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Measuring the complexity of mega construction projects in China—A fuzzy analytic network process analysis

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Abstract

Mega construction projects in China are usually very complicated in nature, thus evaluating and understanding these complexities are critical to the success of these megaprojects. However, empirical studies related to the measurement of the complexity of megaprojects remain lacking. This paper aims to fill this gap by developing a complexity measurement model based on the Shanghai Expo construction project in China using fuzzy analytic network process (FANP). Firstly, a complexity measurement model consisting of 28 factors, which are grouped under six categories, namely, technological, organizational, goal, environmental, cultural and information complexities, is formulated through literature review using the content analysis technique. The model is then refined by a two-round Delphi survey conducted in the case megaproject. Finally, the refined model and suggestions for its application are provided based on the survey results. The model is believed to be beneficial for scholars and serve as reference for professionals in managing megaprojects.

Keywords: Mega construction projects; Complexity measurement; Fuzzy analytic network process; Shanghai Expo construction project

1. Introduction

In recent years, rapid urbanization has increased the number of mega construction projects in China, with each megaproject costing over RMB 5 billion or about 700 million USD (Hu et al., 2012; World Bank, 2010). These projects are usually very complicated in nature (Chan et al., 2004; Flyvbjerg et al., 2003). Examples of these projects include the national high-speed rail network, the Shanghai Yangshan deepwater port, and the Beijing Capital International Airport Terminal 3 project. However, understanding the complexity of a specific megaproject in today's complex and dynamic environment is very difficult (Sinha et al., 2006). Because of lacking relevant knowledge, these projects are usually beset with low performance, such as cost overruns and schedule delays (Kennedy et al., 2011; Thomas and Mengel, 2008).

Complexity measurement is therefore a critical issue in managing construction megaprojects. Although practitioners usually use a generic term 'complex' to describe mega projects, but the academics prefer to use complicated more sophisticated term to define the nature characteristics of these projects (Baccarini, 1996; Geraldi et al., 2011; Remington and Pollack, 2007). This study goes along with this idea and used the term 'complex' to describe project environment. Complexity is the state of being involved and intricate as a result of including many varied interrelated parts within a subject (Baccarini, 1996). Therefore, project complexity is defined as complicated characteristics of a project as a result of composing many interconnected parts within a project (Xia and Chan, 2012). Evaluating the complexity of a

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specific project can provide reference for decision makers and managers involved in the project. However, previous studies on project complexity are very limited, with most studies focusing only on the conceptual framework of project complexity (Maylor et al., 2008; Sinha et al., 2006). Moreover, seldom do these studies provide a practical model for assessing the complexity of a construction project quantitatively, particularly the mega construction projects in China. Mihm et al. (2003) stated that project complexity is measured by a function of several interrelated factors. Correspondingly, measuring project complexity should adopt a systematic approach. Therefore, this study aims to develop a systematic model for measuring the complexity of mega construction projects in China using the fuzzy analytic network process (FANP) approach and illustrate the use of this model based on a case study of the Shanghai Expo construction.

The analytic network process (ANP), an extension of analytic hierarchy process (AHP), is a main method used in this study. This method can allow for the analysis of complex systems and determine the complexity of project systems (Saaty, 1996). Difficulties or limitations are expected when measuring the complexity levels of the factors of a construction system. Therefore, measuring qualitative factors by using fuzzy numbers helps in speeding up decision making processes and in obtaining highly realistic results (Chan et al., 2009). Thus, the FANP is appropriate to be used in this study to determine the weights of factors/sub-factors in computing project complexity.

The paper is organized as follows. Section 2 first reviews recent works on complexity measurement in construction projects. Section 3 then introduces the FANP. Section 4 develops a refined measuring model using the FANP, followed by a case study on the 2010 Shanghai Expo construction project in China to examine the practicality of the proposed model and discuss the results in Section 5 and 6, respectively. The final section makes conclusions and suggestions for the application of the proposed model.

2. Measuring the complexity of construction projects

Project complexity is an emerging but critical topic in the construction project management field. Many researchers have increasingly recognized the importance of complexity measurement in project diagnosis, particularly in mega construction projects (Baccarini, 1996; Chryssolouris et al., 1994; Frizelle and Gregory, 2000; Little, 1997; Wiendahl and Scholtissek, 1994). With the recognition that project complexity is difficult to be quantified precisely, many scholars have still carried out a great number of research studies to identify the measurement factors and categorize these factors. For instances, Baccarini (1996) and Williams (1999) defined project complexity in terms of differentiation and interdependency. Tatikonda and Rosenthal (2000) believed that project complexity is closely related to interactions among organizational elements and sub-tasks. Remington and Pollack (2007) divided the influencing factors into four dimensions, namely, experience and ability of organization members, project organizational structure and its exchange and coordination with other key participants, project culture, and project business process. Vidal and Marle (2008) identified influencing factors as project size, project variety, project interdependence, and elements of context. Maylor et al. (2008) identified the elements of project complexity as mission, organization, delivery, stakeholders, and team. Geraldi et al. (2011) summarized the project complexity framework including structural, uncertainty, dynamics, pace and socio-political complexity. Xia and Chan (2012) identified six key measures of project complexity, namely, building structure and function, construction method, the urgency of the project schedule, project size/scale, geological condition, and neighboring environment. In addition, several scholars have summarized the categories of project complexity, such as project complexity model ALOE (Vidal and Marle, 2008), two-stage model (Wood and Ashton, 2010), five-dimensional model (Owens et al., 2012), TOE framework in large engineering projects (Bosch-Rekveldt et al., 2011), and house of project complexity in large infrastructure projects (Lessard et al., 2013). Based on these reviews, a six-category framework of project complexity consisting of technological, organizational, goal, environmental, cultural and information complexities is proposed in this study to measure the complexity of construction megaprojects in China.

(1) Technological complexity
Mega construction projects are usually characterized with high technological complexity, such as building type, overlapping of design and construction works, and dependency on project operation. The trend that has innovative and green technologies increasingly in construction, such as three-dimensional technology, energy conservation technologies, and new construction materials, also increases technical complexities in managing mega construction projects (Harty et al., 2007; Hu et al., 2014). Many scholars have reported various kinds of technological complexity in managing projects, such as diversity of technology in project, dependence of technological processes, interaction between the technology system and the external environment, and risk of highly difficult technology (Baccarini, 1996; Bosch-Rekveldt et al., 2011; Maylor, 2003).

(2) Organizational complexity
The execution of a project is conducted by a project organization, which involves project staff, organizational structure and various teams. Consequently, project complexity is also manifested by organizational complexity. As the most central part of project complexity, organizational complexity had received increasing attention in the past two decades such as members' experience, number of hierarchies, and departments of organizational structure influence project complexity (Baccarini, 1996; Bosch-Rekveldt et al., 2011; Xia and Lee, 2004).

