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PROJECT EXTERNAL ENVIRONMENTAL FACTORS AFFECTING PROJECT DELIVERY SYSTEMS SELECTION

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Abstract. Project delivery systems (PDSs) selection is crucial to construction project management success. The matching between construction projects and PDSs is hypersensitive to project external environment. Existing studies on selecting PDSs mainly focus on owner's and project's characteristics and attach less attention to project environmental factors. This study, therefore, aims to formally identify key project external environmental factors affecting PDSs selection using a data-driven approach. Key factors are summarized and identified through the granular computing method based on 61 Chinese project samples. Empirical results indicate that four factors including market competitiveness, technology accessibility, material availability, and regulatory impact are critical to PDSs selection. This study extended previous research findings on PDSs selection from a perspective of project external environments. Research conclusions can be used as references underpinning construction owners selecting appropriate PDSs considering project external environmental factors.

Keywords: project external environment, project delivery systems, granular computing, empirical study, key factors, Chinese projects.

Notations

Variables and functions

- *C* – condition attribute set;
- *D* – decision attribute set;
- *GD* – granularity of condition attributes;
- *F* – information function;
- *RED* – reduction set;
- *S* – decision table;
- *Sig.* – significance of condition attribute;
- *U* – universal decision set;
- *V* – range of *F*;
- *Y* – absolute D-value between the significance of condition attributes and decision attributes.

Abbreviations

- PDS – Project Delivery System;
- DB – Design-Build;
- DBB – Design-Bid-Build;
- EPC – Engineering Procurement Construction.

Introduction

With the large scale of investments and increasingly complex technologies in construction projects, the delivery of projects, which is a long-term and interactive process intertwined with the implementation of construction projects, is hypersensitive to the project external environment. Consequently, the project external environment[1] plays a significant role in selecting project delivery systems (PDSs). Identifying key factors of the project environment is of great importance to guide owners to select proper PDSs for construction projects.

Additionally, a bunch of traditional decision-making methods have been used to select the optimal PDS for a

[1] In this study, the "environment" refers to the broad sense of the project environment, including the social environment, political environment, and natural environment of the project location rather than the narrow sense of the project's construction environment.

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project, such as multi-attribute analysis (Mafakheri, Dai, Slezak, & Nasiri, 2007), distributed programming and wireless identification technologies (Shin, Chin, Yoon, & Kwon, 2011), the artificial neural network (ANN) method (Chen, Liu, Li, & Lin, 2011), the fuzzy multi-attribute decision-making method (Mostafavi & Karamouz, 2010), and the data envelopment analysis (DEA) method (Chen, H. Lu, W. Lu, & Zhang, 2010). However, determining factors affecting PDSs selection is the precondition of applying all of the above-mentioned methods. Selecting improper factors in those decision-making methods may lead to inaccurate results. Existing research mainly identify factors affecting PDS selection through theoretical analysis with rare empirical perspectives, which are unformal and could be limited by experts' knowledge and background (Konchar & Sanvido, 1998; Ibbs, Kwak, Ng, & Odabasi, 2003; Mafakheri et al., 2007).

To address such issue, Liu et al. (2014), Liu et al. (2015b), Liu, Huo, Liao, Gong, and Xue (2015a), Liu, Huo, Liang, Sun, and Hu (2016), Liu et al. (2017) have conducted a series of empirical studies to identify key factor affecting PDSs selection (i.e. owners' characteristics factors, contractors' characteristics factors, and projects' characteristics factors). However, empirical research has not been conducted on the project's external environment that affects PDSs selection extremely. Therefore, the aim of this study is to identify which project environment factors play a principal role in the selection of PDSs. The contribution of this study lies in two aspects: on one hand, this study employs granular computing method that is data-driven to determine the key environmental factors affecting PDSs selection. On the other hand, project environment extremely influences whether a PDS is fit with a given project, however, relative research on project environment is inadequate. This study, therefore, aims to identify the key project external environment factors that influence PDS selection.

This paper is presented in the following structures. First, a comprehensive literature review of previous research on the factors affecting the decision-making of PDSs (including only the project external environmental factors in this study) is provided. This is followed by a presentation of the questionnaire survey on the influencing factors, a description of the survey results and statistical analysis, and the methodological principle of granular computing. Finally, the granular computing model is applied to reduce the redundant influencing factors in the decision table formed by the questionnaire data, and the critical factors of the project's external environment that affect PDS selection are identified and analyzed. The main findings of this study can provide important guidance and help for owners in the selection of appropriate PDSs and may be conducive to enriching and diversifying research methods in the PDSs decision-making area.

1. Literature review

Decision indicators (i.e. influencing factors) are of great significance in the process of choosing an appropriate PDS; different decision indicators mean different selection criteria that may lead to different outcomes. There are factors affecting PDSs selection. Although factors affecting PDSs selection are numerous and complex, the universal factors in the project delivery process can be analyzed from the basic elements of transaction and delivery environment. The transaction subjects and transaction objects are the basic and necessary elements. In addition to these, the transaction process and project implementation are intertwined with each other, and the project construction cannot implement without the support of construction condition and construction market. Therefore, all of the factors affecting PDSs selection can be classified in term of transaction subjects (owners and contractors), transaction objects (project) and transaction environment (project external environment).

