)
	Health and safety policy	(0.7, 0.85, 1)	(0.8, 1.0, 1.0)	(0.1, 0.25, 0.4)	(0.6, 0.75, 0.9)	(0, 0, 0.2)	(0.6, 0.75, 0.9)
	Litigation tendency	(0.5, 0.7, 0.9)	(0.6, 0.75, 0.9)	(0, 0, 0.2)	(0.3, 0.5, 0.7)	(0.8, 1.0, 1.0)	(0.3, 0.5, 0.7)
Financial consideration	Ratio analysis accounts	(0.5, 0.7, 0.9)	(0.3, 0.5, 0.7)	(0.6, 0.75, 0.9)	(0, 0, 0.2)	(0.3, 0.5, 0.7)	(0.8, 1.0, 1.0)
(0.9, 1, 1)	Bank reference	(0.9, 1, 1)	(0.6, 0.75, 0.9)	(0.8, 1.0, 1.0)	(0.6, 0.75, 0.9)	(0.6, 0.75, 0.9)	(0.6, 0.75, 0.9)
	Credit reference	(0.9, 1, 1)	(0.6, 0.75, 0.9)	(0.8, 1.0, 1.0)	(0.3, 0.5, 0.7)	(0, 0, 0.2)	(0.3, 0.5, 0.7)
	Turnover history	(0.7, 0.85, 1)	(0.3, 0.5, 0.7)	(0.6, 0.75, 0.9)	(0.3, 0.5, 0.7)	(0.8, 1.0, 1.0)	(0.3, 0.5, 0.7)
Management resource	Qualification of contractors	(0.7, 0.85, 1)	(0.8, 1.0, 1.0)	(0.6, 0.75, 0.9)	(0.8, 1.0, 1.0)	(0.3, 0.5, 0.7)	(0.8, 1.0, 1.0)
(0.3, 0.5, 0.7)	Qualification of key personnel	(0.5, 0.7, 0.9)	(0.6, 0.75, 0.9)	(0.3, 0.5, 0.7)	(0.3, 0.5, 0.7)	(0.8, 1.0, 1.0)	(0.6, 0.75, 0.9)
	Years with company	(0.3, 0.5, 0.7)	(0.3, 0.5, 0.7)	(0.3, 0.5, 0.7)	(0.8, 1.0, 1.0)	(0.6, 0.75, 0.9)	(0.3, 0.5, 0.7)
	Formal training regime	(0.9, 1, 1)	(0.1, 0.25, 0.4)	(0.3, 0.5, 0.7)	(0, 0, 0.2)	(0.6, 0.75, 0.9)	(0.8, 1.0, 1.0)
Past experience	Type of project complete	(0.9, 1, 1)	(0.3, 0.5, 0.7)	(0.8, 1.0, 1.0)	(0.3, 0.5, 0.7)	(0.3, 0.5, 0.7)	(0.3, 0.5, 0.7)
(0.7, 0.85, 1)	Size of project complete	(0.7, 0.85, 1)	(0.8, 1.0, 1.0)	(0.6, 0.75, 0.9)	(0.3, 0.5, 0.7)	(0, 0, 0.2)	(0.1, 0.25, 0.4)
	National/local experience	(0.5, 0.7, 0.9)	(0.6, 0.75, 0.9)	(0.3, 0.5, 0.7)	(0.8, 1.0, 1.0)	(0.6, 0.75, 0.9)	(0, 0, 0.2)
Past performance	Failure of a contract	(0.9, 1, 1)	(0.3, 0.5, 0.7)	(0.8, 1.0, 1.0)	(0.6, 0.75, 0.9)	(0.3, 0.5, 0.7)	(0.6, 0.75, 0.9)
(0.5, 0.7, 0.9)	Overruns: Time	(0.5, 0.7, 0.9)	(0, 0, 0.2)	(0.6, 0.75, 0.9)	(0.3, 0.5, 0.7)	(0.3, 0.5, 0.7)	(0.8, 1.0, 1.0)
	Overruns: Cost	(0.5, 0.7, 0.9)	(0.6, 0.75, 0.9)	(0.3, 0.5, 0.7)	(0.6, 0.75, 0.9)	(0.8, 1.0, 1.0)	(0.8, 1.0, 1.0)
	Actual quality achieved	(0.7, 0.85, 1)	(0.3, 0.5, 0.7)	(0.8, 1.0, 1.0)	(0.6, 0.75, 0.9)	(0.3, 0.5, 0.7)	(0.6, 0.75, 0.9)