(3) Goal complexity
Goal complexity is usually caused by several factors, such as various project participants' requirements, project task complexity, and limited resources. Williams (1999) stated that goal complexity is a kind of structural complexity, because almost all projects have multiple objectives. On the other hand, Remington and Pollack (2007) stated that this complexity might stem from ambiguity that existed in

several potential interpretations of goals and objectives, such as unshared goals and goal paths. Specifically, Li et al. (2009) proposed a three-level categorization framework of project goal, including managerial, functional and other goals.

(4) Environmental complexity
Environmental complexity refers to the complexity of a context where a project operates, such as the natural, market, political and regulatory environment (Li et al., 2009). Bosch-Rekveldt et al. (2011) added that this complexity could also be influenced by the complexity of project stakeholders whose interests and needs are also affected by the environment. This statement is echoed by Brockmann and Girmscheid (2008), who proposed social complexity to define the complexity caused by the number and diversity of project stakeholders.

(5) Cultural complexity
Cultural complexity refers to the diversity of the cultural software in the human mindset, which is manifested by a number of factors such as team trust, cognitive flexibility, emotional quotient and system thinking (Brockmann and Girmscheid, 2008). Brockmann and Girmscheid (2008) further categorized this complexity into three levels, namely national culture, industrial culture and organizational culture (Brockmann and Girmscheid, 2008). Mega projects always have multinational participants, who have different cultures and different perspectives. Therefore, cultural diversity increases project complexity, and influences success of project delivery (Brockmann and Girmscheid, 2008).

(6) Information complexity
Information complexity stems from complicated communication among a great number of project stakeholders under complicated contractual arrangements throughout the whole project delivery process. As a result of the expanding scale of mega projects, information dependency among different project participants increases information complexity accordingly. Information complexity is usually influenced by several factors, such as information systems, the degree of obtaining information, levels of processing and transmission of information (Li et al., 2009).

3. FANP

The ANP, which is extended from the well-known AHP, can quantitatively calculate the level of influence or feedback through matrices (Saaty, 1996). The basic assumption of the AHP, which was introduced by Saaty (1980), is the decomposition of a complex problem hierarchically, with a goal at the top of the hierarchy and criteria and sub-criteria at the levels and sub-levels of the hierarchy (Saaty, 1980), respectively. The ANP model represents reality and reliability better than the AHP model because of the better integration of the interactions that exist among the criteria (Taslicali and Ercan, 2006). The ANP feedback approach replaces hierarchies with networks in which the relationships between levels are not easily represented as high or low, dominant or subordinate, direct or indirect (Meade and Sarkis, 1999). The ANP has been widely and effectively applied in many fields that require interactions among diverse variables, including risk assessment (Chen et al., 2011), performance evaluation (Chen and Lee, 2007), and project selection (Cheng and Li, 2005).

In this study, the ANP is used along with the fuzzy set theory, which has been widely used by many researchers (Dağdeviren et al., 2008; Tseng et al., 2008; Yeung et al., 2012), to develop a complexity measurement model. The fuzzy set theory was introduced by Zadeh (1965) to deal with the uncertainty resulting from imprecision and vagueness of language. Fuzzy theory overcomes the deficiency of accurate mathematical logic and language, and emphasizes the fuzziness of the factors applied in comprehensive evaluation. It can also reflect vague data effectively. The linguistic level of each comparison produced by the experts is used to construct fuzzy pairwise comparison matrices in the form of triangular fuzzy numbers (Tseng et al., 2008).

The FANP is an efficient tool to deal with the fuzziness of data on different decision variables (Tseng et al., 2008). Several researchers have been trying to apply the FANP in solving complex problems in a number of fields, such as in fault behavior risk identification in work systems (Dağdeviren et al., 2008), agile concept selection in manufacturing organizations (Vinodh et al., 2011), supplier evaluation and order allocation (Lin, 2009), selection of competitive priorities based on clean production implementation (Tseng et al., 2008), and environmental assessment of location selection (Wu et al., 2009). Nevertheless, only a few have applied the FANP in the architecture, engineering, and construction industry. Given the complexity of a construction project, the FANP is the most suitable and valid for multi-criteria decision-making problems and interdependency relationships (Wu et al., 2009).

The advantages of the FANP are as follows:

- ➢ It allows for complex interrelationships among decision levels and attributes.
- ➢ It can deal with the uncertainty of imprecision and vagueness of language.
- ➢ It can reflect vague data effectively.

4. Research methodology

Project complexity measurement is a function of many factors, each of which can affect another factor. Therefore, a complexity measurement model for mega construction projects was developed in this study using the FANP, which allows for the interrelationships among the factors of project complexity and deals with the fuzziness of fuzzy data.

The methodology used in this study consisted of five steps:

1. Identifying the factors and sub-factors to be used in the model
2. Structuring the ANP model hierarchically (goal, factors, sub-factors)
3. Establishing the single factor evaluation matrix
4. Calculating the weights of the FANP
5. Comprehensive evaluation.

Table 1
Measures of project complexity from the literature review.

Factors	Sub-factors	Baccarini (1996)	Williams (1999)	Maylor (2003)	Remington and Pollack (2007)	Brockmann and Girmscheid (2008)	Vidal and Marle (2008)	Maylor et al. (2008)	Qi and Jiang (2008)	Li et al. (2009)	Remington et al. (2009)	Bosch-Rekveldt et al. (2011)	Vidal et al. (2010, 2011)	Xia and Chan (2012)	Total number of hits of a certain factor
Technological complexity	Diversity of technology in project	√	√	√	√		√	√		√			√		8
	Dependence of technological processes	√	√	√	√		√			√			√		7
	Interaction between the technology system and the external environment	√	√		√		√			√	√		√		7
	Risk of using highly difficult technology				√		√	√			√	√		√	6
Organizational complexity	Number of organizational structure hierarchies	√	√	√		√	√	√		√	√		√		9
	Number of organizational units and departments	√	√	√		√	√	√		√	√		√		9
	Cross-organizational interdependence			√			√	√			√	√	√		6
	Experience and social background of organization members	√		√			√	√	√	√	√				7
Goal Complexity	Uncertainty of goals		√	√	√			√		√	√			√	7
	Uncertainty of project management methods and tools		√	√	√		√	√				√	√		7
	Availability of resources and skills			√			√	√				√	√	√	6
	Diversity of tasks	√		√	√	√	√	√		√		√	√		9

