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Comparing the Performance Quality of Design-Bid-Build and Design-Build Delivery Methods

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Abstract

The choice of delivery method is one of the most important decisions that can determine the quality of construction projects. Two basic delivery methods, design-bid-build and design-build, have been compared in terms of project quality; however, an important quality dimension, performance quality, has generally been ignored in previous studies. In this study, we used existing economic theories to develop a model to examine the performance quality and project profits of these two delivery methods. The equilibrium points of the model were analyzed with consideration given to influencing factors such as cost coefficient, cooperation efficiency, and coordination cost. We made four propositions to facilitate the quality-profit comparisons between design-bid-build and design-build. The first proposition showed that, to maximize personal profit, the project coordinator should always keep a balance between design quality and construction quality, regardless of the delivery method. The other three propositions indicated that both methods can generate relatively higher levels of performance quality and project profits in an appropriate project environment. Based on these propositions, we ranked the performance quality and profits of the two methods within different conditions and used a real project to exhibit the practical value of these findings. Via case study, cooperation efficiency was identified as the most critical factor that determines the selection of delivery method. In addition, three key steps were summarized to facilitate the application of our model.

Keywords: Design-bid-build; Design-build; Economic theories; Performance quality; Project profits; Quality- profit equilibrium points

Introduction

Design-bid-build (DBB) and design-build (DB) are two prevalent delivery methods widely used in various countries such as China, Singapore, United Kingdom and United States (Ling et al. 2004). The construction industry in China has experienced rapid growth because of unprecedented urbanization processes. During this period, DBB and DB were the most commonly adopted tools to deliver construction projects (Chen et al. 2009). In America, DBB dominated the construction industry for a long time because the Federal Acquisition Regulations had strict constraints on the utilization of other delivery methods before 1996 (Hale et al. 2009). At present, DB has become an important alternative for American practitioners because of its favorable delivery speed (Minchin et al. 2013). In terms of application, these two delivery methods have been successfully used to develop highway and bridge projects in America (Minchin et al. 2013). The study conducted by Park et al. (2015) indicates that DBB and DB can be effectively utilized to develop public housing projects such as in the case of South Korea. In summary, DBB and DB have been widely used and accepted by practitioners from all over the world. In a project, the delivery method can significantly affect the risk allocation, the incentive mechanism for performance improvement, the scope of work, and the efficiency of cooperation among different participants (Gordon 1994). The choice of delivery method is one of the most important decisions that has a critical effect on project performance and construction quality (Al Khalil 2002; Gordon 1994; Park et al. 2015). Therefore, numerous studies have been conducted to optimize the selection between DBB and DB by comparing them with each other. However, no consistent conclusion has been reached to determine which of the two methods is superior in terms of project quality.

Inconsistent observations yielded from previous comparisons

Based on empirical data collected from 351 U.S. building projects, Konchar and Sanvido (1998) employed multivariate linear regression models to predict and compare the performance of DBB and DB projects. The results of their study showed that DB projects could achieve better quality performance. Park et al. (2015) conducted an empirical analysis of DBB and DB projects, primarily focusing on large-sized public apartment housing projects in South Korea.

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This empirical comparison covered the cost, time, and quality performance of targeted projects, and the results showed that the DB method yielded better performance than DBB in every dimension. These findings are consistent with the study conducted by Okunlola Ojo et al. (2011). By comparing the project performance of 68 construction projects in Nigeria that applied DBB and DB methods, Okunlola Ojo et al. (2011) found that DB projects were superior in quality performance. However, based on a questionnaire survey with DB professionals, Balson et al. (2012) found that DBB projects performed significantly better than DB projects in terms of project quality. Furthermore, these authors identified several key factors that attributed to the poor quality performance of DB projects in Queensland. Mahdi and Alreshaid (2005) developed a multi-criterion decision-making methodology using the analytical hierarchy process in order to help practitioners select a proper delivery method for their projects. These authors argued that DBB delivery method was better than DB in terms of project quality. This argument resonates with the study conducted by Al Khalil (2002) that focused on developing decision models for delivery method selection.