Many previous studies have examined the owners' characteristics, contractors' characteristics, and project characteristics that affect PDSs selection (Lam, A. P. Chan, & D. W. Chan, 2007; Liu, Huo, Wang, Shen, & Chen, 2013; Liu et al., 2014, 2015a, 2015b, 2016). With regard to the project's external environment, many researchers and scholars have also attached attention to environmental factors for PDSs selection. For example, based on principal component analysis, Luu, Ng, and Eng Chen (2003) determined the influencing factors of PDSs and these factors regarding the project's external environment mainly involve market competitiveness, technology accessibility, regulatory feasibility, and material availability. In further studies, Luu, Ng, and Chen (2005) and Luu, Ng, Chen, and Jefferies (2006), respectively, used a case-based reasoning (CBR) approach and a fuzzy CBR prototype for the selection of PDSs to show that the factors of the project external environment that affect the decision-making of PDSs are market competitiveness, contractor availability, technology accessibility, the availability of material, regulatory effect, and political effect. It is noteworthy that the decision-making of PDSs depends on the project external environment in addition to the owners' characteristics factors, contractors' characteristics factors and the project characteristics factors (Liu et al., 2013, 2014, 2015a, 2015b, 2016).

Through literature review, the external project environment factors and their descriptions, as well as supporting documents, are shown in Table 1. To be specific, Luu et al. (2003) argued that project external environmental parameters have both positive and negative impacts on the selection of procurement methods. For example, material availability and technology feasibility may positively enhance project economic performances but can negatively lead to project risks. Furthermore, Mahdi and Alreshaid (2005) evidenced that whether regulatory and statutory requirements permit the use of an alternative project delivery method may be dominant the PDS selection. Mafakheri et al. (2007) supported this idea by concluding that getting earlier approvals from regulatory and statutory departments is a need to be considered in selecting appropriate PDSs. On top of that, they found that culture biases toward bidding can impose impacts on the PDS selection processes (Mafakheri et al., 2007).

Although numerous environmental factors are considered in existing studies (Luu et al., 2003, 2005, 2006; Mahdi & Alreshaid, 2005; Mafakheri et al., 2007), they are determined through theoretical analysis and expert judgments, which leads to inconsistent criteria of external environmental factors for selecting proper PDS. The critical project environment factors affecting PDSs selection remain unformal and unexplored. To address this issue, this study proposes a granular computing model combining with a questionnaire survey to identify the key project external environment factors affecting PDSs selection in a formal manner. The results can provide significant guidance to owners in the selection of appropriate PDSs in the field of construction.

The reason why we choose the granular computing model is that this model has many advantages over other methods (Zadeh, 1997; Yager, 2008). For example, (1) the former enables people to concentrate only on things that they are interested in and ignore some insignificant details. The granular computing model can narrow the search range aiming to the problems and can reduce the complexity of problem-solving with high computational efficiency (Liu, Geng, & Zhang, 2005). (2) The information that people get for decision-making is always incomplete, undefined and vague (Wei, 2011). In this case, it is difficult to distinguish different elements completely, while considering granular computing is an acceptable choice. It can effectively process incomplete, undefined and vague information obtained by decision makers without prior information (Wang, Y. Liu, Li, & J. Liu, 2017), which is suitable for dealing with empirical data in this study.

2. Research methodology

To investigate critical factors of project external environments affecting PDSs, a comprehensive literature review has been combined with a questionnaire survey. To be specific, the identified nine factors from the literature review (shown in Table 1) will be designed into questionnaires to collect actual external environment data from successful projects (i.e. projects which were completed satisfying the requirements of project parties, including schedule, budget, and performance standards). The main reason for selecting successful projects lies in that only successful projects could indicate the match between the PDS and the corresponding project. For instance, one project adopted a Design-Build (DB) PDS, and another project adopted a Design-Bid-Build (DBB) alternative from the early stages of the project. Ultimately, the former project achieved successful performances, whereas the latter failed. Alternatively, the DB PDS suited the first project, whereas a mismatch existed between the DBB option and the second project. The match between PDSs and the projects further implies that the factors were feasible and rational when the owners choose a PDS. Thus, the factors identified through this way (i.e. mining data from successful projects) were valuable and can be the important reference and support for owners' future decision-making. Taking the identified key factors into account, when choosing a PDS is of importance for the implementation of the project and makes the project more likely to succeed.

