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An Uncertain Multiple Attribute Decision Making Model for Choosing Project Delivery Methods of Power Transmission Project

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Abstract

The investments of power transmission projects are steadily increasing in recent 20 years. However, it is rare to investigate the suitability of the project delivery methods for power transmission projects. In fact, it is not an easy task to select an appropriate project delivery method as a large amount of ambiguous and uncertain information exists. This paper thus aims to develop an uncertain multiple attribute decision making (MCDM) model to help owners of power transmission projects to choose a suitable project delivery method. Based on review of previous studies, several decision-making attributes were identified including capacity of owners, preference of owners, capacity of contractors, project characteristics and market factors. Decision-making rules were determined by using uncertain decision making operators. The weighting of different attributes was examined by analytic hierarchy process (AHP). The evaluation values of different alternatives were calculated by the uncertain MCDM model. The real case study was conducted to verify the feasibility of the proposed model. The practical application of the proposed uncertain MCDM model is expected to benefit the owner's decision making in the selection of the project delivery methods of power transmission projects.

Subject Areas

Civil Engineering, Electric Engineering

Keywords

Project Delivery Methods, Power Transmission Projects, Uncertain Multiple Attribute Decision Making

1. Introduction

With the rapid urbanization development in China, the construction and transmission capacity of power grid have been greatly improved. In past 20 years, over 20 ultra-high vacuum power transmission projects have been completed in China (State Grid 2022) [1]. Investment in 2020 was over 473.4 billion (State Grid 2022) [1]. Most of power transmission projects were delivered by traditional design-bid-build (DBB) method. However, it becomes difficult for project owners to manage contractors from different power transmission projects. Problems gradually exit, for example, unprofessional construction management, weak initiative of project participants and waste of construction materials. In recent years, Engineering Procurement Construction (EPC) contract has been adopted in several pilot power transmission projects.

The power system reform was promoted until 2015. The target of power system reform sets to establish a uniform power market in the whole country. In Fourteenth Five Year Plan, the Chinese government clearly put forward to promote market-oriented reform of competitive links in energy, railway, telecommunications, public utilities and other industries (State Council, 2021) [2]. In 2020, the National Development and Reform Commission has proposed to complete the three year action plan of mixed-ownership reform and steadily push forward the reform on power grid and railways (National Development and Reform Commission, 2020) [3]. Therefore, different project delivery methods will be applied to power transmission projects, which induce competitiveness and huge changes on current project contracting methods.

In fact, there are different project delivery methods that have been applied to power transmissions projects, including DBB, Design-build (DB) and EPC. However, it is still uncertain about how to select the appropriate project delivery method for different kinds of power transmission projects. The investigation on indicators of project delivery selection for specific power transmission projects has been limited. Hence, this paper aims at investigating the uncertain multiple attribute decision making (MADM) method for project delivery selection of power transmission projects. It will provide empirical suggestions on contract methods and project delivery methods for power transmission projects under the power market-oriented reform in China.

2. Project Delivery Selection

Project delivery is defined as a process by which designers, constructors, and various consultants provide professional services for completing project to the owner (Molenaar *et al.* 2010) [4]. Project delivery facilitates the organization of project participants to interact for transforming the owner's objectives into finished buildings (ASCE, 2000) [5]. It is one of critical factors of project success which significantly influences the delivery of project schedule, cost, quality and contract management (Al Khalil, 2002 [6]; Kumaraswamy & Dissanayaka, 2001 [7]). Therefore, it has been attracted attentions from previous researchers on selecting an appropriate project delivery method for specific project types (Hong *et al.*, 2008 [8]; Ojiako *et al.*, 2008 [9]; Oyetunji & Anderson, 2006 [10]).

In order to meet different objectives of power transmission projects, a variety of delivery systems have been adopted including traditional DBB, DB and EPC (Chen *et al.*, 2005) [11]. Different delivery systems define the sequence of events, contractual obligations, participant relationships, and specific mechanisms for overseeing project performance (Dorsey 1997) [12]. DBB is the most used method for power transmission projects. Under DBB, the power project owners are required to separate project design and construction contracts to different qualified companies. The design bids are early than construction bids. Normally, the contractors with the lowest bidding prices build such projects. Due to the separation of design works and construction projects, DBB has several shortcomings that result in frequent claims and disputes between the project participants and cost and time overruns.