Generally speaking, some scholars believed that the DB can achieve better quality than DBB (e.g., Konchar and Sanvido 1998; Okunlola Ojo et al. 2011; Park et al. 2015), because the former can provide the following benefits: 1) improved cooperation and teamwork between designer and contractor, 2) fewer incidences of misunderstanding and conflicts as a result of improved communication, and 3) earlier involvement of the contractor at the project design stage (Gordon 1994; Molenaar et al. 1998; Okunlola Ojo et al. 2011). Meanwhile, other scholars argued that DBB is superior to DB (e.g., Balson et al. 2012; Mahdi and Alreshaid 2005; Ratnasabapathy and Rameezdeen 2006). The main reasons for their argument include: 1) the independent checks in DBB can help identify project faults and develop a balance of decision-making power, 2) the clear allocation of design and construction responsibilities can encourage both parties to exert further efforts towards quality improvement, and 3) the independent relationships between the designer and contractor can avoid compromised project schemes (Al Khalil 2002; Balson et al. 2012; Mahdi and Alreshaid 2005). The inconsistency of previous literature motivated the authors of this study to conduct further investigation on the quality comparison of DBB and DB.

Why performance quality?

Quality is a complex and multi-dimensional objective (Basu 2014; Turner 2014), and thus, analyses based on different quality dimensions can achieve significantly different results (Garvin 1984). We focused on a basic quality dimension, namely, performance quality, to simplify this study. The reason is that existing comparative analyses of DBB and DB have not paid sufficient attention to this important dimension of project quality.

Typically, the definitions of quality can be classified into two basic categories: conformance quality and performance quality (Hendricks and Singhal 1996). Conformance quality is related to the quality standards adopted in projects, and emphasizes the reduction of quality defects (Garvin 1984; Hendricks and Singhal 1996). It can be measured by indicators such as incidence of defects, conformance to quality requirements, extent of call backs, frequency of defect occurrences, and elimination of failures (based on the studies of

Bajpai and Willey 1989; Crosby 1980; Garvin 1984; Hendricks and Singhal 1996). Meanwhile, performance quality reflects the characteristics, functions, physical features, and other product factors that can provide additional values for clients (Garvin 1984; Hendricks and Singhal 1996). It can also be defined as the "attributes that exhibit a 'more is better' property for all consumers (Desai 2001)." Performance quality is usually related to primary operating characteristics, fitness for use, functions, and other valuable features of products (based on the studies of Garvin 1984; Hendricks and Singhal 1996; Juran 1989; Moorthy and Png 1992).

Conformance quality reflects a production-oriented perspective that emphasizes the control of defects and the conformance to quality standards. By contrast, performance quality represents a consumer-oriented viewpoint that focuses on providing valuable construction attributes for consumers. According to Garvin (1984), disregarding performance quality can cause dissatisfaction among consumers, even when the product has met all quality standard requirements. With increasingly fierce competition in the marketplace, practitioners in the construction industry should pay more attentions to consumer satisfaction (Maloney 2002). According to Kamara et al. (2002), "the acknowledged importance of clients as the driving force in the construction industry has led to repeated calls for the construction industry to deliver better value." Consequently, one can expect that performance quality is becoming increasingly important in the construction industry. Although previous studies have compared the project quality of the DBB and DB methods, most of them have only focused on conformance quality while ignored performance quality.

For example, in the research conducted by Konchar and Sanvido (1998), project quality only referred to "the degree to which the facility met expected facility requirements." This definition of quality emphasized the conformance to quality requirements and ignored the importance of performance quality. In some studies, although the "client's satisfaction" of DBB and DB projects was taken into consideration, key performance quality indicators such as "fitness for use" were generally omitted (e.g., Okunlola Ojo et al. 2011; Park et al. 2015). To bridge this research gap, we developed an economic model to analyze and compare the performance quality and profitability of DBB and DB projects operating within different project environments. To facilitate the decision making for project participants, we ranked the quality-profit equilibrium points of the two methods in different scenarios. Furthermore, a real case in Chengdu was presented to test the application and practical value of this research.