In the questionnaire, we set those nine project external environment factors obtained from the literature review as nine questions. The questionnaires were distributed to practitioners in the Chinese construction industry, including clients, contractors, consultants, and project management enterprises. The survey respondents were invited to

Table 1. Project external environmental factors that affect the decision-making of PDSs

#	Project external environmental factors	Descriptions	Supporting documents
C1	Market competitiveness	Refers to the level of competition in the construction market and the numbers of eligible and qualified contractors in the market environment	Luu et al. (2003, 2005, 2006)
C2	Inclement weather	Refers to the impact of severe weather on project implementations	Luu et al. (2003)
C3	Material availability	Measures the degree of availability of necessary materials from the market	Luu et al. (2003, 2005)
C4	Technology accessibility	Measures the degree of availability of necessary technologies from the market	Luu et al. (2003, 2005)
C5	Natural disasters	Refers to the impact extent of natural disasters on project implementations	Luu et al. (2003)
C6	Regulatory impacts	Refers to the impact of rules and regulations on the project procurement process	Mahdi and Alreshaid (2005) Luu et al. (2003, 2005, 2006) Mafakheri et al. (2007)
C7	Political impacts	Refers to the influence degree of national political systems on PDSs	Mahdi and Alreshaid (2005)
C8	Cultural differences	Refers to the influence degree of cultural differences on PDSs	Luu et al. (2003, 2005) Mafakheri et al. (2007)
C9	Objections of neighbors	Refers to the level of opposition of neighbors to PDSs	Luu et al. (2003, 2005)

compare and screen out the previous projects they had participated in and to select a relatively successful project. Then, they would fill in the useful information regarding project external environment factors of these successful projects. Finally, project external environment data on these successful projects were collected as research sources for further attributes reduction with granular computing in the following.

2.1.Survey design

The questionnaire was divided into two main sections soliciting empirical information regarding basic respondent profiles and their viewpoints on how project external environment factors affect the selection of PDSs (see Appendix 2).

– Section 1: Profile of respondents. This section was designed to solicit demographic information about the respondents, including their company's nature, job title, position, work experience in the construction sector and contact information (such as e-mail address or telephone number). This section assured the authenticity and reliability of the data collected. Additionally, if there were deviations (for example, inconsistent content), we could verify the data by e-mail or telephone.

– Section 2: Factors affecting PDS selection. This section was the core of the questionnaire and contained two parts. The first part is about the delivery system adopted in the successful project. The second part involved important external environment factors, including market competitiveness, inclement weather, material availability, technology accessibility, natural disasters, regulatory impacts, political impacts, cultural differences, and objections of neighbors. For example, one of the questions was, "From your viewpoint, how do you think of the material accessibility in the construction market for delivering this project?", and its corresponding options were "extremely inaccessible, inaccessible, neutral, accessible, extremely accessible". The respondents circled the option that best described the external environment factor. Based on these two parts, we could obtain related information about the important factors in the external environment corresponding to a certain PDS. Prior to a full-scale survey, we consulted two experts in the field of construction in China to verify the questions in the questionnaire. The survey questionnaire was refined and finalized on the basis of the experts' feedbacks.

2.2. Data collection

The survey was conducted in the following ways to collect empirical data regarding owners' characteristics (Liu et al., 2014), contractors' characteristics (Liu et al., 2015a, 2015b), projects' characteristics (Liu et al., 2016), and project external environmental factors.

1. In class: One of the researchers distributed questionnaires while teaching a class aimed at Master of Engineering Management. They were also participants in the construction industry and many of them were senior organization managers/directors. A total of 84 copies were distributed, representing 20.79% of the total questionnaires.
2. E-mail: we searched the contact information of construction-related companies in the industry. We then sent these contacts a total of 294 questionnaires (accounting for 72.77%) through e-mail. These companies were from the Association of China Water Engineering, some energy and chemical companies, the Association China Architectural Engineering, and metallurgical enterprise.
3. Site investigation: We visited hydroelectric companies in Sichuan Province, China, such as Hydro China Shengda Co., Ltd., the Shenxigou hydroelectric station, and Shawan hydroelectric station. We interviewed personnel at these project sites to obtain information on the PDSs and project external environmental factors. The interviewees completed 26 questionnaires on the spot, which accounted for 6.44% of the total.

As a result, a total of 404 questionnaires were distributed in China construction industry and 61 valid ones were collected.

2.3. Sample composition

Among the 61 copies, the percentages of various project types and PDS methods are illustrated in detail in Figure 1. In many cases, it might be not easy to distinguish DB and Engineering, Procurement, and Construction (EPC) due to the general contracting model they share. Therefore, we defined DB, EPC, and Turnkey, which are often confusing. DB PDS means that that the general project contractors undertake project design and construction and are wholly responsible for the quality, safety, schedule, and cost of the project, in accordance with the contract. EPC means that the general project contractors undertake project design procurement, construction, and service work in commissioning and are wholly in charge of the quality, safety, schedule, and cost of the project in light of the contract. Turnkey is an extension of the EPC PDS (MOHURD, 2003). From the data in the collected questionnaires, we found that few projects adopted CM, Turnkey, Partnering, and other delivery systems, and we deleted these samples in the subsequent analysis. Therefore, we chose only projects that adopted the DBB, DB and EPC options as valid samples. The composition of the survey respondents' roles was demonstrated in Table 2.