	Dependence of relationship among tasks	√		√	√		√			√		√	√		7
	Dynamics of task activities			√		√	√	√		√		√	√		7
Environmental complexity	Multiple stakeholders		√		√	√	√	√	√		√	√	√		9
	Environment of changing policy and regulation				√		√		√	√	√	√	√	√	8
	Environment of changing technology				√		√		√	√	√		√	√	7
	Environment of changing economy				√		√		√	√	√	√	√	√	8
	Environment of changing nature				√		√		√	√	√	√	√	√	8
Cultural complexity	Multiple participating countries			√		√	√	√	√		√	√			7
	Project team's trust					√		√	√			√			4
	Sense of cooperation					√	√	√	√				√		5
	Cultural differences					√	√	√	√		√		√		6
Information complexity	Information uncertainty													√	1
	Level of processing information							√		√					2
	Capacity of transferring information							√		√					2
	Degree of obtaining information						√	√		√					3
	Integration of more than one system or platform						√						√		2
		8	8	13	13	9	23	19	10	17	14	13	19	8	–

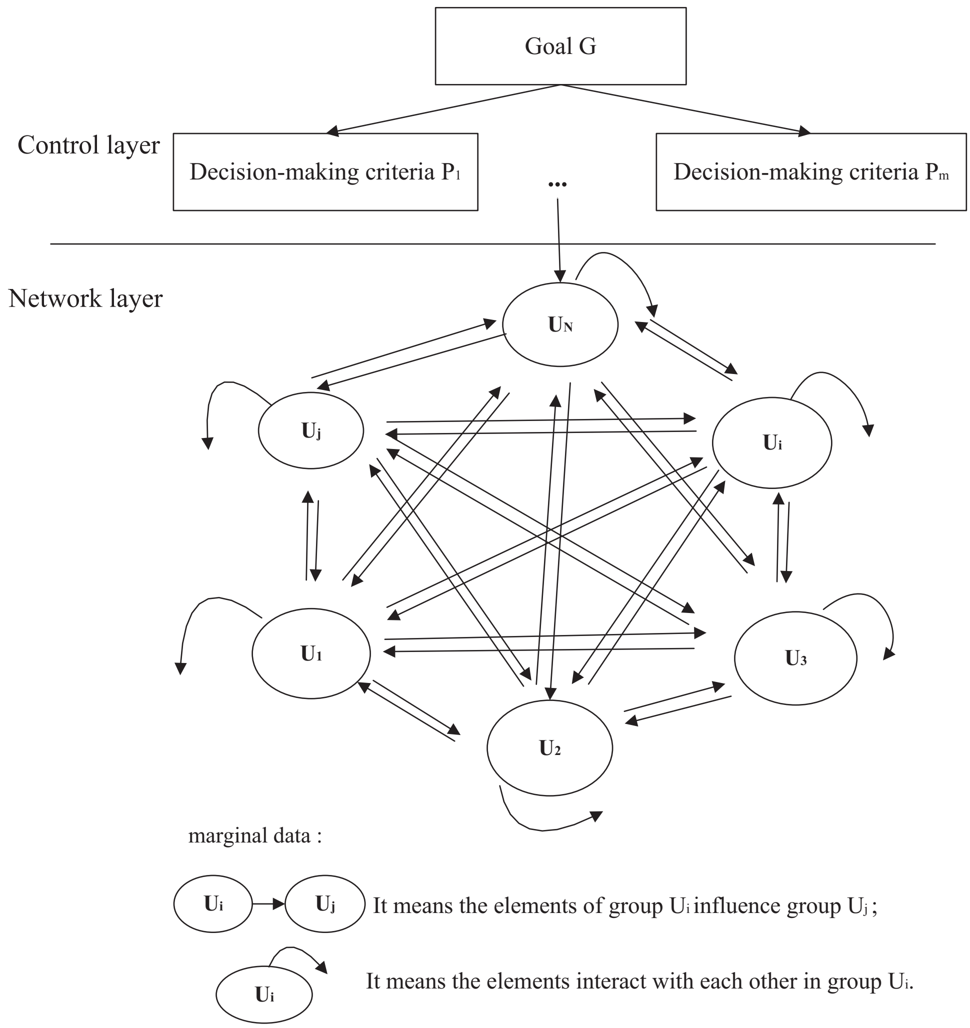

Fig. 1. Network structure of ANP model.

4.1. Identifying the factors and sub-factors

The factors and sub-factors for measuring project complexity were identified and selected by the following two steps:

Step 1: The common measures for megaprojects were extracted through the literature review using the content analysis technique. Content analysis is usually adopted to determine the major facets of a set of data by counting the number of times a topic has been depicted (Fellows and Liu, 2008). In conducting content analysis, all the main ideas of each work in the literature are first marked down; the similar points and ideas are then grouped together (Xu et al., 2010). After the content analysis, a total of 28 complexity measurements were identified under six groups as shown in Table 1 (He et al., 2012). In Table 1, each of these groups represents a kind (factor) of project complexity; meanwhile, each measurement of each factor is treated as a sub-factor. Vidal et al. (2011) stated that the classification of factors would not reduce

Table 2
Linguistic scale for importance.

Linguistic scale for importance	Triangular fuzzy scale	Triangular fuzzy reciprocal scale
Equally important (EI)	(1/2 1 3/2)	(2/3 1 2)
Weakly more important (WMI)	(5/2 3 7/2)	(2/7 1/3 2/5)
Strongly more important (SMI)	(9/2 5 11/2)	(2/11 1/5 2/9)
Very strongly more important (VSMI)	(13/2 7 15/2)	(2/15 1/7 2/13)
Absolutely more important (AMI)	(17/2 9 19/2)	(2/19 1/9 2/17)

Note: Scales of ‘(3/2 2 5/2)’, ‘(7/2 4 9/2)’, ‘(11/2 6 13/2)’, and (15/2 8 17/2) are the middle values of the triangular fuzzy scale; and scales of (2/5 1/2 2/3), (2/9 1/4 2/7), (2/13 1/6 2/11), and (2/17 1/8 2/15) are the corresponding triangular fuzzy reciprocal scales.

the reliability because the ANP model effectively integrates the correlation among the different project complexity factors.

Step 2: The critical measures applied in the 2010 Shanghai Expo construction project in China were refined through a two-round Delphi questionnaire survey. The Delphi questionnaire survey method is used to obtain the consolidated views of a group of experts via several rounds of intensive questionnaires interspersed with controlled opinion feedback (Linstone et al., 1975). In this study, two rounds of Delphi questionnaires were carried out. The purpose of the first round of Delphi questionnaire was to build the consensus among the panelists regarding the complexity of each factor related to megaprojects. A list of complexity measures identified in Step 1 was provided to design the questionnaire for reference. At this stage, a five-point Likert rating scale was adopted, with scores ranging from 1 to 5 (1 = simple, 2 = mildly complicated, 3 = moderately complicated, 4 = highly complicated, and 5 = extremely complicated). In the second round of the Delphi survey, the experts were asked to re-assess the ratings in light of the consolidated results obtained in the first round of the survey.