Both DB and EPC are classified as integrated project delivery methods which integrate project design and construction. In power sector, EPC has been increasingly applied into electrical power station projects and photovoltaic power projects (Zhao *et al.*, 2020) [13]. But the applications of DB and EPC in power transmission projects are still limited. Power transmission projects involve enormous investment, in which over 60% of investments are spent on electricity equipment. In consideration of high standards on electricity equipment, the procurement of equipment is directly organized by the project owner. Hence, the applications of EPC on power transmission projects are rare. In recent years, there are several pilot power transmission projects which are attempted to adopt DB and EPC as project delivery methods for improving efficiency of project investment and management (Wu *et al.*, 2006) [14].

The selection of project delivery methods is influenced by several factors, which have been investigated by previous studies (Chen *et al.*, 2016 [15] [16]; Qiang *et al.*, 2015 [17]). Owner's abilities including technical ability, financing ability, project management ability and project experiences are identified as prominent factors affecting project delivery selection (Chan *et al.*, 2004) [18]. Generally, more experienced clients are more skilled in construction technology and prefer more control in projects (Yang *et al.*, 2010) [19]. They will prefer to apply traditional DBB method. In China, owners would evaluate their technical ability and past experience, and then make trade-off of authority with consultants and contractors (Lu *et al.*, 2015) [20].

Due to the long history of the planned economy environment, many Chinese owners' preferences influence the selection of project delivery methods. As contractors share abundant risks under EPC method, the bid prices of EPC are often higher than DBB. If project prices are regarded as important for the owners, the owners might not choose DB nor EPC methods (Chen *et al.*, 2016) [15] [16]. Normally, project outcome performance such as schedule, cost and quality performances are considered universally as basic factors for project delivery selection (Chen *et al.*, 2009) [21]. In China, project delivery methods should be tailored for accommodation of owners' business culture, including risk allocation and management modes (Qiang *et al.*, 2015) [17].

Project characteristics including project complexity, project size and project investment scales are the primary concern of owners when selecting project delivery methods (Azhar *et al.*, 2014) [22]. Project complexity is composed of technical complexity and organizational complexity, and the organizational complexity should be tailored to the technical complexity (Baccarini, 1996) [23]. Project size and investment scales are other dimension reflecting how challenging the project is. Project size together with project investment scales may contribute to project risks and affect the risk allocation among participants (Chen *et al.*, 2011) [24].

Market factors are also critical for project delivery selection. As construction laws and regulations on construction projects in China are still rigorous, it should be considered firstly before making decisions on project delivery methods (Qiang *et al.*, 2015) [17]. Over the years, China's construction industry has been soaring with more and more mega projects delivered by Chinese companies. No. of suitable contractors in the market and contractors' credibility should be put more emphasis. Clients should confirm that there are sufficient competent and credible contractors in the market before proceeding with a certain project delivery method (Chen *et al.*, 2004) [18].

3. Uncertain Multiple Attribute Decision Making Model

3.1. Indicators of the Project Delivery Selection

Based on literature review, 19 decision-making attributes for project delivery were determined. In order to ensure the feasibility of decision-making attributes, eight professionals with over 10 years working experiences on power transmission projects were invited to review the initial attributes. Professional experts were interviewed to revise the decision-making attributes in consideration of characteristics of power transmission projects. Terrain condition and length of transmission projects were included in the attributes. One attributed named as preference on market shares was deleted due to the monopolistic characteristics of power transmission projects. There were totally 20 attributes which were classified into four categories, *i.e.*, capacity of owners, preference of owners, capacity of contractors, project characteristics and market factors (**Table 1**).

In order to use decision making attributes listed in **Table 1** for select appropriate project delivery methods, the decision making rules were further defined in consideration of construction laws and regulation and contracts of different project delivery methods (**Table 2**). These decision making rules of different attributes were adopted in the uncertain multiple attribute decision making (MADM) model for project delivery selection of power transmission projects.

3.2. Project Delivery Selection Model

In order to choose appropriate project delivery methods of power transmission

Table 1. Decision-making attributes for project delivery methods of power transmission projects.

Categories	Items	Decision-Making Attributes
C1: Capacity of owners	A1	Project management capacity of owners
	A2	Similar project experiences of owners
C2: Preference of owners	A3	Preference on project prices
	A4	Preference on project progress
	A5	Preference on project quality
	A6	Preference on involvement in project design
	A7	Preference on involvement in procurement of materials and equipment
	A8	Preference on risk allocation among project participants
	A9	Attitude on project changes
C3: Capacity of contractors	A10	Construction management capacity of contractors
	A11	Project implementation ability of contractors
	A12	Similar project experiences of contractors
	A13	Reputation of contractors
C4: Project Characteristics	A14	Project investment scales
	A15	Project complexity
	A16	Terrain condition
	A17	Length of transmission projects
C5: Market factors	A18	Similar project in the markets
	A19	No. of suitable contractors in the market
	A20	Mandatory requirements of project delivery by construction laws and regulations

Table 2. Decision-making rules for each attribute for project delivery methods of power transmission projects.

