

Project Delivery System Mode Decision Based on Uncertain AHP and Fuzzy Sets

Liu Kaishan¹, Li Huimin²

¹ Business School, Hohai University, Nanjing 210098, China;

² North China University of Water Resources and Electric Power, Zhengzhou 450011, China.

Abstract The project delivery system mode determines the contract pricing type, project management mode and the risk allocation among all participants. Different project delivery system modes have different characteristics and applicable scope. For the owners, the selection of the delivery mode is the key point to decide whether the project can achieve the expected benefits, it relates to the success or failure of project construction. Under the precondition of comprehensively considering the influence factors of the delivery mode, the model of project delivery system mode decision was set up on the basis of uncertain AHP and fuzzy sets, which can well consider the uncertainty and fuzziness when conducting the index evaluation and weight confirmation, so as to rapidly and effectively identify the most suitable delivery mode according to project characteristics. The effectiveness of the model has been verified via the actual case analysis in order to provide reference for the construction project delivery system mode.

1. Introduction

The project delivery system mode determines the rights, liabilities and risk allocation of all participants^[1], and greatly influences the project progress, cost and quality, thus, the selection of the project delivery system mode is crucial for the construction of project, it relates to the success or failure of project construction. The common project delivery system modes include DBB, DB, EPC, CM, etc.^[2-3] For the study on the selection of the delivery mode, Ibrahim^[4] and Mohammed^[5] discussed the relevant factors that influence the selection of the delivery mode, and constructed the corresponding optimum model of delivery mode on the basis of the analytic hierarchy process. Wang Maoxin, et al^[6] analyzed the characteristics and applicable scopes of the main current delivery modes, and then analyzed the optimum delivery mode of the project from the perspective of cost control on this basis. Florence, et al^[7] constructed the selection model for the project delivery system mode by applying the artificial neural network. On the basis of discussing the relevant factors which influence the selection of the project delivery system mode, Hui Jingru^[8] and Zhang Lishan^[9] constructed the model of the project delivery system mode decision by using the fuzzy comprehensive evaluation method. Wang Sen, et al^[10] constructed the PPP project delivery system mode decision method based on the intuitionistic fuzzy set theory. Liu xun, et al^[11] constructed the construction project delivery system mode decision method on the basis of FOWGA operators. Wang Shouxu, et al^[12] constructed the optimum model of the delivery mode on the basis of considering the owner's preference and the requirements on the schedule, quality, cost and other factors based on AHP-GRAP method, but ignored the factors of project properties, project construction environment, etc. The above studies construct the decision models for the selection of the project delivery system mode from



different perspectives or by considering different influence factors or using different methods, which has a guiding significance for the selection of the project delivery system mode to a certain extent, however, there are still some common problems that the factors considered are not comprehensive and the determination of index weight is not reasonable, etc., and the constructed decision models cannot be well operated and their applications are also very limited.

The paper constructed the model of the project delivery system mode decision on the basis of uncertain AHP and the fuzzy set theory. The model can well consider the uncertainty and fuzziness during index evaluation and weight determination so as to make the selection of the project delivery system mode more reasonable, and provide reference for the owner's decision of selecting the delivery mode.

2. Establishment of Index System

The scale of construction project is relatively large and the construction environment is more complex, thus, there are many factors influencing the selection of the project delivery system mode. In addition, different delivery modes have different applicable scopes. The project property and the project construction environment factor greatly determine the applicable delivery mode of the project. At the same time, different delivery modes have different requirements on the owner's management ability and management experience. The reference [13] constructed the index system of the selection of the delivery mode, which is shown in table 1 from the delivery subject, delivery subject and delivery environment.