e_{ij}	o_1	o_2	o_3	o_4	o_5	Row-sum	Ranking
o_1	0.5	0	0.5	0	0	1	4
o_2	1	0.5	1	1	1	4.5	1
o_3	0.5	0	0.5	0	0	1	4
o_4	1	0	1	0.5	1	3.5	2
o_5	1	0	1	0	0.5	2.5	3

In the above-mentioned matrix, financial consideration o_2 with maximum summing scale value on row is ranked 1st on fuzzy concept "importance," so it is taken as a comparison benchmark whose fuzzy weight is set as very high (VH) (0.9, 1.0, 1.0), main criteria o_2 is superior to past experience o_4, and the superiority degree is "slight" (see Table 1 and Fig. 3), so, the fuzzy weight of o_4 is high (H) (0.7, 0.85, 1.0); o_2 is superior to past performance o_5, and the superiority degree is "rather" (see Table 1), then, fuzzy weight of o_5 is moderate high (MH) (0.5, 0.7, 0.9); o_2 is superior to contractor's organization o_1 and management resource o_3 (the ranking order of o_1 and o_3 are the same in the sorting consistency scale matrix previously mentioned), and the superiority degree is "extra." So fuzzy weight of o_1 and o_3 is moderate low (ML) (0.1, 0.3, 0.5), then, fuzzy ratings of contractors regarding subcriteria (quality control policy) can be expressed as

$$(o_1,o_2,o_3,o_4,o_5) = \{(0.3,0.5,0.7),\ (0.9,1,1),\ (0.3,0.5,0.7),\ (0.7,0.85,1),\ (0.5,0.7,0.9)\}$$

Similarly, the fuzzy weights of subcriteria criteria can be obtained that is listed in Table 4.

As for the determination of the fuzzy rating of contractors, five bidders are compared with each other with respect to subcriteria (quality control policy) on the fuzzy characteristic of excellence based on the complementary paired comparison method (Chen 1994), the sorting consistency scale matrix is obtained as follows:

e_{ij}	A	B	C	D	E	Row-sum	Ranking
A	0.5	0.5	0	0	0.5	1.5	2
B	0.5	0.5	0	0	0.5	1.5	2
C	1	1	0.5	0.5	1	4	1
D	1	1	0.5	0.5	1	4	1
E	0.5	0.5	0	0	0.5	1.5	2

Contractors C and D with maximum summing scale value on row is ranked first on the fuzzy concept of excellence, so C or D is a comparison standard. We set the fuzzy ratings of Contractors C and D as very good (VG) (0.8, 1.0, 1.0). As for subcriteria quality control policy, Contractor C or D is superior to contractors A, B, and E (the ranking order of Contractors A, B, and E are the same in the sorting consistency scale matrix) on the fuzzy concept of excellence, and the superiority degree is Remarkable (see Table 2 and Fig. 4), so, their fuzzy rating is Fair (F) (0.3, 0.5, 0.7), then, the fuzzy ratings of Contractors A, B, C, D, and E regarding subcriteria (quality control policy) can be expressed as

$$\{(0.3,0.5,0.7)(0.3,0.5,0.7)(0.8,1.0,1.0)(0.8,1.0,1.0)(0.3,0.5,0.7)\}$$

Similarly, the fuzzy ratings of contractors regarding the other criteria can be obtained, which are all listed in Table 4.

Approach A: Fuzzy Number Recognition Method

According to Eq. (5), we can obtain the fuzzy evaluation value FLD_j of contractors regarding the first main criteria "contractor's organization" according to Table 4.