4.2. Structuring the ANP model hierarchically

The ANP model was structured hierarchically (goal, factors, and sub-factors) according to the factors and sub-factors of project complexity (Dağdeviren et al., 2008). The ANP consists of two parts: the control layer, including goal and decision-making rules; and the network layer, that is, the network structure of elements interacting with one another (Saaty, 1996). The complicated interrelationships among decision levels and attributes are considered while determining the weights in the ANP method. The factor set is defined as $U = \{U_1, U_2, \cdots, U_i, \cdots, U_N\}$, $i = 1, 2, \cdots, N$, where N is the number of factors; and each U_i is composed of several sub-factors, $U_i = \{U_{i1}, U_{i2}, \cdots, U_{in_i}\}$; n_i is the number of sub-factors under each factor. Consequently, a network structure can be built to integrate these factors and their sub-factors, and the relationship of interdependence among these components (factors/sub-factors) was listed in Fig. 1.

4.3. Establishing the single factor evaluation matrix

The comment set is a kind of language description of an evaluation index for various hierarchies from the comments of all experts; the comment set is written as $V = \{V_1, V_2, \ldots, V_m\}$. The complexity level from the sub-factor to the individual factor was evaluated using the questionnaire survey. Therefore, the single factor evaluation matrix R is established from U to V as

$$R = \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1m} \\ r_{21} & r_{22} & \cdots & r_{2m} \\ \cdots & \cdots & \cdots & \cdots \\ r_{n1} & r_{n2} & \cdots & r_{nm} \end{bmatrix}.$$

4.4. Calculating the weights of the FANP

In the ANP method, the fixed scale is used for paired comparison. However, the discrete scale of 1 to 9 has certain shortcomings, including its disregard for the uncertainty and vagueness of language; Zadeh (1965) therefore put forward the fuzzy set theory to deal with uncertainty caused by imprecision and vagueness. In the current study, the triangular fuzzy numbers were used to deal with the shortcoming (Tseng et al., 2008), as shown in Table 2.

Given k experts participating in the interview, according to a certain factor, the judgment of expert k for the relative importance between factors U_i and U_j is determined as B_{ijk}, and the pairwise comparison judgment matrices are given by $B(k) = (B_{ijk})$. Suppose that n evaluation indexes are to be considered, the decision-making weights of these indexes can be determined from the following processes:

1) Establishing the pairwise comparison judgment matrix
A pairwise comparison judgment matrix contains the views of decision-making experts, but the judgment of the relative importance of these views is uncertain. Therefore, the fuzzy triangular numbers were used to integrate the opinions of experts in this study so as to build a fuzzy judgment matrix based on the subjective opinions of the decision makers (Tseng et al., 2008; Wu et al., 2009). The fuzzy judgment matrix is as follows:$B = (B_{ij})$, where B_{ij} is the triangular fuzzy numbers and can be determined as $B_{ij} = (L_{ij}, M_{ij}, U_{ij})$, $L_{ij} \le M_{ij} \le U_{ij}$. Where $L_{ij} = \min_k(B_{ijk})$, $M_{ij} = Geomean_k(B_{ijk})$, and $U_{ij} = \max_k(B_{ijk})$.
2) Determining the fuzzy weight vector
Based on the fuzzy judgment matrix $B = (B_{ij})$, the geometric mean of the column vector was used to determine the corresponding fuzzy weight vector. Specifically, for any j, $r_j = \left(B_{1j} \bullet B_{2j} \bullet \cdots \bullet B_{n_i j}\right)^{1/n_i}$, $j = 1, 2, \cdots, n_i$, and where, $\bullet$ represents the multiplication of the triangular fuzzy numbers, and then r_j can be normalized as $w_j = r_j/(r_1 + r_2 + \cdots + r_{n_i})$.
3) Analysis of weight decision
Firstly, the concept of cut set in fuzzy analysis was used to carry out the defuzzication analysis of weight, and $\alpha \in [0, 1]$ was used to represent the cut parameter. Assume that $w_i = (w_i^L, w_i^M, w_i^U)$, $w_i{}^L(\alpha) = \left(w_i^M - w_i^L\right)\alpha + w_i^L$, $w_i{}^U(\alpha) = \left(w_i^U - w_i^M\right)\alpha + w_i^M$, and $w_i(\alpha, \lambda) = \lambda w_i^U(\alpha) + (1 - \lambda) w_i^L(\alpha)$. Secondly, the $w_i(\alpha, \lambda)$ can be normalized as $W_i(\alpha, \lambda) = w_i(\alpha, \lambda) / \left(\sum_i w_i(\alpha, \lambda)\right)$.
Notably, the decision weight clearly depends on two parameters α and λ. α can be viewed as a stable or fluctuating condition. When $\alpha = 0$ indicates that the comprehensive weight includes every expert's decision-making information, and that the range of uncertainty is the greatest; $\alpha = 1$ represents the comprehensive weight, including the decision-making information with the least weight, which is equivalent to the integrated decision-making weight of experts without fuzzification. The λ can be viewed as the degree of a decision maker's pessimism (Hsu and Yang, 2000). When $\lambda = 0$, the decision maker is more

optimistic and, thus, the expert consensus is upper-bound of the triangular fuzzy number. Conversely, when $\lambda = 1$, the decision maker is pessimistic.

4) Obtaining the weight vector matrix W_{ij}
The weight vector matrix of each element in group U_1 was W_{11}, which is written as

$$W_{11} = \left(W^{(11)}, W^{(12)}, \cdots, W^{(1n_1)}\right) = \begin{bmatrix} w_{11}^{(11)} & w_{21}^{(12)} & \cdots & w_{n_1 1}^{(1n_1)} \\ w_{12}^{(11)} & w_{22}^{(12)} & \cdots & w_{n_1 2}^{(1n_1)} \\ \cdots & \cdots & \cdots & \cdots \\ w_{1n_1}^{(11)} & w_{2n_1}^{(12)} & \cdots & w_{n_1 n_1}^{(1n_1)} \end{bmatrix}.$$

This method was then re-calculated to obtain $W_{22}, W_{33}, \cdots, W_{n_i n_i}$. During the calculation of $W_{ij}(i \neq j)$, the triangular fuzzy judgment matrix could be obtained after a pairwise comparison in $U_j(j = 1, 2, \cdots, N)$ according to a certain rule and the influence degree of this rule on each element in $U_i(i = 1, 2, \cdots, N)$. Consistency check and fuzzy comprehensive evaluation were then performed to obtain the local weight vector matrix $W_{ij}(i \neq j)$.