2.4. Data analysis method

In this study, redundancy reduction of project external environment factors was conducted based on the granular computing method (see Appendix 1 for more details). Current advances manifest that the granular computing model, as a development of the rough set theory, has become an important research method to handle inaccurate,

Table 2. Profiles of survey respondents

Role	Working experience (years)				Sum	Percentage
	<5	5–10	10–15	>15		
Clients (owners)	1	2	5	6	14	22.95%
Contractors	2	5	7	12	26	42.62%
Consultants (designers)	1	1	2	5	9	14.75%
Project management companies	1	1	2	4	8	13.12%
others	0	0	1	3	4	6.56%

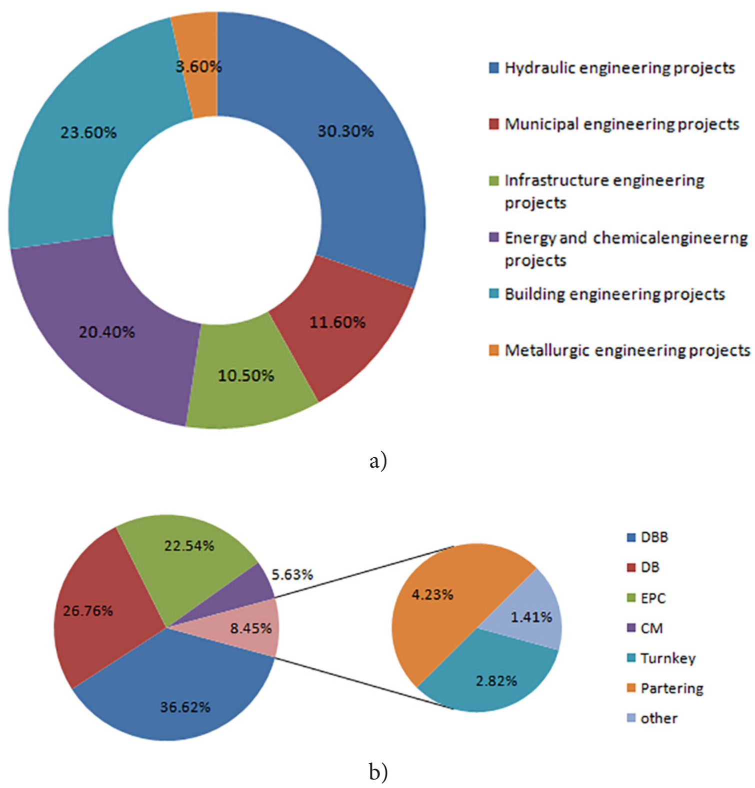

Figure 1. Sample composition: a) distribution of respondent project types and b) distribution of respondent PDSs

fuzzy, incomplete, and massive information. From the perspective of rough set theory, knowledge is a granularity, which means that the higher the knowledge granularity is and the rougher the knowledge is, the more uncertain the knowledge is, and vice versa.

Suppose there exists a decision table $S=(U,C,D,V,F)$, in which *C*, representing the nine projects external environment factors influencing decision-making for PDSs in this study, is a condition attribute set and $C_i \in C(i=1,2,\cdots,9)$, and *D*, manifesting three PDSs (i.e. DBB, DB, and EPC PDS), is a decision attribute set. Therefore, the basic steps of attribute reduction based on the granular computing method are given as follows:

Input: the decision table $S=(U,C,D,V,F)$;

Output: the reduction set $RED(C)$.

Step 1: Initialize the $RED(C)$ to an empty set.

Step 2: Calculate the granularity of each condition attribute $GD(C_i)$ and the granularity of each decision attribute $GD(D)$ as well as the significance of every condition attribute $Sig(C_i)$, where $C_i \in C$.

Step 3: Calculate the D-value between the significance of the condition attributes and the significance of the decision attributes and take its absolute value, that is, for $\forall C_i \in C$, calculate $|Sig(C_i)-Sig(D)|$, i.e. $|GD(C_i)-GD(D)|$. The larger the value $Y_i=|GD(C_i)-GD(D)|$ will be, the greater the importance of its corresponding condition attributes is and the more important that factor is to the decision-making of PDSs. According to the descending order of the absolute value of the D-value, a sequence can be obtained based on the descending order of the significance of attributes.

Step 4: Add the most important attribute C_i that is not chosen currently to $RED(C)$, i.e. $C_i \in C-RED(C)$, and the value $|GD(C_i)-GD(D)|$ is maximum, then set $RED(C)=RED(C)\cup\{C_i\}$. If $\left|GD\left(RED(C)\right)-GD(D)\right|\le\varepsilon$, then go to Step 5. otherwise, return to the current Step 4.

Step 5: Output the minimum reduction set $RED(C)$.

3. Empirical study

3.1. Data processing

Because of the large sample sizes, we encoded the questionnaire data to make them convenient to process. In the completed questionnaires, question options A and B were measured by 1 (i.e. referring to a relatively low level); option C was measured by 3 (i.e. referring to a medium level); and options D and E were measured by 5 (i.e. referring to a relatively high level). As shown in Table 3, C1 to C9 represent the condition attributes and are measured by a 1, 3, and 5 scale; D represents the decision attribute and is measured by 1, 2, and 3, referring to the PDSs (i.e. DBB, DB, and EPC, respectively); the column of the project represents the research universe; and X1 to X61 represent the 61 construction projects. The encoded questionnaire data are shown in detail in Table 3.