Table 1 Index system for the selection of the project delivery system mode

Rating subject	First level index	Second-level index
Influence factors of project delivery system mode	Project property C_1	Project scale C_{11}
		Project technical difficulty C_{12}
		Project economic property C_{13}
		Project designed depth C_{14}
	Owner management ability, experience and requirement C_2	Owner's management ability and experience C_{21}
		Owner's requirements on time limit C_{22}
		Owner's requirements on quality C_{23}
		Owner's requirements on investment control C_{24}
	Project construction environment C_3	Project construction condition C_{31}
		Potential contractor's competitiveness C_{32}
		Completeness of construction rules C_{33}
		Integrity of market subject C_{34}

3. Uncertain Analytical Hierarchy Process

As an index weight determination method with qualitative and quantitative combination, the analytical hierarchy process can effectively determine the index weight, however, the evaluation effect of traditional analytical hierarchy process lacks of objectivity and impartiality and cannot comprehensively consider the uncertainty of index, and experts often find it difficult to give an exact degree of importance of index. Thus, the paper adopted the improved uncertain analytical hierarchy process which uses the interval number to express the judgment matrix so as to determine the index weight, and the detailed steps are as follows [14-15]:

3.1 Construct the uncertain judgment matrix

The traditional analytical hierarchy process uses definite values to express the degree of importance of indexes, however, experts often find it difficult to give a exact degree of importance of index. because of the fuzziness and uncertainty of the index. The utility interval number is used for expressing the

scoring result, i.e., $[a_{ij}^-, a_{ij}^+]$. Wherein, $\frac{1}{9} \leq a_{ij}^- = \frac{1}{a_{ji}^+} \leq 9$, $a_{ii}^- = a_{ii}^+ = 1$, the higher the index score is, the

more significant it will be. According to experience and knowledge, the experts compare and score the factors in pair by referring to the judgment rules and then can get the interval judgment matrix A which can reflect the significance of each index.

$$A = \begin{bmatrix} [1,1] & [a_{12}^-, a_{12}^+] & \cdots & [a_{1n}^-, a_{1n}^+] \\ [a_{21}^-, a_{21}^+] & [1,1] & \cdots & [a_{2n}^-, a_{2n}^+] \\ \vdots & \vdots & \ddots & \vdots \\ [a_{n1}^-, a_{n1}^+] & [a_{n2}^-, a_{n2}^+] & \cdots & [1,1] \end{bmatrix} \quad (1)$$

3.2 Weight calculation

There are many weight calculation methods for the uncertain judgment matrix, such as the group eigenvalue method, the least square method, the optimum matrix transfer method, etc.,^[16], wherein the optimum matrix transfer method is simple and convenient in calculation, and the calculation results are highly reliable. The paper adopts the optimum matrix transfer method to calculate the index weight and the calculation steps are as follows:

(1) Split the judgment matrix $A = (a_{ij})_{n \times n}$ into two matrixes of $A^- = (a_{ij}^-)_{n \times n}$ and $A^+ = (a_{ij}^+)_{n \times n}$, and then respectively calculated them;

(2) Solve the dissymmetry interval matrix. Defined the matrix $B = \ln A = (\ln a_{ij})_{n \times n}$, then the matrix B is the dissymmetry interval matrix;

(3) Solve the optimum transfer matrix $T = (t_{ij})_{n \times n}$ of the matrix B , wherein:

$$t_{ij} = \frac{1}{n} \sum_{k=1}^n (b_{ik} - b_{jk}) \quad (2)$$

The consistency interval matrix $A^* = \exp(T) = (e^{t_{ij}})_{n \times n}$ can be obtained from the optimum transfer matrix $T = (t_{ij})_{n \times n}$.

(4) Normalize the matrix A^* , and then solved the weight of each index:

$$w_i = \sum_{j=1}^n a_{ij}^* / \sum_{k=1}^n \sum_{j=1}^n a_{kj}^* \quad (3)$$

Define the index weights calculated out from the two matrixes of $(a_{ij}^-)_{n \times n}$ and $(a_{ij}^+)_{n \times n}$ as w_i^- and w_i^+ , then the final index weight interval calculated out from the uncertain analytic hierarchy process was $(w_i^-, w_i^+)_{n \times n}$.

(5) Solve the index weight. Took the average value of the weight interval (w_i^-, w_i^+) as the weight of each index as follows:

$$w_i = \frac{(w_i^- + w_i^+)}{2} \quad (4)$$

The calculation results were normalized, then the index weight $W = (w_1, w_2, \dots, w_n)$ can be obtained.