5) Calculating supermatrix W and weighted supermatrix $\underline{W}$
After calculating all $W_{ij}(i, j = 1, 2, \cdots, N)$, the supermatrix W could be obtained as

$$W = \begin{bmatrix} W_{11} & W_{12} & \cdots & W_{1N} \\ W_{21} & W_{22} & \cdots & W_{2N} \\ \cdots & \cdots & \cdots & \cdots \\ W_{N1} & W_{N2} & \cdots & W_{NN} \end{bmatrix}.$$

The relative importance of the factors was pairwise compared according to the same method above; the relative weight matrix A could then be obtained as

$$A = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1N} \\ a_{21} & a_{22} & \cdots & a_{2N} \\ \cdots & \cdots & \cdots & \cdots \\ a_{N1} & a_{N2} & \cdots & a_{NN} \end{bmatrix}.$$

Subsequently, the weighted supermatrix W could be obtained after multiplying the relative weighted matrix A with supermatrix W:

$$\underline{W} = \begin{bmatrix} a_{11}W_{11} & a_{12}W_{12} & \cdots & a_{1N}W_{1N} \\ a_{21}W_{21} & a_{22}W_{22} & \cdots & a_{2N}W_{2N} \\ \cdots & \cdots & \cdots & \cdots \\ a_{N1}W_{N1} & a_{N2}W_{N2} & \cdots & a_{NN}W_{NN} \end{bmatrix}.$$

6) Solving the supermatrix $\underline{W}$
$\underline{W}$ is the weighted supermatrix obtained under one certain criteria. By replicating this calculation process, the final weighted supermatrix $\underline{W}$ could be obtained after synthesizing all the supermatrixes according to each criteria in $P_t(t = 1, 2, \cdots, m)$. Excel was then used to calculate the $\underline{W}^{\infty} = \lim_{n \to \infty} \underline{W}^n$, and its column vector is the limit relative weight vector C. The overall complexity level based on six kinds of project complexity then can be computed based on the weight through the following process: Firstly, the processed weight of sub-factors C_{in_i} was calculated by $C_{in_i} = C_n / \sum_{i=1}^{n_i} C_n(n_i)$, and then processed values X_n' were gotten through multiplying the processed weight with mean values. Finally, the complexity level of different complexities can be gotten through $X_i = \sum_{i=1}^{n_i} X_n'(n_i)$.

4.5. Comprehensive evaluation

The synthesized operator $M(\bullet,\oplus)$ of the comprehensive evaluation was chosen in this study because the weighted average operator considers all the elements. The limit relative weight vector C was synthesized with the single factor evaluation matrix R, then the fuzzy comprehensive evaluation set was obtained as $B = C \bullet R = (b_1, b_2, \cdots, b_m)$. The maximum value is corresponding to the overall level of project complexity in the project.

5. Case study

This study selected the 2010 Shanghai World Expo construction project as a case study to validate the proposed measurement model.

5.1. Background

The 2010 Shanghai World Expo construction project, with a total investment of RMB 28 billion and a floor area of 2.4 million m^2, can be considered a complex system (Expo Shanghai China, 2010). The construction period spanned 37 months, and consisted of over 400 single projects. The Shanghai Expo construction headquarters comprised 10 functional management divisions (FMDs) and 10 on-site project management teams (PMTs). Many engineering construction units are also involved in this case project, including 50 main designers, 60 construction contractors, and 60 project supervision consultants. Apart from the headquarters, 40 foreign countries and enterprises also planned to participate in the Expo by building their own self-built pavilions. Thus, the Shanghai Expo project is a typical example of a megaproject in China, so analyzing the complexity of this project can provide a theoretical guidance for other megaprojects in China. The proposed FANP attempts to measure the complexity of the Shanghai Expo construction project through the following steps.

5.2. Identifying project complexity measures

The list of complexity measures identified above was prepared to design the questionnaire for the Delphi questionnaire survey that would help determine the complexity of each factor in the 2010 Shanghai Expo construction project. The majority of Delphi studies involve 15 to 20 respondents (Ludwig, 1997), so 20 managers who participated in the 2010 Shanghai Expo project were invited as the prospective panel in this study. These participants come from real estate developers, construction

Table 3
Background information of the respondents.

1) Type of firm/department					
Category	Real estate developer	Construction company	Consultancy firm	Government department	University
Percentage	5%	15%	50%	10%	20%
2) Industry experience of survey respondents					
Category	Below 1 year	1–5 years	6–10 years	11–20 years	Over 20 years
Percentage	5%	15%	25%	35%	20%
3) Professional qualifications					
Category	Senior professional title	Medium-grade professional title	Junior professional title		
Percentage	25%	40%	35%		

companies, consultancy firms, government departments, and universities. Eighty percent of the participants have over 5 years work experience, and most of them hold above medium-grade professional titles in their organizations (Table 3).

In the first round of the Delphi questionnaire survey, the perception of the participants on the relative complexity of each of the 28 factors was acquired and ranked by calculating the normalized values (Table 4). In the second round of the Delphi survey, the participants were asked to re-assess the ratings in light of the consolidated results obtained in the first round of the survey. At this stage, a consensus among the panelists regarding the refined project complexity framework was finally built. Only the project complexity measures with normalized values equal to or greater than 0.30 were considered as important and were selected for the subsequent FANP because they cover all the groups of complexity. That is to say, 12 complexity measures were selected to comprise the refined project complexity framework for FANP measurement (Table 5).

5.3. Structuring ANP model of project complexity

According to the project complexity measures selected above, the project complexity consists of six factors: organizational complexity (U_1), cultural complexity (U_2), environmental complexity (U_3), technological complexity (U_4), information complexity (U_5), and goal complexity (U_6). Each component can be further divided into several elements; specifically, $U_1 = \{U_{11}, U_{12}, U_{13}\}$ = {number of organizational units and

Table 4
Ranking of complexity measures for the Shanghai Expo construction project.

No.	Sub-factors	Mean value	Normalization	Ranking
1	Number of organizational units and departments	3.90	1.00	1
2	Cross-organizational interdependence	3.85	0.95	2
3	Multiple participating countries	3.80	0.89	3
4	Multiple stakeholders	3.75	0.84	4
5	Project team's trust	3.70	0.79	5
6	Sense of cooperation	3.70	0.79	5
7	Risk of using highly difficult technology	3.45	0.53	7
8	Cultural differences	3.40	0.47	8
9	Degree of obtaining information	3.40	0.47	8
10	Experience and social background of organization members	3.30	0.37	10
11	Dependence of relationship among tasks	3.30	0.37	10
12	Environment of changing policy and regulation	3.30	0.37	10
13	Interaction between the technology system and the external environment	3.20	0.26	13
14	Integration of more than one system or platform	3.20	0.26	13
15	Dynamics of task activities	3.15	0.21	15
16	Environment of changing technology	3.15	0.21	15
17	Information uncertainty	3.15	0.21	15
18	Dependence of technological processes	3.10	0.16	18
19	Uncertainty of goals	3.10	0.16	18
20	Uncertainty of project management methods and tools	3.10	0.16	18
21	Availability of resources and skills	3.10	0.16	18
22	Environment of changing economy	3.10	0.16	18
23	Capacity of transferring information	3.10	0.16	18
24	Diversity of technology in project	3.05	0.11	24
25	Diversity of tasks	3.05	0.11	24
26	Level of processing information	3.05	0.11	24
27	Number of organizational structure hierarchies	3.00	0.05	27
28	Environment of changing nature	2.95	0.00	28

$Normalized\ value = \frac{average\ actual\ value - average\ minimum\ value}{average\ maximum\ value - average\ minimum\ value}$.