As for Contractor A

$$^{1}\mathrm{FLD}_A^* = (0.8\ 1\ 1) \otimes (0.3\ 0.5\ 0.7) \oplus (0\ 0\ 0.2) \otimes (0.5\ 0.7\ 0.9) \oplus (0.3\ 0.5\ 0.7) \otimes (0.7\ 0.85\ 1) \oplus (0.3\ 0.5\ 0.7) \otimes (0.9\ 1\ 1) \oplus (0.8\ 1\ 1) \otimes (0.7\ 0.85\ 1) \oplus (0.6\ 0.75\ 0.9)$$

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$$\otimes (0.5\ 0.7\ 0.9) = (1.58\ 2.8\ 4.09)$$

As for the other four contractors

$$^{1}\mathrm{FLD}_{\mathrm{B}}^{*} = (1.09\ 2.075\ 3.44)$$

$$^{1}\mathrm{FLD}_{\mathrm{C}}^{*} = (1.64\ 2.838\ 4.08)$$

$$^{1}\mathrm{FLD}_{\mathrm{D}}^{*} = (2.01\ 3.2\ 4.19)$$

$$^{1}\mathrm{FLD}_{\mathrm{E}}^{*} = (1.4\ 2.65\ 4.02)$$

According to Eq. (5), a_3^* can be calculated as

$$a_3^* = \max_j a_3^j = \max(4.09, 3.44, 4.08, 4.19, 4.02) = 4.19$$

Then, regarding contractor's organization, the fuzzy ratings of contractors can be calculated based on Eq. (5)

$$^{1}\mathrm{FLD}_{\mathrm{A}} = (1.58\ 2.8\ 4.09)/4.19 = (0.377\ 0.668\ 0.976)$$

$$^{1}\mathrm{FLD}_{\mathrm{B}} = (1.09\ 2.075\ 3.44)/4.19 = (0.260\ 0.495\ 0.821)$$

$$^{1}\mathrm{FLD}_{\mathrm{C}} = (1.64\ 2.838\ 4.08)/4.19 = (0.391\ 0.677\ 0.974)$$

$$^{1}\mathrm{FLD}_{\mathrm{D}} = (2.01\ 3.2\ 4.19)/4.19 = (0.480\ 0.764\ 1)$$

$$^{1}\mathrm{FLD}_{\mathrm{E}} = (1.4\ 2.65\ 4.02)/4.19 = (0.334\ 0.632\ 0.960)$$

Therefore, we can obtain the final fuzzy ratings of contractors regarding over all criteria based on Eq. (5)

$$\mathrm{FLD}_{\mathrm{A}} = (0.244\ 0.534\ 0.920)$$

$$\mathrm{FLD}_{\mathrm{B}} = (0.320\ 0.638\ 1.00)$$

$$\mathrm{FLD}_{\mathrm{C}} = (0.222\ 0.507\ 0.899)$$

$$\mathrm{FLD}_{\mathrm{D}} = (0.217\ 0.493\ 0.874)$$

$$\mathrm{FLD}_{\mathrm{E}} = (0.233\ 0.532\ 0.907)$$

According to Eq. (2), we can calculate the distance between each FLD_j and the standard linguistic scale (see Table 3) where a Euclidean distance measurement is used (i.e., $p=2$), as it is most commonly used and reasonable and practicable for practitioners.

We calculate the distance based on Eq. (2) to determine the levels those contractors belong to. A contractor (final evaluation, fuzzy number) belongs to the level that is closest to the contractor's fuzzy rating (FLD_j) among all levels

$$d_g(\mathrm{FLD}_{\mathrm{A}}, EL) = \left(\tfrac{1}{3}((0.244-0)^2 + (0.534-0.1)^2 + (0.920 - 0.2)^2)\right)^{1/2} = 0.505$$

$$d_g(\mathrm{FLD}_{\mathrm{A}}, VL) = 0.415 \quad d_g(\mathrm{FLD}_{\mathrm{A}}, MH) = 0.198$$

$$d_g(\mathrm{FLD}_{\mathrm{A}}, L) = 0.330 \quad d_g(\mathrm{FLD}_{\mathrm{A}}, H) = 0.237$$

$$d_g(\mathrm{FLD}_{\mathrm{A}}, ML) = 0.256 \quad d_g(\mathrm{FLD}_{\mathrm{A}}, VH) = 0.305$$

$$d_g(\mathrm{FLD}_{\mathrm{A}}, F) = 0.206 \quad d_g(\mathrm{FLD}_{\mathrm{A}}, VH) = 0.387$$

Similarly, the distance between the other contractors and the standard linguistic scale (Table 3) can be obtained and listed in Table 5.