3.2. Reliability and validity test

Reliability tests ensure the stability and consistency of the influencing factors of PDSs in this questionnaire survey, that is, whether the survey could measure the objects and variables in a stable manner. The software IBM SPSS20.0 (Statistical Package for the Social Science) was applied to conduct the reliability analysis of the 61 valid questionnaires samples. The Cronbach's Alpha of the 9 influencing factors is 0.866 > 0.7 (alpha >0.90 means excellent; alpha >0.80 means good; alpha >0.70 means acceptable; alpha >0.60 means questionable; alpha >0.50 means poor; and alpha <0.50 means unacceptable (George & Mallery, 2003)). Additionally, the Cronbach's Alpha does not obviously increase when deleting any of the items, which indicates that the question settings of the 61 questionnaires are valid and reasonable and the questionnaire are acceptable for use in further analysis.

Validity tests ensure the accuracy of the measuring variables based on the methods of measurement and generally refer to the validity and correctness of the questionnaires, that is, how well the questionnaire measured the variables and attributes. The higher the validity is, the higher the authenticity of the questionnaire test results representing the test behavior is. Consequently, the Kaiser-Meyer-Olkin (KMO) measure value is 0.766. According to Kaiser, it is acceptable to conduct a further analysis when the KMO is higher than 0.7. In addition, the concomitant probability provided by Bartlett's Test of Sphericity is 0.000 < 0.05 (significance level), which indicates that the null hypothesis of Bartlett's Test of Sphericity is rejected. Overall, the results show that the research questionnaire has good validity, and the correctness of questionnaire data is acceptable for conducting further research steps.

3.3. Attribute reduction adopting Granular Computing method

Suppose there exist a decision table $S=(U,C,D,V,f)$, wthere C is conditional attributes sets. In this study, C represents nine project external environmental factors affecting the decision-making of PDSs and $Ci\in C\,(i=1,2,\cdots,n)$. D is decision attributes set and, in this study, it represents three PDSs (i.e. DBB, DB, and EPC). Therefore, the basic procedure of attributes reduction based on Granular Computing is as follows:

Input: decision table $S=(U,C,D,V,f)$;

Output: reduction set $RED(C)$.

Step 1: Initialize the $RED(C)$ to an empty set.

Step 2: Calculate the granularity of each condition attribute (represents the influencing factors) $GD(C_i)$ and the granularity of each decision attribute (represents the PDSs) $GD(D)$ as well as the significance of each condition attribute $Sig(C_i)$, where $C_i\in C$.

First, compute the significance of each attribute with equivalence partitioning in it. Take C_1, for example. Based on the value of C_1 in the 61 construction projects, these

Table 3. The encoded data of questionnaire options

Project	C1	C2	C3	C4	C5	C6	C7	C8	C9	D
X1	1	3	1	1	5	1	5	5	5	2
X2	1	1	1	1	1	1	1	3	1	1
X3	1	3	1	1	1	1	1	1	1	1
X4	5	5	5	5	3	5	3	3	3	3
…	…	…	…	…	…	…	…	…	…	…
…	…	…	…	…	…	…	…	…	…	…
X58	5	5	5	5	3	5	3	1	3	3
X59	5	5	5	5	1	5	3	1	3	2
X60	1	1	1	1	1	1	3	1	3	1
X61	1	3	3	1	1	1	3	1	3	1

projects can be divided into three groups. That is, 44 projects are classified into a group because the values of C_1 in them are equal. 16 projects are classified into another group. Then, according to the following steps, we can obtain the significance of C_1:

$$U/\{C_1\}=\{\{X1,X2,X3,X5,X6,X9,X10,X11,X12, X13,X14,X15,X17,X18,X19,X20,X21, X22,X23,X24,X25,X27,X28,X29,X30, X31,X33,X34,X35,X36,X38,X39,X43, X45,X48,X49,X51,X52,X53,X55,X56, X57,X60,X61\},\{X40\},\{X4,X7,X8,X16, X26,X32,X37,X41,X42,X44, X46,X47, X50,X54,X58,X59\}$$

$$GD(C_1)=\frac{44^2+16^2+1^2}{61^2}=\frac{2193}{3721},$$

$$Sis(C_1)=Dis(C_1)=1-GD(C_1)=\frac{1528}{3721}.$$

Similarly, the significance of each condition attribute $Sig(C_i),(i=2,3,\cdots,9)$ can be obtained, as follows:

$$Sis(C_2)=\frac{1814}{3721}, Sis(C_3)=\frac{1707}{3721}, Sis(C_4)=\frac{1582}{3721},$$

$$Sis(C_5)=\frac{2592}{3721}, Sis(C_6)=\frac{1638}{3721}, Sis(C_7)=\frac{2376}{3721},$$

$$Sis(C_8)=\frac{2216}{3721}, Sis(C_9)=\frac{2372}{3721}.$$

The granularity and significance of decision attributes are shown as follows:

$$U/D=U/\{Dec\}=\{\{X2,X3,X10,X12,X13,X15,X18, X19,X20,X21,X22,X23,X24,X25,X28,X29, X30,X31,X33,X34,X35,X39,X45,X49,X60, X61\},\{X1,X6,X14,X16,X17,X26,X27,X32, X37,X38,X40,X41,X42,X51,X52,X54,X55, X57,X59\},\{X4,X5,X7,X8,X9,X11,X36,X43, X44,X46,X47,X48,X50,X53,X56,X58\}$$

$$GD(D)=\frac{26^2+19^2+16^2}{61^2}=\frac{1293}{3721},$$

$$Sig(D)=Dis(D)=1-GD(D)=\frac{2428}{3721}.$$

Step 3: Calculate the D-value between the significance of the condition attribute and the significance of the decision attribute and take its absolute value, as follows:

$$y1=\frac{900}{3721}, y2=\frac{164}{3721}, y3=\frac{721}{3721}, y4=\frac{846}{3721}, y5=\frac{236}{3721},$$

$$y6=\frac{790}{3721}, y7=\frac{52}{3721}, y8=\frac{212}{3721}, y9=\frac{56}{3721}.$$

Obviously, the sequence is $y1>y4>y6>y3>y5>y8>y2>y9>y7$, and as a result, the descending sequence of attribute significance is $\{C_1,C_4,C_6,C_3,C_5,C_8,C_9,C_7\}$, with the parameter ε being 0.2 (Actually, this is threshold value and it varies with a sample of factors, and it will change according to specific condition) (Qiao, 2011).

Step 4: Set attribute $RED(C)=\{C_1\}$; then, $GD(RED)=GD(C_1)=\frac{2193}{3721}$, because $GD(RED)-GD(D)=\frac{900}{3721}>\varepsilon$. Next, put the attribute C_4 into $RED(C)$ again. At the moment, according to the equivalent division of current reduction set $U/RED(C)$, so $GD(RED)=GD(C1,C4)=\frac{2107}{3721}$, $|GD(RED)-GD(D)|=\frac{814}{3721}>\varepsilon$ can be obtained. Then, put attribute C_6 into $RED(C)$ again. Similarly, $GD(RED)=GD(C1,C4,C6)=\frac{2077}{3721}$, $|GD(RED)-GD(D)|=\frac{784}{3721}>\varepsilon$ was obtained. Next, put attribute C_3 into $RED(C)$ again. Finally, $GD(RED)=GD(C1,C4,C6,C3)=\frac{1995}{3721}$, $|GD(RED)-GD(D)|=\frac{702}{3721}<\varepsilon$ was obtained.

Step 5: Therefore, the minimum reduction set $RED(C)=\{C1,C4,C6,C3\}$.

Consequently, the key factors of the project external environment that affect the decision-making of PDSs are identified: market competitiveness, technology accessibility, material availability, and regulatory impact.

4. Discussion and analysis

Based on the above attribute reduction by the granular computing model, we can determine that the key external environmental factors influencing decisions of PDSs are market competitiveness, technology accessibility, material availability, and regulatory impact.

4.1. Market competitiveness

The degree of market competition reflects the availability of contractors. Obviously, it is the contractors who provide construction management ability and undertake the project. Therefore, the number of the contractors and their abilities definitely affect the owners' choice of PDSs. To some degree, the fiercer the construction market competition is, the more contractors are available. For instance, when there are more contractors, the owner can choose DB or EPC PDS, and this could lower the tender offer and the cost to some extent and lead to design optimization as the bidders of DB or EPC take the competition into account. Therefore, DB or EPC bidders can be unique in an optimal design and construction process due to their advantageous abilities. The integrated management of design, procurement, and construction can reduce the transaction cost and management cost, which could ensure that the cost, quality, and duration of the project meet the owner's requirement. Similarly, when there are more professional contractors, the owner, by choosing DBB, can also reduce the tender price by taking advantage of the market competition, selecting excellent contractors and exploiting their advantages to the fullest. However, when market competition is not fierce, there are fewer general contractors capable of undertaking design and construction. The contractors are less likely to estimate the status of the project and more likely to carry out the tender price incorrectly, leading to risks of higher cost and project delay. Similarly, when there are fewer professional designers and contractors, the owner cannot lower the tender price through competition, and there is a risk that the owner could not choose the appropriate professional contractors when adopting DBB PDS.

In addition, the Chinese market is not mature enough to provide various and multiple levels of contractors at present. Based on the PDSs' statistical results on the questionnaire, DB and EPC contractors are lacking compared to DBB contractors. Thus, the division of labor based on specialization should be continued. High-level specialized contractors should be fostered in China, competent enterprises should be encouraged to pursue the integration of design, construction, and procurement, and more general contractors of DB and EPC should be trained.

4.2. Technology accessibility

The technology involves design or construction abilities and techniques related to contractors, such as scheduling techniques (including fundamental scheduling techniques and advanced scheduling techniques), unique or specialized building techniques (e.g., industrial production plant) and techniques that require facilities for the design to be completed in great detail.