Table 5
Refined complexity framework for the Shanghai Expo construction project.

Factors	Organizational complexity (U_1)	Cultural complexity (U_2)	Environmental complexity (U_3)	Technological complexity (U_4)	Information complexity (U_5)	Goal complexity (U_6)
Sub-factors	Number of organizational units and departments (U_{11})	Multiple participating countries (U_{21})	Multiple stakeholders (U_{31})	Risk of using highly difficult technology (U_{41})	Degree of obtaining information (U_{51})	Dependence of relationship among tasks (U_{61})
	Cross-organizational interdependence (U_{12})	Project team's trust (U_{22})	Environment of changing policy and regulation (U_{32})			
	Experience and social background of organization members (U_{13})	Sense of cooperation (U_{23})				
		Cultural differences (U_{24})				

departments, cross-organizational interdependence, experience and social background of organization members}; $U_2 = \{U_{21}, U_{22}, U_{23}, U_{24}\}$ = {multiple participating countries, project team's trust, sense of cooperation, cultural differences}; $U_3 = \{U_{31}, U_{32}\}$ = {multiple stakeholders, environment of changing policy and regulation}; $U_4 = \{U_{41}\}$ = {risk of using highly difficult technology}; $U_5 = \{U_{51}\}$ = {degree of obtaining information}; and $U_6 = \{U_{61}\}$ = {dependence of relationship among tasks}. These factors are not independent. Based on a previous measurement framework, the ANP model was structured hierarchically, as shown in Fig. 2.

5.4. Establishing the single factor evaluation matrix

According to the impact of influencing factors on project complexity, the comment set is V = {simple, mildly complicated, moderately complicated, highly complicated, extremely complicated} = $\{V_1, V_2, V_3, V_4, V_5\}$. The complexity level from the sub-factor to each individual factor was evaluated using the questionnaire survey. After sorting the questionnaire results, the single factor evaluation matrix R was established from U to V as

$$R = \begin{bmatrix} 0.05 & 0.10 & 0.20 & 0.20 & 0.45 \\ 0.05 & 0.10 & 0.25 & 0.15 & 0.45 \\ 0.05 & 0.20 & 0.40 & 0.10 & 0.25 \\ 0.05 & 0.05 & 0.25 & 0.35 & 0.30 \\ 0.05 & 0.05 & 0.25 & 0.45 & 0.20 \\ 0.05 & 0.05 & 0.20 & 0.55 & 0.15 \\ 0.05 & 0.05 & 0.55 & 0.15 & 0.20 \\ 0.05 & 0.10 & 0.15 & 0.45 & 0.25 \\ 0.05 & 0.10 & 0.40 & 0.40 & 0.05 \\ 0.05 & 0.15 & 0.25 & 0.40 & 0.15 \\ 0.05 & 0.25 & 0.05 & 0.55 & 0.10 \\ 0.05 & 0.25 & 0.25 & 0.25 & 0.20 \end{bmatrix}.$$

5.5. Calculating the weights of the FANP

1) Calculating the sub-factor weight

In the calculation of the supermatrix, the matrix is a fuzzy supermatrix expressed by the triangular fuzzy numbers. Therefore, the weight vector depends on two parameters α and λ. This study chose $\alpha = 0$ and $\lambda = 1$; $\alpha = 0$ indicates the weight containing every experts' decision information, and $\lambda = 1$ indicates the experts' conservative attitude. The calculation process is as follows:

To the element set U_1, the weight vector was calculated by comparing the effect sizes of elements U_{11}, U_{12}, U_{13} to U_{11} under U_{11}, as in Table 6.

Using the eigenvalue method, the ranking vector was obtained as $\left(w_{11}{}^{(11)} \quad w_{12}{}^{(11)} \quad w_{13}{}^{(11)}\right)^T = (0.600 \quad 0.200 \quad 0.200)^T$, which is the influence ranking vector of elements U_{11}, U_{12} and U_{13} to U_{11}.

Similarly, the ranking vector of elements U_{11}, U_{12} and U_{13} to U_{12} can be calculated as $\left(w_{21}{}^{(11)} \quad w_{22}{}^{(11)} \quad w_{23}{}^{(11)}\right)^T = (0.2000.6000.200)^T$; U_{13} is $\left(w_{31}{}^{(11)} \quad w_{32}{}^{(11)} \quad w_{33}{}^{(11)}\right)^T = (0.200 \quad 0.200 \quad 0.600)^T$.

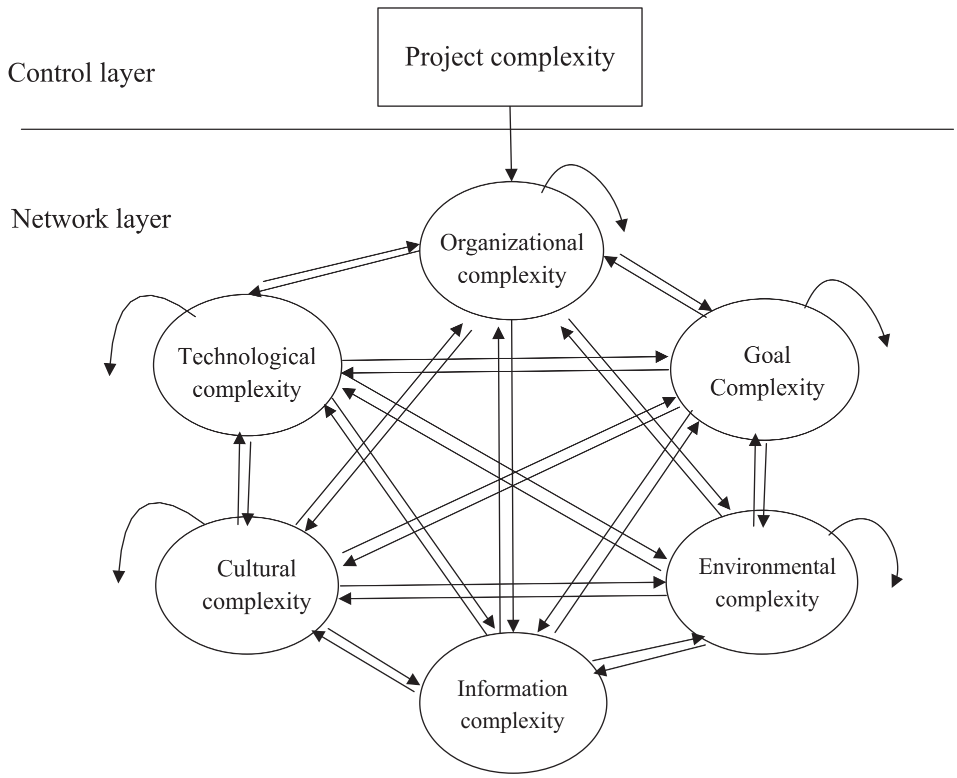

Fig. 2. ANP structure for project complexity.