4. Fuzzy set theory

Indicated by the above index system, the factors influencing the selection of the project delivery system mode is highly fuzzy. It is very difficult to precisely and quantitatively analyze them. However, the theory of fuzzy sets is the judgment method which can effectively solve fuzziness, and also the evaluation effect is relatively objectives and reasonable. The paper adopted the theory of fuzzy sets to select the delivery mode^[17,18]. The detailed steps are as follows:

(1) Determine the evaluation factor set U . $U = \{u_1, u_2, \dots, u_n\}$, u_i is the i^{th} evaluation factor of the subject to be evaluated;

(2) Determine the judgment set V . $V = \{v_1, v_2, \dots, v_m\}$, v_j is the j^{th} evaluation rank;

(3) Establish the single factor evaluation matrix R . All evaluation factors were evaluated one by one according to the judgment set so as to get the single factor evaluation matrix;

$$R = \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1m} \\ r_{21} & r_{22} & \cdots & r_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ r_{n1} & r_{n2} & \cdots & r_{nm} \end{bmatrix} \quad i=1,2,\dots,n; \quad j=1,2,\dots,m \quad (5)$$

Wherein, r_{ij} is the membership degree of the judgment factor u_i of the evaluated object, to the judgment grade v_j ;

(4) Determine index weight W . $W = \{w_1, w_2, \dots, w_n\}$, $\sum_{i=1}^n w_i = 1$, w_i is the relative significance of the i^{th} judgment factor;

(5) Synthetic evaluation. Select the composition operator, and then compose the weight W with the single factor evaluation matrix R to get the synthetic evaluation vector. The common composition operators include (\wedge, \vee) , $(\bullet, +)$, etc.;

(6) Sorting identification: select the corresponding identification principles, such as the maximum value, the maximum membership degree method, etc., and the sorting identification was carried out to the evaluated subject according to the synthetic evaluation result.

5. Case Analysis

A construction project intends to select the most applicable delivery mode from four delivery modes including DBB, DB, EPC and CM. Twenty experts from the relevant fields are invited for deciding the selection of the delivery mode of the project. For convenient evaluation, the index evaluation grades were set as A, B, C, D and E. Based on the established index evaluation system, experts were asked to directly judge the second level indexes according to the fitness between the index and the evaluated object, and then it was analyzed according to the experts' evaluation results.

5.1 Determination of membership degree matrix

According to the corresponding evaluation results given by the experts, the number of the experts of the corresponding same evaluation scale of each evaluation index of each delivery mode was counted, and then divided by the total number of experts to get the corresponding membership degree matrix. Set N_{ij} as the number of experts of the evaluation factor u_i under a mode given by the experts and about the evaluation scale v_j , then:

$$r_{ij} = N_{ij} / N \quad (6)$$

Wherein, N is the total number of experts who participate in the decision-making. Take DBB mode as an example, according to the experts' evaluation results, the evaluation data are processed according to formula (6), and then all membership degree matrixes are solved as follows:

Table 2 Membership degree matrix R_{11} of project property C_1 of DBB mode

	Excellent	Good	Medium	Bad	Terrible
Project scale C_{11}	0.75	0.15	0.10	0	0
Project technical difficulty C_{12}	0.50	0.30	0.20	0	0
Project economic property C_{13}	0	0.30	0.40	0.30	0
Project designed depth C_{14}	0.20	0.50	0.15	0.15	0

Table 3 Membership degree matrix R_{12} of owner management ability, experience and requirement C_2 of DBB mode

	Excellent	Good	Medium	Bad	Terrible
Owner's management ability and experience	0.35	0.40	0.20	0.05	0

C_{21}					
Owner's requirements on time limit C_{22}	0.50	0.35	0.15	0	0
Owner's requirements on quality C_{23}	0.70	0.20	0.10	0.30	0
Owner's requirements on investment control C_{24}	0.55	0.20	0.15	0.10	0