Items	Decision-Making Attributes	Decision-Making Rules
C1: Capacity of owners		
A1	Project management capacity of owners	The evaluation value of technical and management capacities of owners
A2	Similar project experiences of owners	No. of previous projects experienced by the owners
C2: Preference of owners		
A3	Preference on project prices	$= \frac{\text{Actural contract price} - \text{normal project price}}{\text{Normal project price}}$
A4	Preference on project quality	$= \frac{\text{Material quality} + \text{Workmanship quality} + \text{Design quality}}{3}$
A5	Preference on project progress	$= \frac{\text{Actural duration} - \text{normal anticipated duration}}{\text{Normal anticipated duration}}$
A6	Preference on involvement in project design	Working time of owners' involvement in project design

Continued

A7	Preference on involvement in procurement of materials and equipment	No. of suppliers chosen by owners; Amounts of materials and equipment purchased by owners
A8	Preference on risk allocation among project participants	Risk preference of owners and contractors
A9	Attitude on project changes	No. of project changes
C3: Capacity of contractors		
A10	Construction management capacity of contractors	The evaluation value of technical and management capacities of contractors
A11	Project implementation ability of contractors	No. of projects completed by the contractors
A12	Similar project experiences of contractors	No. of previous projects experienced by the contractors
A13	Reputation of contractors	No. of awards of the contractors
C4: Project Characteristics		
A14	Project investment scales	Project investment amounts
A15	Project complexity	The evaluation value of project complexity
A16	Terrain condition	Terrain condition of transmission projects
A17	Length of transmission projects	Length of transmission projects
C5: Market factors		
A18	Similar project in the markets	No. of similar projects
A19	No. of suitable contractors in the market	No. of suitable contractors in the market
A20	Mandatory requirements of project delivery by construction laws and regulations	No. of mandatory requirements of project delivery

projects, an uncertain MADM was developed as shown in Figure 1. By adopting an uncertain MADM model, the proposed model is composed of several steps: Setting decision objective, Determining decision-making attributes, Developing decision-making rules, Calculating weightings, Calculating group evaluation value of each alternative, Determining ranking of each alternative, and Selecting appropriate project delivery method. The framework of the uncertain MADM model can be shown in Figure 1.

The uncertain MADM Model can be calculated with following steps:

1) Weighting of decision-making attributes were determined by professional experts. The weighting of different attributes was represented as $\omega = \left(\omega_1, \omega_2, \cdots, \omega_n\right)$, with $\omega_j \in \left[0,1\right]$, ($j = 1, 2, \cdots, 20$), $\sum_{j=1}^{n} \omega_j = 1$.

2) Three project delivery methods, which were DBB, DB and EPC, were commonly used in power transmission projects. Hence, it was assumed that three alternatives would be chose, which were expressed as $x_i \in X \left(i = 1, 2, 3\right)$.

3) Decision maker D_k should determine uncertain language assessment value $\tilde{r}_{ij}^{(k)}$ of each attribute A_i. The assessment matrix was then calculated as $\tilde{R}_k = \left(\tilde{r}_{ij}^{(k)}\right)_{3\times21}, \tilde{r}_{ij}^{(k)} \in \tilde{S}$.