Therefore, the fuzzy judgment matrix of U_1 (organizational complexity) was

$$W_{11} = \begin{bmatrix} 0.600 & 0.200 & 0.200 \\ 0.200 & 0.600 & 0.200 \\ 0.200 & 0.200 & 0.600 \end{bmatrix}.$$

After calculating the fuzzy judgment matrix of the other element sets in the same way, the fuzzy supermatrix of the sub-factor weight could finally be obtained as

$$W = \begin{bmatrix} W_{11} & W_{12} & W_{13} & W_{14} & W_{15} & W_{16} \\ W_{21} & W_{22} & W_{23} & W_{24} & W_{25} & W_{26} \\ W_{31} & W_{32} & W_{33} & W_{34} & W_{35} & W_{36} \\ W_{41} & W_{42} & W_{43} & W_{44} & W_{45} & W_{46} \\ W_{51} & W_{52} & W_{53} & W_{54} & W_{55} & W_{56} \\ W_{61} & W_{62} & W_{63} & W_{64} & W_{65} & W_{66} \end{bmatrix}.$$

Table 6
The relative importance of the organizational complexity element set under U_{11}.

U_{11}	U_{11}	U_{12}	U_{13}	w
U_{11}	(1 1 1)	(5/2 3 7/2)	(5/2 3 7/2)	0.600
U_{12}	(2/7 1/3 2/5)	(1 1 1)	(1/2 1 3/2)	0.200
U_{13}	(2/7 1/3 2/5)	(2/3 1 2)	(1 1 1)	0.200

2) Calculating the factor weight
Taking the factors as elements, the FANP was used to determine the weight of each factor as

$$A = \begin{bmatrix} a_{11} & a_{12} & a_{13} & a_{14} & a_{15} & a_{16} \\ a_{21} & a_{22} & a_{23} & a_{24} & a_{25} & a_{26} \\ a_{31} & a_{32} & a_{33} & a_{34} & a_{35} & a_{36} \\ a_{41} & a_{42} & a_{43} & a_{44} & a_{45} & a_{46} \\ a_{51} & a_{52} & a_{53} & a_{54} & a_{55} & a_{56} \\ a_{61} & a_{62} & a_{63} & a_{64} & a_{65} & a_{66} \end{bmatrix} = \begin{bmatrix} 0.207 & 0.193 & 0.069 & 0.107 & 0.125 & 0.125 \\ 0.044 & 0.049 & 0.419 & 0.313 & 0.125 & 0.125 \\ 0.269 & 0.272 & 0.069 & 0.074 & 0.375 & 0.125 \\ 0.197 & 0.200 & 0.069 & 0.074 & 0.125 & 0.375 \\ 0.102 & 0.104 & 0.187 & 0.140 & 0.125 & 0.125 \\ 0.181 & 0.182 & 0.187 & 0.292 & 0.125 & 0.125 \end{bmatrix}.$$

After obtaining W and A, the fuzzy weighted supermatrix was obtained as

$$\underline{W} = A \bullet W = \begin{bmatrix} a_{11}W_{11} & a_{12}W_{12} & a_{13}W_{13} & a_{14}W_{14} & a_{15}W_{15} & a_{16}W_{16} \\ a_{21}W_{21} & a_{22}W_{22} & a_{23}W_{23} & a_{24}W_{24} & a_{25}W_{25} & a_{26}W_{26} \\ a_{31}W_{31} & a_{32}W_{32} & a_{33}W_{33} & a_{34}W_{34} & a_{35}W_{35} & a_{36}W_{36} \\ a_{41}W_{41} & a_{42}W_{42} & a_{43}W_{43} & a_{44}W_{44} & a_{45}W_{45} & a_{46}W_{46} \\ a_{51}W_{51} & a_{52}W_{52} & a_{53}W_{53} & a_{54}W_{54} & a_{55}W_{55} & a_{56}W_{56} \\ a_{61}W_{61} & a_{62}W_{62} & a_{63}W_{63} & a_{64}W_{64} & a_{65}W_{65} & a_{66}W_{66} \end{bmatrix}.$$

3) Solving the supermatrix $\underline{W}$
As $\underline{W} \succ 0$, $\underline{W}$ is a prime matrix and an irreducible matrix. Given that the sum of each column is 1, every column of $\underline{W}^{\infty}$

Table 7
The degree of different complexities of Shanghai Expo project.

Factors	Sub-factors	Mean value	Weight	Processed weight	Processed value	Complexity degree
Organizational complexity (U_1)	U_{11}	3.90	0.054348	0.203487	0.79	3.50
	U_{12}	3.85	0.037272	0.139551	0.54	
	U_{13}	3.30	0.175464	0.656962	2.17	
Cultural complexity (U_2)	U_{21}	3.80	0.043657	0.183886	0.70	3.60
	U_{22}	3.70	0.058331	0.245690	0.91	
	U_{23}	3.70	0.044105	0.185769	0.69	
	U_{24}	3.40	0.091323	0.384654	1.31	
Environmental complexity (U_3)	U_{31}	3.75	0.035631	0.162177	0.61	3.37
	U_{32}	3.30	0.184072	0.837823	2.76	
Technological complexity (U_4)	U_{41}	3.45	0.049319	1.000000	3.45	3.45
Information complexity (U_5)	U_{51}	3.40	0.094379	1.000000	3.40	3.40
Goal complexity (U_6)	U_{61}	3.30	0.132099	1.000000	3.30	3.30

is the eigenvector of the weighted supermatrix $\underline{W}$ corresponding to eigenvalue 1, and 1 is the single value; therefore, $\underline{W}$ has no other eigenvalue except 1.

Then, the normalized eigenvector of $\underline{W}$ was calculated with Excel as

$$\underline{W}^{\infty} = \begin{pmatrix} 0.054348, & 0.037272, & 0.043657, & 0.035631, & 0.058331, & 0.044105, \\ 0.049319, & 0.091323, & 0.094379, & 0.175464, & 0.132099, & 0.184072 \end{pmatrix}^T.$$

Therefore, the weight of the sub-factors were obtained as

$$C = \begin{pmatrix} 0.054348, & 0.037272, & 0.043657, & 0.035631, & 0.058331, & 0.044105, \\ 0.049319, & 0.091323, & 0.094379, & 0.175464, & 0.132099, & 0.184072 \end{pmatrix}.$$

Then, the complexity level of each group was calculated on the bases of weight as Table 7.