A conceptual model of DBB and DB

Please place Fig. 1 here

Based on previous studies, we developed a conceptual model to exhibit the characteristics of DBB and DB. As shown in Fig. 1 and Table 1, the model contains two basic delivery methods that set different responsibilities, payment modes, and coordination approaches for the main participants. In the DBB method, the project owner divides the project tasks into two parts (i.e., the design component and the construction component), and separately awards them to two entities (i.e., a designer and a contractor; see Fig. 1; Al Khalil 2002; Mahdi and Alreshaid 2005). Considering the lack of official contracts between the designer and the contractor, the two parties typically make decisions and complete their work independently. However, in the DB method, the owner contracts the entire project to only one entity (a DB contractor) that undertakes all the design and construction tasks of the project (see Fig. 1; Al Khalil 2002; Janssens 1991; Mahdi and Alreshaid 2005). The designer and the contractor within the DB contractor typically make decisions and carry out their work based on cooperation and coordination. We compared the DBB and DB delivery methods in Table 1 on the base of previous literature (Al Khalil 2002; Gordon 1994; Janssens 1991; Mahdi and Alreshaid 2005). One can see that the two methods exhibit varying characteristics, and consequently have different advantages and disadvantages. Therefore, the project participants may undertake unique quality strategy based on different delivery methods.

Please place Table 1 here

Methodology selection

Most previous studies related to the quality comparison of DBB and DB projects were conducted using empirical data and statistical analyses (e.g., Konchar and Sanvido 1998;

Park et al. 2015). Different evaluation methods were employed to measure project quality in these studies. For example, Park et al. (2015) evaluated project quality from two dimensions (i.e., design quality and construction quality) and adopted eight indicators to measure these dimensions. However, Konchar and Sanvido (1998) employed "the degree to which the facility met expected facility requirements" (including seven indicators) to measure the project quality of DBB and DB projects. The inconsistency of quality evaluation may cause significantly different conclusions in the comparisons of DBB and DB methods. Given that only a few studies have investigated project quality from a performance quality perspective, existing literature cannot provide a reasonable evaluation tool for this research. Therefore, the application of empirical tools may generate ambiguous conclusions in terms of performance quality comparison. Empirical studies also suffered from the difficulty in collecting data. Most studies had to focus on one particular type of projects and failed to yield general conclusions. For instance, Park et al. (2015) focused on large-sized public apartment housing projects and did not examine other types of projects. To avoid these potential limitations, we developed a model that was based on existing economic theories to investigate the performance quality of DBB and DB projects, instead of employing empirical methods.

Economic theories related to performance quality were originally employed to develop competitive strategies for companies with multiple product lines (e.g., Banker et al. 1998; Moorthy 1988; Moorthy and Png 1992). These theories were then used for product design and production optimization within different business environments. For instance, Chen

(2001) developed a quality-based model to design green products for consumers that had different preferences. To date, these economic models have been introduced to the field of logistics management to optimize quality strategies in supply chain design (e.g., Shi et al. 2013). Previous studies indicated that these models had the advantage of explaining the behaviors, cooperative relationships, and motivations of the heterogeneous actors in an economic activity. Construction projects are related to a set of typical production activities involving heterogeneous entities (i.e., owner, designer, and contractor), and the delivery method can affect the relationships, motivations, and behaviors of the main participants. Consequently, this method is applicable to the research demands of this study.