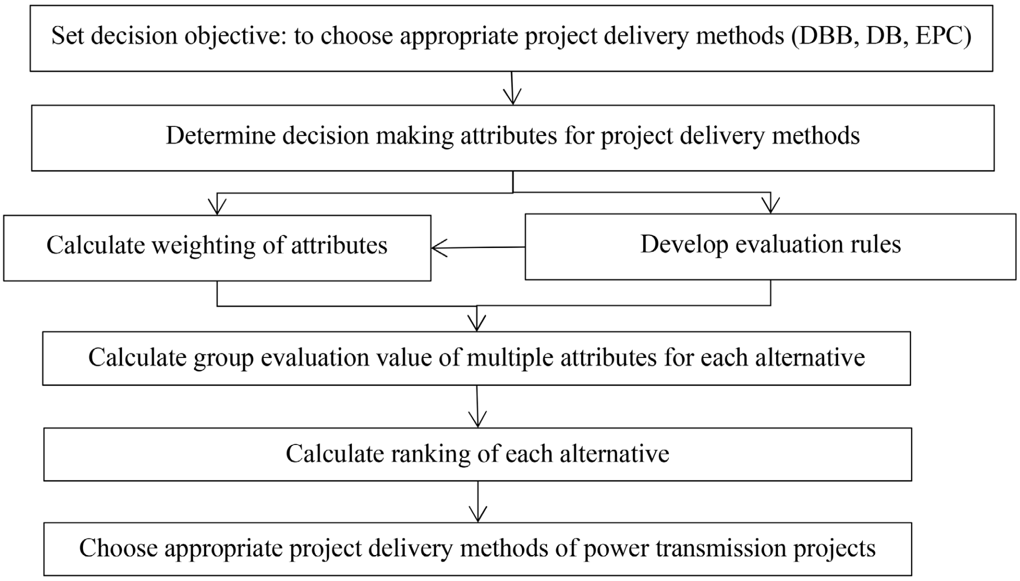

Figure 1. The framework of uncertain MADM model for project delivery of power transmission projects.

4) Uncertain extended weighted arithmetic average (UEWAA) operator was used to estimate the evaluation value of multiple attributes for each alternative x_i. The evaluation value of multiple attributes for each alternative x_i was represented as $\tilde{z}_i^{(k)}(\omega)(i=1,2,3;k=1,2,\cdots,t)$.

The UEWAA operator was calculated with following equation.

$$\mathrm{UEWAA}_{\omega}(\tilde{\mu}_1,\tilde{\mu}_2,\cdots,\tilde{\mu}_n)=\omega_1\tilde{\mu}_1\oplus\omega_1\tilde{\mu}_1\oplus\cdots\oplus\omega_n\tilde{\mu}_n$$

where $\omega=(\omega_1,\omega_2,\cdots,\omega_n)$ was weight vector of uncertain language variables $(\tilde{\mu}_1,\tilde{\mu}_2,\cdots,\tilde{\mu}_n)$.

5) Uncertain linguistic hybrid aggregation (ULHA) operator was further used to estimate the group evaluation value of multiple attributes for each alternative. It was calculated as:

$$\begin{aligned}\tilde{z}_i(\lambda,w')&=\mathrm{ULHA}_{\lambda,w'}\left(\tilde{r}_i^{(1)},\tilde{r}_i^{(2)},\cdots,\tilde{r}_i^{(n)}\right)\\&=\omega_1'\tilde{v}_i^{(1)}\oplus\omega_2'\tilde{v}_i^{(2)}\oplus\cdots\oplus\omega_t'\tilde{v}_i^{(t)},i=1,2,3\end{aligned}$$

where $w'=(w_1',w_2',\cdots,w_n')$ was weight vector of ULHA operator $w_k'\in[0,1](k=1,2,\cdots,t)$.

6) Both UEWAA operator and ULHA operator were applied to determine the ranking of different alternatives by using following equation.

$$v_P\left\{\mathrm{ULHA}_{\lambda,w}^{(i)}\left[\mathrm{UEWAA}_{\omega}^{(k,i)}\left(\tilde{r}_{ij}^{(k)}\right)\right]\right\}$$

where $\tilde{r}_{ij}^{(k)}$ was the uncertain language assessment value of $x_i\in X\ (i=1,2,3)$;

$\mathrm{UEWAA}_{\omega}^{(k,i)}$ was the aggregated value of uncertain language assessment value of different alternatives;

$\mathrm{ULHA}_{\lambda,w}^{(i)}$ was the group evaluation value of multiple attributes for each alternative;

v_p was the ranking of group evaluation value of each alternative.

(6) Value of each alternatives ($p_{ij} = p\left(\tilde{z}_i\left(\lambda, w'\right) \geq \tilde{z}_j\left(\lambda, w'\right)\right)\left(i, j = 1, 2, 3\right)$) was determined by following rules. The possibility matrix was also established as $P = \left(P_{ij}\right)_{3\times3}$.

Rule 1: $p\left(\tilde{a} \geq \tilde{b}\right) = \dfrac{\min\left\{l_{\tilde{a}} + l_{\tilde{b}}, \max\left(a^U - b^U, 0\right)\right\}}{l_{\tilde{a}} + l_{\tilde{b}}}$

Rule 2: $p\left(\tilde{a} \geq \tilde{b}\right) = \min\left\{\max\left(\dfrac{a^U - b^U}{l_{\tilde{a}} + l_{\tilde{b}}}, 0\right), 1\right\}$

7) Based on possibility matrix *P*, the ranking of each alternative was obtained by using the equation of $v_i = \dfrac{1}{n(n-1)}\left(\sum_{j=1}^{n} p_{ij} + \dfrac{n}{2} - 1\right), i = N$. With the ranking of each alternative ($v = \left(v_1, v_2, v_3\right)$), decision makers can choose the optimum alternative for project delivery methods of power transmission projects.