5.6. Comprehensive evaluation result

For comprehensive evaluation, the composition operator $M(\bullet,\oplus)$, that is, the weighted average operator, was chosen. This operator is applicable in the comprehensive evaluation of all elements. The calculation result is as follows:

$$B = C \bullet R = (0.050000,\ 0.151195,\ 0.245026,\ 0.358906,\ 0.194872).$$

According to the principle of membership maximum, the maximum value in B is 0.358906, which equals to the ‘highly complicated’; thus this result indicates that the overall complexity level of the Shanghai Expo project is highly complex. In B, the second largest value was 0.245026, which equals to the ‘moderately complicated’. This value indicates that the complexity of the case project could also be controlled at a moderately complex level if proper strategies are developed and carried out.

6. Discussions

The six complexities of the case study were examined through an in-depth analysis. Compared with the average level of the megaproject complexity obtained by analyzing six megaproject

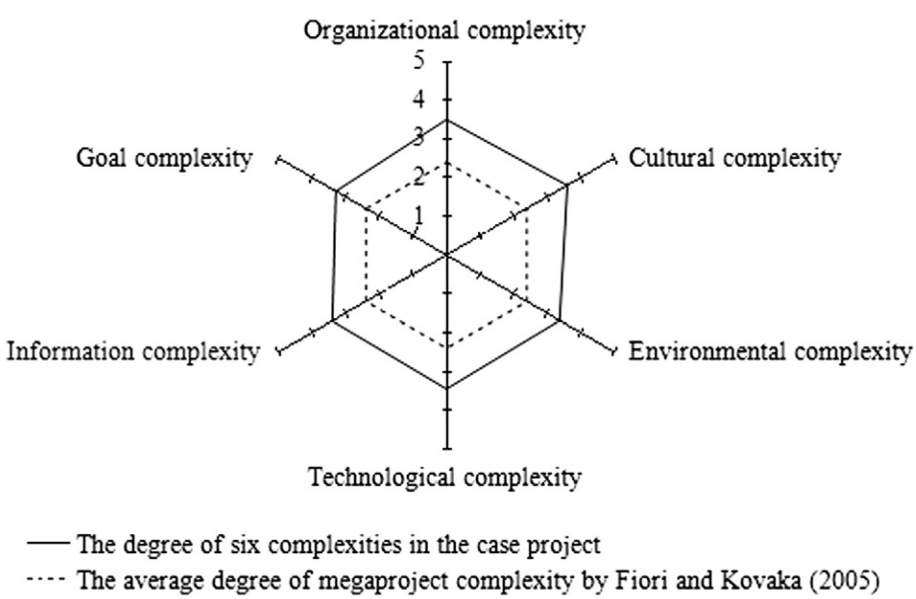

Fig. 3. Comparison of complexities between the case project and the average degree.

cases worldwide (Fiori and Kovaka, 2005), the value of each of the six complexities in the case project is higher than the average level as shown in Fig. 3. The most complexity of Shanghai Expo project is cultural complexity, followed successively by organizational complexity, technological complexity and information complexity. Environmental complexity and goal complexity both ranked last. Thus, the Shanghai Expo project is regarded as an example of a construction megaproject with high complexity.

To deal with these complexities in the case project, the client adopted the program management approach to simplifying the complexities and sustaining a control of the dispensed execution of the project. Based on the successful implementation of the new managerial approach, the case project was completed 11 days ahead of schedule and attained prescribed objectives in safety, quality, and environment within the approved budget. Remington and Pollack (2007) stated that program management is a pragmatic means of dealing with nearly all kinds of project complexity. In the case project, the client adopted various strategies and measures to deal with each of the six complexities, respectively (Hu et al., 2013).

For cultural complexity, the client established close partnerships with major designers and contractors by adopting the incentives (Hu et al., 2011, 2012). Meanwhile, the client also established a coordination division tasked with strengthening team building within the client organization (SECH Office, 2008).

For organizational complexity, the local government constructed a client-led program organization by employing an external consultant. Within the program organization, 10 FMDs were established to integrate the dispensed execution works of the 10 sub-project conducted by 10 PMTs, respectively (SECH Office, 2008).

For technological complexity, the client established a separate technology management division within its organization to manage the technical issues in constructing the pavilions, infrastructures, and facilities in the Shanghai Expo site (SECH Office, 2008).

For information complexity, the central program control information system was utilized by the client to realize timely collection and analysis of progress information and meet information needs of decision makers in the case project. In addition, the client established a separate communication management system to promote and integrate communication activities among designers, contractors, suppliers, and governmental agencies (Hu et al., 2014).

For environmental complexity, the client organized several rounds of internal discussions to analyze the contextual limits on project execution at the project beginning and the local government established a project governance board headed by the Deputy Mayor to facilitate the execution of the whole project during the construction process (SECH Office, 2008).

For goal complexity, the client organization applied the project breakdown structure and work breakdown structure (PBS/WBS) tools to align tasks of different organizational units within the client organization and each of the overall objectives of the megaproject (SECH Office, 2008, 2009). In addition, corresponding FMDs, such as the Cost Management Division, Time Management Division, as well as Safety and Quality Management Division were established within the client organization to monitor the implementation of all key objectives.

7. Conclusions

This study developed a complexity measurement model based on the 2010 Shanghai Expo construction project in China using the FANP. Comparing with previous studies, this study has made two contributions in the research methodology. On the one hand, this study has made a distinct contribution to knowledge from previous studies by adopting a holistic approach, FANP, in the modeling of project complexity. The FANP involves the application of triangular fuzzy numbers derived from the ANP to represent the comparison judgments of decision makers when deciding the final priority for different decision criteria, and this approach can reflect the interactions among numerous elements and deal with uncertainty and vagueness of language. On the other hand, the research methodology proposed in this study can be replicated to other megaprojects not only in China, but also in other locations to quantify various kinds of project complexity for improving the decision making of construction megaprojects and maintaining their execution performance.

Based on quantifying the level of project complexity of a particular megaproject, decision makers and clients involved can get knowledge of related issues and thus develop more appropriate organization and strategy arrangements for the project execution. Meanwhile, contractors can make use of such information to improve managerial decisions in tendering, project goal setting, risk assessment and staffing (Xia and Chan, 2012). Three recommendations are made in this study for future practice and research:

(1) A complexity measurement process should be implemented at the earliest possible lifecycle phase and then reviewed at subsequent phase boundaries, and a continued review of project complexity may be carried out. In future research, intelligent software that can compute the project complexity regularly for real-time control and continual managerial improvement in managing mega projects should be developed.
(2) Proper strategy and organization arrangements should be made to respond to various kinds of complexity in a project and their potential changes as a result of changes in its environment. The case study has provided a brief example for this issue.
(3) Leadership can also be used to deal with project complexity (International Centre for Complex Project Management, 2011; Mueller et al., 2012). This issue is not fully addressed in this study, but it deserves more research concern in the future.

Conflict of interest

There is no conflict of interest.

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