Model development

Model description

Please place Fig. 2 here

To simplify the expression, the term “quality” only refers to “performance quality” in the subsequent parts of this paper. In this model, we assume that the only purpose of these participants is to maximize their personal profits. The decision-making sequence of the key players is presented in Fig. 2. First, at the preparatory phase of a project, the owner determines the incentive intensity for quality improvement to encourage other participants to exert effort towards better quality. Then, the subsequent design process is pushed forward by the designer, and the design quality is determined based on a tradeoff between payment and design cost. Finally, during the construction stage, the contractor determines the construction quality based on the design quality and incentive mechanism of the project. The design scheme of a project significantly affects the construction process and cannot be freely changed by the contractor under most conditions (e.g., in the construction industry of China, unaccepted changes in a design plan are strictly prohibited by law). Thus, we assume that construction quality cannot exceed design quality, that is $\mathrm{X_{Cs}} \geq \mathrm{X_{Ct}}$. The key parameters in the model are summarized in the *Notation* section.

DBB method

Objective function of the owner

In the DBB delivery method, the unit value of the project is $\mathrm{p} \cdot \mathrm{X_{Ct}}$ (based on the work of Moorthy 1988; Moorthy and Png 1992), which implies that an improvement in the project quality (the construction quality) increases the unit value of the project. p denotes the willingness to pay for project quality. A higher p indicates that the end consumer is willing to pay more money for quality improvement. As a result, the total value of the project is given by $\mathrm{q} \cdot \mathrm{p} \cdot \mathrm{X_{Ct}}$. The total project value is delivered to the owner upon completion of the project. However, the payments for other participants $\mathrm{q} \cdot \mathrm{X_{Cs}} \cdot \mathrm{Pay_{Cs}} + \mathrm{q} \cdot \mathrm{X_{Ct}} \cdot \mathrm{Pay_{Ct}}$ and the cost of management $\mathrm{F_M(q)}$ are covered by the owner as well. $\mathrm{Pay_i}$ can reflect the incentive intensity for quality improvement. A higher $\mathrm{Pay_i}$ can encourage participant i to exert more effort towards quality improvement. Management costs for the owner $\mathrm{F_M(q)}$ is a function of q and its value increases with q. This function mainly covers the costs related to the identification of the demands of end consumers, inspection and evaluation tasks associated with project quality, project initiation activities, and other necessary coordination activities for the project. By considering the project value and the cost for the owner, we express the profit function of the owner as $\mathrm{\Pi_I^N = q \cdot p \cdot X_{Ct} - q \cdot X_{Cs} \cdot Pay_{Cs} - q \cdot X_{Ct} \cdot Pay_{Ct} - F_M(q)}$.

Objective function of the designer and the contactor

In the DBB method, the designer can obtain payment $\mathrm{q \cdot X_{Cs} \cdot Pay_{Cs}}$ from the owner. A higher level of design quality $\mathrm{X_{Cs}}$ helps the designer acquire a higher payment. Meanwhile, the total cost of the design is $\mathrm{q \cdot UC_{Cs}}$, where $\mathrm{UC_{Cs}}$ is a quadratic function of quality $\mathrm{UC_{Cs} = \phi_{Cs} \cdot X_{Cs}^2}$ (Desai 2001; Moorthy 1988; Moorthy and Png 1992). In this function, ϕ_{Cs} can reflect the sensitivity of the design cost to changes in project quality. A high ϕ_{Cs} implies that the design cost is very sensitive to changes in project quality. In other words, a small change in project quality can lead to a sharp variation in the unit cost. By integrating the payment and the design cost, the profit of the designer is given by $\mathrm{\Pi_{Cs}^N = q \cdot X_{Cs} \cdot Pay_{Cs} - q \cdot UC_{Cs}}$. Similarly, we can determine the profit function of the contractor as $\mathrm{\Pi_{Ct}^N = q \cdot X_{Ct} \cdot Pay_{Ct} - q \cdot UC_{Ct} = q \cdot X_{Ct} \cdot Pay_{Ct} - q \cdot \phi_{Ct} \cdot X_{Ct}^2}$.