4. Case Study

The case project is a 220 kV transmission line which is build based on general design of State Grid. The length of transmission project is 178.1 kilometers. The project estimates are over RMB 70,739 million. The planned project duration is 24 months. The transmission project is designed to cross railway project. The highest power tower is over 300 meter, which significantly increases construction difficulty. 15 experts with previous transmission project experiences were invited to evaluate the weighting of 20 decision-making attributes listed in Table 1. The analytic hierarchy process (AHP) was applied to calculate the weighting of different attributes. The AHP method, which was developed by Saaty (1990) [25], is a multi-criteria decision making method and helps to obtain the best decision among several vital alternatives considering the various attributes (Naziris *et al.*, 2016 [26]; Higgins and Benaroya, 2020 [27]; Wang *et al.*, 2022 [28]). The key steps of the method are as follows:

Step 1: Building the AHP model. The goals, factors and objects of decision are divided into the highest level, middle level and lowest level according to their mutual relations.

Step 2: Building pairwise comparison matrix. According to Saaty (1990) [25], factors should compare two factors or items with each other to improve accuracy. The matrix equation is

$$A = \left(a_{ij}\right)_{n\times n} = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{bmatrix}$$

where a_{ij} is the importance of criterion *i* compared with criterion *j*. $a_{ij} > 0$, $a_{ij} \times a_{ji} = 1$ and the nine importance intensities given by Saaty and their assignments are listed in Table 3.

Step 3: Examining for consistency. The consistency index (*CI*) defined as *CI* =

$(\lambda_{\max} - n)/(n - 1)$, where $\lambda_{\max}$ and n are the maximum eigenvalue and the size of the matrix, respectively. The consistency fraction (CR) is calculated as $CR = CI/RI$. The random index values (RI) is shown in **Table 4**. The acceptable upper bound of CR is 0.10. If the consistency ratio is above 0.10, then the decision maker needs to revise decisions.

Step 4: Calculating the normalized matrix of each attribute.

Step 5: Hierarchical single sorting and hierarchical global sorting. Hierarchical single sorting is the ranking of the importance weights of attributes related to the attribute in the previous level. The ranking of the relative importance weights of all attributes in a certain level to the top level is called hierarchical global sorting, which is conducted from the highest level to the lowest level in turn. The results were illustrated in **Table 5**.

In order to select project delivery methods for the case project, three professional experts were invited to evaluate three project delivery methods (*i.e.*, DBB, DB and EPC) based on decision-making rules of each attribute. The evaluation results were adopted to establish decision-making judgement matrix (**Table 6**).

Based on the weighting and decision-making matrix listed in **Table 5** and **Table 6**, the UEWAA operator ($\mathrm{UEWAA}_{\omega}(\tilde{\mu}_1, \tilde{\mu}_2, \cdots, \tilde{\mu}_n) = \omega_1 \tilde{\mu}_1 \oplus \omega_1 \tilde{\mu}_1 \oplus \cdots \oplus \omega_n \tilde{\mu}_n$) was calculated in order to estimate the evaluation value of multiple attributes for each project delivery method. The evaluated value for DBB which was assessed by Expert 1 was estimated as following equation, where ω_i is calculated in **Table 5** and $\tilde{\mu}_i$ refers to the opinions of Expert 1 shown in **Table 6**. The evaluation value of different project delivery methods was illustrated in **Table 7**.

$$\begin{aligned}
\tilde{z}_1^1 = {} & 0.0959 \times [S_{-2}, S_{-1}] \oplus 0.0320 \times [S_{-1}, S_0] \oplus 0.0272 \times [S_{-1}, S_1] \oplus 0.0405 \times [S_2, S_3] \\
& \oplus 0.0741 \times [S_{-3}, S_{-1}] \oplus 0.0601 \times [S_1, S_2] \oplus 0.0452 \times [S_{-2}, S_{-1}] \oplus 0.0673 \times [S_1, S_2] \\
& \oplus 0.0580 \times [S_0, S_1] \oplus 0.0355 \times [S_{-1}, S_0] \oplus 0.0378 \times [S_1, S_2] \oplus 0.0448 \times [S_{-1}, S_{-1}] \\
& \oplus 0.0397 \times [S_{-2}, S_{-1}] \oplus 0.0514 \times [S_1, S_2] \oplus 0.1081 \times [S_2, S_3] \oplus 0.0411 \times [S_2, S_3] \\
& \oplus 0.0544 \times [S_{-2}, S_{-1}] \oplus 0.0284 \times [S_1, S_2] \oplus 0.0235 \times [S_2, S_3] \\
= {} & [S_{0.2819}, S_{2.0139}]
\end{aligned}$$