Table 5. The Distances between Contractors and Standard Fuzzy Levels

	Contractor									
Levels	A		B		C		D		E	
(EL)	0.505		0.587		0.484		0.468		0.497	
(VL)	0.415		0.493		0.395		0.378		0.407	
(L)	0.330		0.404		0.312		0.296		0.323	
(ML)	0.256		0.320		0.243		0.228		0.250	
(F)	0.206	Λ	0.249		0.201	F	0.191	F	0.203	Λ
(MH)	0.198	MH	0.203	Λ	0.205		0.202		0.199	MH
(H)	0.237		0.202	H	0.252		0.255		0.241	
(VH)	0.305		0.245		0.324		0.331		0.311	
(EH)	0.387		0.316		0.408		0.417		0.394	

According to Table 5, contractors can be classified into three groups, i.e., (Level H: Contractor B) > (Level MH: Contractor A, Contractor E) > (Level F: Contractor D, Contractor C), here, the greater than symbol > means "superior to." Obviously, Contractor B is superior to the other contractors. Regarding Group 2, the distance between Contractor A and Level H is shorter than that of Contractor E, and the distance between Contractor E and Level F is shorter than that of Contractor A (see Table 5, we use the symbols ∨ and ∧ to denote "close to"), so we believe that Contractor A is superior to Contractor E. But as for Contractors C and D, it is difficult for us to judge which one is better based on Table 5. Therefore, the detailed ranking order can be expressed as: *Contractor B > Contractor A > Contractor E > (Contractors D* and *C)*.

Approach B: Weight Center Method

According to the FLD_j obtained from Eq. (5), we calculate their weight center as follows [see Eqs. (6) and (7)]:

$$W_{\mathrm{A}} = \frac{a_1 + a_2 + a_3}{3} = \frac{0.244 + 0.334 + 0.920}{3} = 0.566$$

$$W_{\mathrm{B}} = \frac{a_1 + a_2 + a_3}{3} = \frac{0.320 + 0.638 + 1}{3} = 0.653$$

$$W_{\mathrm{C}} = \frac{a_1 + a_2 + a_3}{3} = \frac{0.222 + 0.507 + 0.899}{3} = 0.543$$

$$W_{\mathrm{D}} = \frac{a_1 + a_2 + a_3}{3} = \frac{0.217 + 0.493 + 0.874}{3} = 0.528$$

$$W_{\mathrm{E}} = \frac{a_1 + a_2 + a_3}{3} = \frac{0.233 + 0.532 + 0.907}{3} = 0.558$$

So, the over all ranking order is: *Contractor B > Contractor* A > *Contractor E > Contractor C > Contractor D*.

Approach C: Fuzzy TOPSIS Method

We have obtained the final fuzzy evaluation value (FLD_j) of each contractor, then we can construct the ideal solution (fuzzy number) and the negative-ideal solution according to Eqs. (8) and (9).

For simplify, we define the ideal solution and negative-ideal solution as ${}^{G}\tilde{A} = [1,1,1]$ and ${}^{B}\tilde{A} = [0,0,0]$, respectively.

According to Eq. (10), we can obtain the FT_j ($j = 1, 2, 3, 4, 5$).

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$$d_g(\mathrm{FLD_A}, {}^G\widetilde{A})\left(\tfrac{1}{3}((0.244-1)^2+(0.534-1)^2+(0.920-1)^2)\right)^{1/2} = 0.515$$

$$d_g(\mathrm{FLD_A}, {}^B\widetilde{A}) = \left(\tfrac{1}{3}((0.244-0)^2+(0.534-0)^2+(0.920-0)^2)\right)^{1/2} = 0.630$$

$$\mathrm{FT_A} = \frac{d_g(\mathrm{FLD_A}, {}^G\widetilde{A})}{d_g(\mathrm{FLD_A}, {}^G\widetilde{A}) + d_g(\mathrm{FLD_A}, {}^B\widetilde{A})} = \frac{0.515}{0.515+0.630} = 0.450$$

Similarly, we can obtain the other FT_j of contractors: $\mathrm{FT_B}$=0.385, $\mathrm{FT_C}$=0.468, $\mathrm{FT_D}$=0.478, $\mathrm{FT_E}$=0.456. So, the ranking order is: *Contractor B > Contractor A > Contractor E > Contractor C > Contractor D*.