Table 4 Membership degree matrix R_{13} of project construction environment C_3 of DBB mode

	Excellent	Good	Medium	Bad	Terrible
Project construction condition C_{31}	0.75	0.15	0.10	0	0
Potential contractor's competitiveness C_{32}	0.80	0.20	0	0	0
Completeness of construction rules C_{33}	0.75	0.20	0.05	0	0
Integrity of market subject C_{34}	0.55	0.20	0.15	0.10	0

5.2 Confirmation of index weight

Relevant experts were invited to progressively give out the interval judgment values of the relative degree of importance of each index about the relative degree of importance of each index. To ensure the accuracy of the evaluation results, the judgment value of the index is often given by multiple experts. Take the project property C_1 as an example, the interval judgment value A_{C_1} of the relevant significance given by the experts are shown as table 5:

Table 5 Judgment matrix of index of project property C_1

	Project scale C_{11}	Project technical difficulty C_{12}	Project economic property C_{13}	Project designed depth C_{14}
Project scale C_{11}	(1,1)	(1,2)	(2,3)	(1,2)
Project technical difficulty C_{12}	(1/2,1)	(1,1)	(1,2)	(1,1)
Project economic property C_{13}	(1/3,1/2)	(1/2,1)	(1,1)	(1/2,1)
Project designed depth C_{14}	(1/2,1)	(1,1)	(1,2)	(1,1)

Split the judgment matrix to get:

$$A_{C_1}^- = \begin{bmatrix} 1 & 1 & 2 & 1 \\ 1/2 & 1 & 1 & 1 \\ 1/3 & 1/2 & 1 & 1/2 \\ 1/2 & 1 & 1 & 1 \end{bmatrix} \quad A_{C_1}^+ = \begin{bmatrix} 1 & 2 & 3 & 2 \\ 1 & 1 & 2 & 1 \\ 1/2 & 1 & 1 & 1 \\ 1 & 1 & 2 & 1 \end{bmatrix}$$

Solved the dissymmetry interval matrix:

$$B_{C_1}^- = \begin{bmatrix} 0 & 0 & 0.69 & 0 \\ -0.69 & 0 & 0 & 0 \\ -1.10 & -0.69 & 0 & -0.69 \\ -0.69 & 0 & 0 & 0 \end{bmatrix} \quad B_{C_1}^+ = \begin{bmatrix} 0 & 0.69 & 1.39 & 1.10 \\ 0 & 0 & 0.69 & 0 \\ -1.10 & 0 & 0 & 0 \\ -0.69 & 0 & 0.69 & 0 \end{bmatrix}$$

The optimum transfer matrix:

$$T_{C_1}^- = \begin{bmatrix} 0 & 0.35 & 0.79 & 0.35 \\ -0.35 & 0 & 0.45 & 0 \\ -0.79 & -0.45 & 0 & -0.45 \\ -0.35 & 0 & 0.45 & 0 \end{bmatrix} \quad T_{C_1}^+ = \begin{bmatrix} 0 & 0.62 & 1.07 & 0.79 \\ -0.62 & 0 & 0.45 & 0.17 \\ -1.07 & -0.45 & 0 & -0.27 \\ -0.79 & -0.17 & 0.27 & 0 \end{bmatrix}$$

Consistency interval matrix:

$$A_{C_1}^{*-} = \begin{bmatrix} 1 & 1.41 & 2.21 & 1.41 \\ 0.71 & 1 & 1.57 & 1 \\ 0.45 & 0.64 & 1 & 0.64 \\ 0.71 & 1 & 1.57 & 1 \end{bmatrix} \quad A_{C_1}^{*+} = \begin{bmatrix} 1 & 1.86 & 2.91 & 2.21 \\ 0.54 & 1 & 1.57 & 1.19 \\ 0.34 & 0.64 & 1 & 0.76 \\ 0.45 & 0.84 & 1.32 & 1 \end{bmatrix}$$

According to formula (3), normalized the consistency interval matrix to solve the weight of each index:

$$W_{C_1}^- = (0.35, 0.25, 0.16, 0.25), \quad W_{C_1}^+ = (0.43, 0.23, 0.15, 0.19)。$$

According to the calculation and solution of formula (4), the weight of the index of the project property C_1 is: $W_{C_1} = (0.39, 0.24, 0.15, 0.22)$.