ULHA operator was further used to estimate the group evaluation value of multiple attributes for each alternative. Take DBB as an example, the group evaluation value was estimated as:

Table 3. Saaty's scale for pair-wise comparisons.

Importance intensity	Definition
1	Equal importance
3	Moderate importance
5	Strong importance
7	Very strong importance
9	Absolute importance
2, 4, 6, 8	Intermediate values

Table 4. Random index value table.

n	1, 2	3	4	5	6	7	8	9	10
RI	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

Table 5. Weighing of Decision-making attributes and consistency test.

Item	ω_i	Categories of decision-making attributes					Weighting of decision-making attributes	Consistency test	Integrated consistency test
		C1	C2	C3	C4	C5			
		0.1279	0.3724	0.1579	0.2358	0.1149			$\lambda_{\max} = 4.1179$ CI = 0.0393 RI = 0.090 CR = 0.0437 < 1
A1	ω_1	0.7500					0.0959	$\lambda_{\max} = 2$ CI = 0	
A2	ω_2	0.2500					0.0320		
A3	ω_3		0.0731				0.0272	$\lambda_{\max} = 9.6277$ CI = 0.0785 RI = 1.45 CR = 0.0541 < 1	
A4	ω_4		0.1088				0.0405		
A5	ω_5		0.1989				0.0741		
A6	ω_6		0.1613				0.0601		
A7	ω_7		0.1215				0.0452		
A8	ω_8		0.1807				0.0673		
A9	ω_9		0.1557				0.0580		
A10	ω_{10}			0.2250			0.0355	$\lambda_{\max} = 8.1531$ CI = 0.08339 RI = 1.23 CR = 0.0678 < 1	
A11	ω_{11}			0.2396			0.0378		
A12	ω_{12}			0.2838			0.0448		
A13	ω_{13}			0.2516			0.0397		
A14	ω_{14}				0.2178		0.0514	$\lambda_{\max} = 7.5814$ CI = 0.0685 RI = 1.81 CR = 0.0378 < 1	
A15	ω_{15}				0.1497		0.0353		
A16	ω_{16}				0.4583		0.1081		
A17	ω_{17}				0.1742		0.0411		
A18	ω_{18}					0.4736	0.0544	$\lambda_{\max} = 4.2174$ CI = 0.0725 RI = 0.90 CR = 0.0805 < 1	
A19	ω_{19}					0.2473	0.0284		
A20	ω_{20}					0.2049	0.0235		

$$
\begin{aligned}
\tilde{z}_1(\lambda,\omega) &= 0.067\times\left[S_{0.2819}, S_{2.0139}\right] \oplus 0.267\times\left[S_{-0.3045}, S_{1.2467}\right] \\
&\quad \oplus 0.666\times\left[S_{-0.1055}, S_{1.8221}\right] \\
&= \left[S_{-0.1327}, S_{1.6813}\right]
\end{aligned}
$$

Based on the equation of $p_{ij} = p\left(\tilde{z}_i\left(\lambda, w'\right) \geq \tilde{z}_j\left(\lambda, w'\right)\right)\left(i, j = 1, 2, 3\right)$, the possibility matrix was developed.

Table 6. Decision-making matrix for three project delivery methods.