Approach D: Simple Defuzzification Method

Based on Eq. (11), we can obtain the defuzzification of fuzzy ratings of contractors

$$e_A = (a_1 + 2a_2 + a_3)/4 = \frac{0.244 + 2(0.334) + 0.920}{4} = 0.558$$

$$e_B = 0.649, \quad e_C = 0.534, \quad e_D = 0.519, \quad e_E = 0.551$$

The overall ranking order is: *Contractor B > Contractor A > Contractor E > Contractor C > Contractor D*.

Suppose that prequalification committee introduces a cutoff rule for prequalification as follows: only the top three contractors will be considered in the second stage (final contractor selection: Bidder evaluation), therefore, Contractors C and D are to be eliminated from further consideration based on the above-mentioned approach. After that, prequalified bidders are asked to submit two separate proposals, i.e., a technical proposal and a price proposal, which are evaluated by a bidder evaluation committee to choose the best one.

The prequalification decisions (ranking order) obtained from four approaches are similar. From the viewpoints of the writers, FNR is a suitable method to evaluate a contractor, by which we can express our assessment as a nature language, for example, "this contractor is extremely excellent [extremely high (EH)]," however, it is difficult for us to rank the contractors that belong to the same standard fuzzy level, in case study, we cannot identify the ranking order of Contractors C and D. The other three approaches are suitable to rank the contractor and easy to operate.

Fuzzy decision framework in this paper can help the prequalification committee to select qualified contractors to bid for the construction project. In practice, the owners can choose the suitable one to prequalify bidders, from the writers' view point, the FT, FNWC, and simple defuzzification methods are easier to operate than FNR, in application, maybe we will face such a situation where the results of the four approaches are not identical, in order to deal with this problem, we can take the intersection of three approaches as our final decision (short list).

Conclusions

Construction project contractor prequalification is a complex multicriteria decision-making problem involving fuzzy characteristics and uncertainties, and there is a need for prequalification techniques that are capable of taking multiple criteria into consideration. This paper proposes a fuzzy framework to solve construction contractor prequalification problems that takes ful advantage of the experts' knowledge, experiences, and makes the decision maker feel comfortable to give judgment on prequalification issue. The framework includes decision criteria analysis, weights assessment, and ranking orders determination of contractors [including four approaches: FNR, FT, FNWC, and the simple defuzzification methods], it is an efficient and feasible framework for a practitioner.

A case study of a tunnel construction project contractor prequalification in China is presented to illustrate the methodology, which demonstrates the feasibility and practicality of the fuzzy approaches to the contractor prequalification problem.

References

Bubshait, A. A., and Al-Gobali, H. (1996). "Contractor prequalification in Saudi Arabia." *J. Manage. Eng.*, 12(2), 50–54.

Chaudhuri, B. B., and Rosenfeld, A. (1996). "On a metric distance between fuzzy sets." *Pattern Recogn. Lett.*, 17(11), 1157–1160.

Chen, C. T. (1998). "A study of fuzzy group decision-making method." *6th National Conf. on Fuzzy Theory and Its Applications*.

Chen, C.-T. (2001). "A fuzzy approach to select the location of the distribution center." *Fuzzy Sets Syst.*, 118(1), 65–73.

Chen, S. (1994). *Fuzzy system decision-making theory and its application*, University of Technology Press, Dalian, China (in Chinese).

Chen, S. (1996a). "Non-structured decision making analysis and fuzzy optimum seeking theory for multi-objective systems." *Journal of Fuzzy Mathematics*, 4(2), 835–842.

Chen, S. J., and Hwang, C. L. (1992). *Fuzzy multiple attribute decision making: Methods and application*, Springer, New York.