DB method

Objective function of the owner

In the DBB delivery method, an owner has to deal with multi-point coordination and inspection of the other participants because of the separation between the designer and the contractor (Franks and Harlow 1998). However, these responsibilities become internal coordination issues of the DB contractor team in the DB method, which do not affect the owner (Mahdi and Alreshaid 2005). Consequently, the management cost for the owner is reduced to $\mathrm{F_M(q) \cdot r}$ where 0<r<1. In addition, the owner can send the entire payment $\mathrm{q \cdot X_{Ct} \cdot Pay}$ to only one party, based on the final outcome of the DB contractor. Consequently, the profit function of the owner in DB is given by $\mathrm{\Pi_I^C = q \cdot p \cdot X_{Ct} - q \cdot X_{Ct} \cdot Pay - F_M(q) \cdot r}$.

Objective Function of the Designer and the Contactor within the DB Contractor

In the DBB method, the total profit of the designer and the contractor is equal to $\mathrm{q \cdot (X_{Ct} \cdot Pay_{Ct} + X_{Cs} \cdot Pay_{Cs}) - q \cdot (\phi_{Ct} \cdot X_{Ct}^2 + \phi_{Cs} \cdot X_{Cs}^2)}$. The first term of the function represents the total payment received from the owner, and the second term reflects the total cost of the design/construction work. In the DB method, the designer and contractor receive only one payment $\mathrm{q \cdot X_{Ct} \cdot Pay}$ from the owner. The total cost of design-construction changes to $\mathrm{q \cdot \theta \cdot (\phi_{Cs} \cdot X_{Cs}^2 + \phi_{Ct} \cdot X_{Ct}^2)}$, because of the cooperation between the designer and the contractor. θ reflects the cooperation efficiency between different parties (Banker et al. 1998). A reduction in θ indicates an improvement in the cooperation efficiency of the DB contractor. “Cooperation efficiency” typically reflects “the degree to which the cooperators in an activity can benefit from their cooperation (Zhe et al. 2009)." A higher cooperation efficiency can help the designer and contractor lower their design/construction cost (Banker et al. 1998). Meanwhile, compared with the DBB method, some additional costs for the contractor and the designer emerge in the DB method as a result of the communication and coordination work (between the designer and the contractor), which is transferred from the owner to the DB contractor. According to Malone (1987), the cost of communication and coordination between two parties involves two portions: a fixed cost that is used to establish the communication/coordination channel, and a variable cost that is related to the frequency of channel use. The channel use frequency is positively related to the quantity and quality of work; thus, the cost function of the communication/coordination work is given by $\mathrm{T} = \mathrm{T}_{\mathrm{SC}} + \mathrm{q} \cdot \mathrm{X}_{\mathrm{Ct}} \cdot \mathrm{V}_{\mathrm{SC}}$. When the payment, design/construction cost and communication/coordination cost are considered, the total profit of the designer and the contractor is equal to $\Pi_{\mathrm{Cs+Ct}}^{\mathrm{C}} = \mathrm{q} \cdot \mathrm{Pay} \cdot \mathrm{X}_{\mathrm{Ct}} - \mathrm{q} \cdot \theta \cdot (\phi_{\mathrm{Cs}} \cdot \mathrm{X}_{\mathrm{Cs}}^2 + \phi_{\mathrm{Ct}} \cdot \mathrm{X}_{\mathrm{Ct}}^2) - \mathrm{T}_{\mathrm{SC}} - \mathrm{q} \cdot \mathrm{X}_{\mathrm{Ct}} \cdot \mathrm{V}_{\mathrm{SC}}$.

Model analyses

Proposition 1: To achieve the maximum personal profit from a project, the coordinator of the project should always match the construction quality with the design quality, regardless of the delivery method (i.e., $\mathrm{X}_{\mathrm{Cs}}^{\mathrm{N}*} = \mathrm{X}_{\mathrm{Ct}}^{\mathrm{N}*} = \frac{\mathrm{Pay}_{\mathrm{Ct}}}{2\phi_{\mathrm{Ct}}} = \frac{\mathrm{Pay}_{\mathrm{Cs}}}{2\phi_{\mathrm{Cs}}}$ and $\mathrm{X}_{\mathrm{Cs}}^{\mathrm{C}*} = \mathrm{X}_{\mathrm{Ct}}^{\mathrm{C}*}$;).