$\tilde{R}_i$	Expert 1			Expert 2			Expert 3		
	DBB	**DB**	**EPC**	**DBB**	**DB**	**EPC**	**DBB**	**DB**	**EPC**
A1	$[S_{-2},S_{-1}]$	$[S_2,S_3]$	$[S_2,S_3]$	$[S_{-2},S_0]$	$[S_1,S_3]$	$[S_1,S_3]$	$[S_0,S_1]$	$[S_1,S_2]$	$[S_2,S_3]$
A2	$[S_{-1},S_0]$	$[S_{-2},S_{-1}]$	$[S_{-3},S_{-1}]$	$[S_{-2},S_{-1}]$	$[S_0,S_1]$	$[S_0,S_2]$	$[S_2,S_3]$	$[S_1,S_2]$	$[S_0,S_2]$
A3	$[S_{-1},S_1]$	$[S_{-1},S_1]$	$[S_{-1},S_1]$	$[S_{-3},S_{-2}]$	$[S_1,S_2]$	$[S_1,S_3]$	$[S_1,S_2]$	$[S_1,S_3]$	$[S_1,S_3]$
A4	$[S_2,S_3]$	$[S_1,S_3]$	$[S_{-1},S_2]$	$[S_0,S_1]$	$[S_1,S_3]$	$[S_1,S_2]$	$[S_2,S_3]$	$[S_1,S_3]$	$[S_1,S_2]$
A5	$[S_{-3},S_{-1}]$	$[S_1,S_2]$	$[S_2,S_3]$	$[S_0,S_1]$	$[S_2,S_3]$	$[S_1,S_2]$	$[S_{-1},S_1]$	$[S_1,S_3]$	$[S_2,S_3]$
A6	$[S_1,S_2]$	$[S_2,S_3]$	$[S_2,S_3]$	$[S_2,S_3]$	$[S_1,S_2]$	$[S_{-1},S_1]$	$[S_2,S_3]$	$[S_{-1},S_1]$	$[S_{-2},S_{-1}]$
A7	$[S_{-2},S_{-1}]$	$[S_2,S_3]$	$[S_0,S_2]$	$[S_1,S_2]$	$[S_2,S_3]$	$[S_{-1},S_0]$	$[S_{-2},S_0]$	$[S_0,S_1]$	$[S_0,S_1]$
A8	$[S_1,S_2]$	$[S_2,S_3]$	$[S_2,S_3]$	$[S_{-2},S_{-1}]$	$[S_0,S_2]$	$[S_1,S_2]$	$[S_{-3},S_{-2}]$	$[S_{-2},S_{-1}]$	$[S_{-1},S_0]$
A9	$[S_0,S_1]$	$[S_2,S_3]$	$[S_2,S_3]$	$[S_1,S_2]$	$[S_{-1},S_0]$	$[S_{-1},S_0]$	$[S_2,S_3]$	$[S_{-1},S_0]$	$[S_{-2},S_{-1}]$
A10	$[S_{-1},S_0]$	$[S_1,S_3]$	$[S_1,S_2]$	$[S_{-3},S_{-2}]$	$[S_1,S_2]$	$[S_1,S_3]$	$[S_{-3},S_{-2}]$	$[S_{-2},S_{-1}]$	$[S_{-1},S_0]$
A11	$[S_1,S_2]$	$[S_2,S_3]$	$[S_1,S_3]$	$[S_{-2},S_{-1}]$	$[S_1,S_2]$	$[S_1,S_2]$	$[S_{-3},S_{-2}]$	$[S_1,S_2]$	$[S_1,S_3]$
A12	$[S_{-1},S_{-1}]$	$[S_2,S_3]$	$[S_1,S_3]$	$[S_2,S_3]$	$[S_1,S_2]$	$[S_1,S_2]$	$[S_{-3},S_{-2}]$	$[S_0,S_2]$	$[S_1,S_3]$
A13	$[S_{-2},S_{-1}]$	$[S_2,S_3]$	$[S_2,S_3]$	$[S_{-2},S_{-1}]$	$[S_2,S_3]$	$[S_2,S_3]$	$[S_{-2},S_{-1}]$	$[S_2,S_3]$	$[S_2,S_3]$
A14	$[S_1,S_2]$	$[S_2,S_3]$	$[S_2,S_3]$	$[S_2,S_3]$	$[S_1,S_2]$	$[S_0,S_1]$	$[S_{-1},S_0]$	$[S_1,S_2]$	$[S_2,S_3]$
A15	$[S_2,S_3]$	$[S_1,S_2]$	$[S_0,S_1]$	$[S_{-1},S_0]$	$[S_{-2},S_0]$	$[S_{-3},S_{-1}]$	$[S_2,S_3]$	$[S_0,S_1]$	$[S_{-3},S_{-2}]$
A16	$[S_2,S_3]$	$[S_2,S_3]$	$[S_1,S_2]$	$[S_{-2},S_{-1}]$	$[S_{-3},S_{-1}]$	$[S_{-3},S_{-2}]$	$[S_{-1},S_0]$	$[S_{-3},S_{-1}]$	$[S_{-3},S_{-2}]$
A17	$[S_{-2},S_{-1}]$	$[S_1,S_2]$	$[S_1,S_2]$	$[S_2,S_3]$	$[S_{-1},S_1]$	$[S_{-1},S_0]$	$[S_3,S_{-1}]$	$[S_1,S_2]$	$[S_0,S_1]$
A18	$[S_1,S_2]$	$[S_2,S_3]$	$[S_2,S_3]$	$[S_{-2},S_{-1}]$	$[S_2,S_3]$	$[S_2,S_3]$	$[S_{-2},S_{-1}]$	$[S_2,S_3]$	$[S_2,S_3]$
A19	$[S_1,S_2]$	$[S_2,S_3]$	$[S_2,S_3]$	$[S_2,S_3]$	$[S_1,S_2]$	$[S_0,S_1]$	$[S_{-1},S_0]$	$[S_1,S_2]$	$[S_2,S_3]$
A20	$[S_2,S_3]$	$[S_2,S_3]$	$[S_1,S_2]$	$[S_1,S_3]$	$[S_0,S_1]$	$[S_{-2},S_{-1}]$	$[S_1,S_2]$	$[S_{-2},S_{-1}]$	$[S_{-3},S_{-2}]$