Cheng, C.-H., and Lin, Y. (2002). "Evaluating the best main battle tank using fuzzy decision theory with linguistic criteria evaluation." *Eur. J. Oper. Res.*, 142(1), 174–186.

Gonzalez, A. (1990). "A study of the ranking function approach through mean values." *Fuzzy Sets Syst.*, 35(1), 29–41.

Groenen, P. J. F., and Jajuga, K. (2001). "Fuzzy clustering with squared Minkowski distances." *Fuzzy Sets Syst.*, 120(2), 227–237.

Heilpern, S. (1997). "Representation and application of fuzzy numbers." *Fuzzy Sets Syst.*, 91(2), 259–268.

Holt, G. D., et al. (1994). "Evaluating prequalification criteria in contractor selection." *Build. Environ.*, 29(4), 437–448.

Hsu, H. M., and Chen, C. T. (1994). "Fuzzy hierarchical weight analysis model for multicriteria decision problem." *J. Chinese Inst. Indust. Engs.*., 11(3), 129–136.

Kaufmann, A., and Gupta, M. M. (1988). *Fuzzy mathematical models in engineering and management science*, North-Holland, Amsterdam, The Netherlands.

Kaufmann, A., and Gupta, M. M. (1991). *Introduction to fuzzy arithmetic theory and application*, Van Nostrand Reinhold, New York.

Klir, G. J., and Yan, B. (1995). *Fuzzy sets and fuzzy logic theory and applications*, Prentice-Hall, London.

Li, Y., Chen, S., and Nie, X. (2005). "Fuzzy pattern recognition approach to construction contractor selection." *Fuzzy Optimization and Decision Making*, 6(2), 103–118.

Lin, C.-T., and Chen, Y.-T. (2004). "Bid/no-bid decision making-a fuzzy linguistic approach." *Int. J. Proj. Manage.*, 22(7), 585–593.

Mabuchi, S. (1988). "An approach to the comparison of fuzzy subsets with an a-cut dependent index." *IEEE Trans. Syst. Man Cybern.*, 18(2), 264–272.

Ng, S. T. (1996). "Case-based reasoning decision support for contactor prequalification." Ph.D. thesis, University of Manchester, Manchester, U.K.

Russell, J. S., and Skibniewski, M. J. (1988). "An expert system for contractor prequalification." *Proc., Conf. on Computing in Civil En-*

J. Constr. Eng. Manage., 2007, 133(1): 40-49

gineering, 239–247.

Russell, J. S., and Skibniewski, M. J. (1990). "QUALIFIER-1: Contractor prequalification model." *J. Comput. Civ. Eng.*, 4(1), 77–90.

Schmucker, K. J. (1985). *Fuzzy sets, nature language computation, and risk analysis*, Computer Science Press.

Sengupta, K. (1998). "Fuzzy preference and Orlovsky choice procedure." *Fuzzy Sets Syst.*, 93(2), 231–234.

Singh, D., and Tiong, R. L. K. (2005). "A fuzzy decision framework for contractor selection." *J. Constr. Eng. Manage.*, 131(1), 62–70.

Sönmez, M., Holt, G. D., Yang, J. B., and Graham, G. (2002). "Applying evidential reasoning to prequalifying construction contractors." *J. Manage. Eng.*, 18(3), 111–119.

Triantaphyllou, E., and Lin, C.-T. (1996). "Development and evaluation of five multiattribute decision making methods." *Int. J. Approx. Reason.*, 14(4), 281–310.

Tsao, C.-T. (2003). "Evaluating investment values of commercial bank stocks using a fuzzy TOPSIS approach." *Journal of Information & Optimization Sciences*, 24(2), 373–396.

Yager, R. R. (1981). "A procedure for ordering fuzzy subsets of the unit interval." *Inf. Sci. (N.Y.)*, 24, 141–161.

Zadeh, L. A. (1965). "Fuzzy sets." *Infect. Control*, 8, 338–353.

Zadeh, L. A. (1973). "The concept of a linguistic variable and its application to approximate reasoning." *ERL-M 411*, Berkeley, Calif.

Zimmermann, H. J. (1991). *Fuzzy set theory and its applications*, 2nd ed., Kluwer Academic, Dordrecht, The Netherlands.

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