In the same way, it can get:

The weights of the indexes of owner management ability and experience and requirement C_2 are:

$$W_{C_2} = (0.25, 0.25, 0.25, 0.25);$$

The weight of the index of project construction environment C_3 is: $W_{C_3} = (0.28, 0.32, 0.20, 0.20)$;

The weight of first level indexes is: $W_C = (0.46, 0.26, 0.28)$ 。

5.3 Synthetic evaluation

The $M(\bullet, +)$ composition operator was used for the evaluation calculation grade by grade by taking the DBB mode as the example and according to the experts' evaluation results and weight calculation results. Firstly, the calculation of second level indexes was carried out, and the composition operation of the three evaluation matrixes of R_{11} , R_{12} and R_{13} of the second level indexes with the corresponding weight coefficient was respectively carried out. Then the evaluation results of the indexed of grade 2 were obtained as follows:

$$B_1 = W_{C_1} R_{11} = (0.455 \quad 0.286 \quad 0.181 \quad 0.079 \quad 0)$$

$$B_2 = W_{C_2} R_{12} = (0.525 \quad 0.288 \quad 0.150 \quad 0.038 \quad 0)$$

$$B_3 = W_{C_3} R_{13} = (0.726 \quad 0.186 \quad 0.068 \quad 0.020 \quad 0)$$

Based on the weights W_C of the first level indexes and the evaluation results B_1 , B_2 and B_3 of the second level indexes, the synthetic evaluation results could be obtained as follows:

$$B = W_C [B_1 \quad B_2 \quad B_3]^T = (0.549 \quad 0.258 \quad 0.141 \quad 0.052 \quad 0)$$

In the evaluation result B , 0.549 is the membership degree of the evaluated objet DBB mode to the evaluation equivalence A as well as 0.258 for B, 0.141 for C and 0.052 for D. The scores of 1.0, 0.8, 0.6, 0.4 and 0.2 were respectively given to the evaluation grades. Then the score set $E = (1 \quad 0.8 \quad 0.6 \quad 0.4 \quad 0.2)$, the composition calculation of the synthetic evaluation results and the score set was carried out, and then the score S_{DBB} of the DBB mode was solved as:

$$S_{DBB} = BE^T = (549 \quad 0.258 \quad 0.141 \quad 0.052 \quad 0) (1 \quad 0.9 \quad 0.75 \quad 0.6)^T = 0.861。$$

In the same way, the score S_{DB} of the DBB mode was 0.873, the score S_{EPC} of EPC mode was 0.802 and the score S_{CM} of CM mode was 0.747.

5.4 Sorting identification

It can be seen from the above calculation results, the total scores of the four delivery modes are sorted as DB > DBB > EPC > CM, which proves the most applicable delivery mode for the project is the DB mode, the DBB mode takes second place, and the CM mode is the most inapplicable. According to the evaluation results, the owner can select the most applicable delivery mode of the project.

6. Conclusion

The project delivery system mode determines the contract pricing type, project management mode and the relationship of rights, interests and liabilities and risk allocation among all participants, etc. For the owner, the selection of the delivery mode relates to the success or failure of project construction. However, the project construction is often complicated, and there are many influence factors. Different delivery modes have different characteristics and applicable conditions. How to select the most applicable delivery mode according to the project construction characteristics is crucial. Under the precondition of comprehensively considering the influence factors of the delivery mode, the paper sufficiently considered the uncertainty and fuzziness during index evaluation and weight confirmation, and constructed the model of the delivery mode decision of the project on the basis of the improved uncertain AHP and the theory of fuzzy sets. Proven by actual cases, the model can rapidly and effectively decide the most applicable delivery mode according to the project characteristic and provide reference for the owner's decision of selecting the delivery mode.

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