Table 7. Evaluated value of each project delivery method.

Alternatives Experts	**Expert 1**	**Expert 2**	**Expert 3**
DBB	$[S_{0.2819},S_{2.0139}]$	$[S_{-0.3045},S_{1.2467}]$	$[S_{-0.1055},S_{1.8221}]$
DB	$[S_{1.5755},S_{4.0278}]$	$[S_{0.4074},S_{2.6852}]$	$[S_{-0.0978},S_{1.918}]$
EPC	$[S_{0.9942},S_{3.5493}]$	$[S_{-0.2006},S_{1.8221}]$	$[S_{-0.1104},S_{1.5344}]$

$$P=\begin{bmatrix} 0.5 & 0.3299 & 0.4811 \\ 0.6701 & 0.5 & 0.6534 \\ 0.5189 & 0.3466 & 0.5 \end{bmatrix}$$

The ranking of each alternative was obtained as $v=(0.3018, 0.3873, 0.3109)$.

Then the ranking of different project delivery methods is DB > EPC > DBB (Liu *et al.*, 2020) [29]. Therefore, DB is the appropriate project delivery method for the case transmission project.

5. Discussion

In case project, three decision-making attributes (*i.e.*, A1, A5 and A16) were evaluated as important for selecting project delivery methods for power transmission projects. Project management capacity of owners influences owners' decisions on project delivery methods. Normally, the State Grid company is the owner of transmission projects in China. The State Grid has extensive experiences on similar projects and fosters high technical ability for managing transmission projects. They tend to control project and share little authority with consultants. Hence, traditional transmission projects were delivered by DBB method.

Owner's preference on project progress achieved a relatively high weighting among all decision-making attributes. As DB method allows design-builders to have total control over design, scope, and budget, it is more likely that DB projects will be completed within schedule (Chen *et al.*, 2016) [15] [16]. DBB methods are required to conduct design and building tender respectively, which induce long project periods. The case project has tight project schedule, which is more appropriate to use DB method.

Terrain condition was evaluated as the most important decision-making attribute for project delivery method of power transmission projects. Project investment, complexity and schedule of power transmission projects are heavily influenced by terrain condition. The terrain conditions of the case project involve almost mountainous regions with significant altitude difference, which increase the complexity of the project. DB method which combined design and construction was proved to appropriate for complex infrastructure projects (Chen *et al.*, 2016) [15] [16]. Thus, DB was selected as better project delivery project for the case transmission project with complex terrain conditions.

6. Conclusions

In order to select appropriate project delivery methods for power transmission projects, this paper aims at developing the uncertain MADM model. Based on literature review, several decision-making attributes were identified including capacity of owners, preference of owners, capacity of contractors, project characteristics and market factors. The uncertain MADM model is composed of several steps including Setting decision objective, Determining decision-making attributes, Developing decision-making rules, Calculating weightings, Calculating group evaluation value of each alternative, Determining ranking of each alternative, and Selecting appropriate project delivery method. The real case study was conducted to verify the feasibility of the proposed model.

The results indicated that capacity of owners, preference on project progress and terrain conditions were the major attributes influencing the decision on project delivery methods for power transmission projects. Based on the calculation of the uncertain MADM model, DB method was finally chosen as appropriate project delivery method for the case transmission project. The results were expected to be further applied in the case project and provide empirical evidence on the project delivery methods of power transmission projects.

Conflicts of Interest

The authors declare no conflicts of interest.

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