The effects of technology accessibility on PDS selection cannot be ignored. The lower the technology accessibility from the external environment for a project is, the fewer contractors there are who are capable of executing large-scale and complicated projects. When the level of technology accessibility is low, the duration, quality, cost and risk sharing could be affected if DB or EPC contractors are allowed to undertake design and construction due to the contractors' limited ability and the close relationship between design and construction. As a result, adopting DBB PDS to divide the project is preferred so that all the subcontractors can use their strengths to ensure that the related technologies are applied sufficiently in all parts of the project, which is beneficial for project's success.

If technology accessibility can be easily obtained from the external environment, this means that there are relatively more DB or EPC general contractors capable of undertaking large-scale and complicated projects. In this case, adopting DBB results in the scattering of technology among the different contractors is not beneficial for the owner's control over technology quality.

4.3. Materials availability

Similar to technology accessibility, material availability has an influence on the selection of PDSs. When the level of material availability from the external environment is low, it is difficult to acquire construction materials during the construction period. In this case, few contractors are equipped with the abilities of design, procurement, and construction simultaneously. Thus, the owner must choose contractors within a larger scope. Hence, adopting DBB (i.e. selecting more contractors based on individual packages to enhance material availability) will reduce the risks of shortages of materials during the construction period.

If the level of material availability from the external environment is relatively high, then there should be more competent contractors. It can help general contractors' value to enhance the integrated management of those materials and lower management costs and transaction costs when choosing DB or EPC PDS. Therefore, it is better to adopt DB or EPC PDS in that case.

4.4. Regulatory impact

The regulatory impact is a special influence factor in PDS selection. The PDS involves contract and procurement model, the owner's administrative style and the contract form. From the data collected with the questionnaires, we can see that the majority of the construction projects in China were adopted DBB PDS, and the DB, and EPC projects occurred relatively less frequently. This finding is closely related to the current Chinese regulation on the PDS and the imperfect Chinese construction market.

First, in accordance with the basic construction procedures in China, design and the construction are separated, which is the typical characteristic of the traditional DBB PDS. Today, the investment subjects are pluralistic, so this one-size-fits-all management does not fit the implementation of the project. This is because design and construction cannot integrate let alone complement one another. However, the stakeholders might encounter risk if they want to break through this system (stipulation). This might be why the owner finds it difficult to choose the general contract, and it is also difficult for the DB and EPC PDS to be conducted in China. Another reason might be that there are many restrictions to the general contract and construction contract in the Chinese "Building Law" and the "Contract Law". Second, the construction supervision system is mandatory, but it is mainly applied in the construction phase, and the service scope of the supervisor is too narrow to meet the owner's requirement. If the owner's management ability is strong enough, this type of supervision style is redundant. Third, the project legal person is responsible for the entire process of the project in the light of the project legal person responsibility system. Obviously, this system is suitable for business projects, but it does not suit public welfare projects. Some behaviors of the government interfering with the market might appear, such as subcontracting at will or avoiding bids. So, in the future, the government should focus on the regulation on the market itself, such as supervision and constraint in owners' and contractors' behaviors rather than the PDS itself.

Therefore, under the precondition of the regulations and laws, if the general contractor's design and construction abilities are strong enough that the contractor is qualified to complete the major structure, it is appropriate for the owner to choose DB or EPC PDS. This is because the design and the construction are not separate, and the cost would be lowered in this case. In addition, if the owner's management ability is strong enough and the owner can be in charge of coordination and communication throughout the process, the owner can adopt the DBB PDS.

Conclusions

The choice of PDSs is related to owners' characteristics (Liu et al., 2014), contractors' characteristics (Liu et al., 2015a, 2015b), projects' characteristics (Liu et al., 2016) and projects' external environment. This study extended the original research results (i.e. key owners' characteristics factors, key contractors' characteristics factors and key projects' characteristics factors) and proposed key factors of projects' external environment affecting PDS selection. Nine project external environment factors that affect PDSs choice were examined through a comprehensive literature review. Four critical factors were identified as the most vital dominants affecting PDS selection, including market competitiveness, technology accessibility, material availability, and regulatory impact. Based on a granular computing method building upon empirical samples collected from 61 Chinese projects, the identification is formal enough in terms of applicability for construction projects in China and acceptability among various construction professionals. This conclusion can be externalized as a reference providing support for construction project owners to make insightful PDS decisions. The limitation of this study is that only three kinds of PDS (i.e. EPC, DBB, and DB) were considered due to sample and data unavailability. The empirical part is based on Chinese context cases, where its external validity (i.e. in the global level) may be limited. Additionally, many respondents have difficulties to clearly distinguish DB and EPC PDS due to their fuzzy general project delivery methods. These are the research directions that should be extended in future studies. Therefore, other PDSs (such as CM, BOT, PPP, etc.) will be further considered and the cases will be extended to cross countries.

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APPENDIX 1. Basic information of the Granular Computing method

Definition 1: Let the four tuples $IS=(U,A,V,F)$ be an information system, $U/A=\{X_1,X_2,\cdots,X_n\}$, and X_i refers to the i-th object. Then, the knowledge granulation of A is defined as $GD(A)$, and $GD(A)=\sum_{i=1}^{n}\frac{|X_i|^2}{|U|^2}$.

The knowledge granulation of A can reflect its discernible ability. Because $\forall u,v\in U$, if $(u,v)\in A$, this means that u and v are indiscernible in A and belong to the same equivalence class of A; otherwise, they are discernible and belong to a different equivalence class of A. Then, $GD(A)$ represents the possibility of the indiscernibility of A for any two objects chosen from U. It indicates that the smaller the $GD(A)$ is, the smaller the possibility of the indiscernibility of A and the stronger the discernible ability of A. Otherwise, the discernible ability of A is weaker.

Definition 2: Let $IS=(U,A,V,F)$ be an information system. Assuming that A is the knowledge in it and $U/A=\{X_1,X_2,\cdots,X_n\}$, then we can obtain the discernibility of A $Dis(A)=1-GD(A)=1-\sum_{i=1}^{n}\frac{|X_i|^2}{|U|^2}$.

The larger the discernibility of A is, the stronger the discernibility of A is.

Property 1: In general, A is assumed to be the knowledge in the information system $IS=(U,A,V,F)$; then, $\frac{1}{|U|}\le GD(A)\le 1,\quad 0\le Dis(A)\le 1-\frac{1}{|U|}$.

Definition 3: Let $IS=(U,A,V,F)$ be an information system, $R\subseteq A$ be an attribute subset and $r\in A-R$ be an attribute. Then, the significance $Sig_R(r)$ of attribute r on attribute subset R is defined as $Sig_R(r)=1-\frac{|R\cup\{r\}|}{|R|}$, where $|R|=|IND(R)|$, assuming that if $U/|IND(R)|=U/R=\{X_1,X_2,\cdots,X_n\}$, then $|R|=card\left(IND(R)\right)=\sum_{i=1}^{n}|X_i|^2$. The improvement of the overall discernibility is represented as $Sig_R(r)$ while adding an attribute r in R; the larger the improvement is, the more important the impact of r on R is. $Sig_R(r)$ can be denoted as $Sig(r)$ for convenience when $R=\varnothing$ and $Sig_R(r)=1-\frac{|R|}{|U|^2}$. Therefore, $0\le Sig(r)\le 1-\frac{1}{|U|}$.

Theorem 1: Assuming that $IS=(U,A,V,F)$ is an information system and $r\in A$ is an attribute, then the significance of attribute r is equal to its discernibility, that is $Sig(r)=Dis(r)=1-GD(r)$.

APPENDIX 2. A responding sample of the questionnaire survey

Introduction

The selection of an appropriate project delivery system (PDS) is one of the critical process within project lifecycle management. This questionnaire is designed to collect empirical information regarding what external environment factors can affect the decision-making on PDSs.

Section 1: Profile of Respondents

1. Your professional title: *Engineer*
2. The nature of your company:

□ Governmental representative □ Owner/client □ *Contractor*
□ Designer □ Consultant □ Academic institution
□ Other:

3. Your working experience in the construction industry (year):

□ 0–5 □ 6–10 □ 11–15
□ *>15*

4. Please select one successfully delivered project that you have participated in:
   a. The project type of this project:

□ *Hydraulic* □ Municipal □ Infrastructure
□ Energy & chemical □ Building □ Metallurgic
□ Other:

   b. The delivery method of this project:

□ *DBB* □ DB □ EPC
□ CM □ Turkey □ Partnering
□ Other:

5. Your contact information: E-mail:____________________; or Tel:________________________

Section 2: Factors affecting PDS selection

1. From your viewpoint, how do you think of the competitiveness condition of the construction market in the local region where this project is located:

□ Very low □ Low □ Neutral
□ *High* □ Very high

2. From your viewpoint, how do you think of the impacts of local laws and regulations on the project delivery:

□ Very low □ *Low* □ Neutral
□ High □ Very high

3. From your viewpoint, how do you think of the impacts of political changes on the project delivery:

□ Very low □ *Low* □ Neutral
□ High □ Very high

4. From your viewpoint, how do you think of the technology accessibility in the construction market for delivering this project:

□ Extremely inaccessible □ Inaccessible □ Neutral
□ Accessible □ *Extremely accessible*

5. From your viewpoint, how do you think of the material accessibility in the construction market for delivering this project:

□ Extremely inaccessible □ Inaccessible □ Neutral
□ Accessible □ *Extremely accessible*

6. How about the frequency of natural disasters during the delivery of this project:

□ *Very rare* □ Occasional □ Frequent
□ Very frequent □ Extremely frequent

7. How about the frequency of inclement weather conditions during the delivery of this project:

□ Very rare □ *Occasional* □ Frequent
□ Very frequent □ Extremely frequent

8. From your viewpoint, how about the differences of organizational culture among different participants involved in this project:

□ *Very low* □ Low □ Neutral
□ High □ Very high

9. From your viewpoint, how about the adverse impacts of this project on local communities and the public:

□ *Very low* □ Low □ Neutral
□ High □ Very high

10. From your viewpoint, how about the objections from the local communities and the public to the delivery of this project:

□ *Very low* □ Low □ Neutral
□ High □ Very high