The proofs of all the propositions can be found in ***the supplementary data, Proofs S1 to***

S4. In the DBB method, the owner takes primary responsibility for the coordination. The owner can drive the construction activity to balance with the design activity by setting proper incentive intensities, although an official coordination channel between the designer and the contractor is lacking. In the DB method, the balance between design quality and construction quality becomes an internal management issue of the DB contractor. The coordination activities are carried out by the DB contractor through an internal coordination/communication channel. Although the coordinator role transfers from one participant to another in the two methods, the balance is always important and profitable for the coordinator. An imbalance between design quality and construction quality can easily cause financial losses. For example, in the WYR hotel project (a DBB project), the owner failed to achieve his profit target because of the gap between the star-standard design and the unqualified construction (Hu 2011). To avoid imbalance issues, sufficient efforts should be exerted to enhance information sharing between the designer and the contractor in a DBB or DB project. For instance, face-to-face meetings can be organized to clarify misunderstandings between different participants.

Comparison between the DBB and DB methods

Proposition 2 (The Profit of the Owner): The owner is more likely to adopt DB in a project only if his management costs can be reduced to a certain degree (i.e.,$\Pi_{I}^{C*} - \Pi_{I}^{N*} > 0 \Leftrightarrow (1-r)\cdot F_{M}(q) > F_{S} = \frac{q\cdot[\theta\cdot p^{2}-(p-V_{SC})^{2}]}{8\theta\cdot(\phi_{Cs}+\phi_{Ct})}$). In addition, improvements in the cooperation efficiency of the DB contractor (the designer and contractor) and reductions in the unit variable cost of coordination can lead the owner to be more likely to select DB (i.e., $\frac{\partial\ (\Pi_I^{C*}-\Pi_I^{N*})}{\partial\ \theta} < 0$; $\frac{\partial\ (\Pi_I^{C*}-\Pi_I^{N*})}{\partial\ v_{SC}} < 0$).

Compared with the coordination responsibilities in the DBB method, these responsibilities are transferred from the owner to the DB contractor in the DB method (Mahdi and Alreshaid 2005). Therefore, the management cost of the owner is lower because of fewer responsibilities. However, the internal coordination costs of the DB contractor can be passed on to the owner through the payment approach. Consequently, the owner has to make a tradeoff between management cost saving and payment variation. When the reduction in management cost can effectively offset the potential increase in payment, DB is preferred by the owner. For instance, DB delivery method was selected as a favorable alternative in the *San Yue Xan Hydropower Station* project, because the project management cost of the owner could be significantly reduced by applying this method (Zhu 2008).

Meanwhile, the decrease in the communication/coordination cost of the DB contractor can directly reduce the financial burdens of the project. Improving cooperation efficiency can help lower the design/construction cost of the DB contractor. As a result, the financing pressure of the DB contractor is significantly reduced and fewer burdens are passed on to the owner through the payment mechanism. Under this condition, the owner prefers the DB method. To obtain more profits, the owner should encourage the DB contractor to enhance the internal communication/coordination channel. For example, the owner can motivate the DB contactor to apply information and communication technologies (ICT) in the project to facilitate the exchange of internal information.

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Proposition 3 (3.1- 3.2): Quality comparison between DBB and DB methods

Proposition 3.1: Compared with DBB, DB can result in better project quality only when the efficiency of the cooperation between the designer and the contractor reaches a favorable level $\theta < 1 - \frac{V_{SC}}{P}$ (i.e., $X^{C*} - X^{N*} > 0 \Leftrightarrow \theta < \delta = 1 - \frac{V_{SC}}{P}$).

Proposition 3.2: Adopting DB is more likely to generate improved quality than adopting DBB, if the designer and contractor have a better cooperation efficiency or the DB contractor's unit variable cost of communication/coordination can be reduced (i.e., $\frac{\partial(X^{C*}-X^{N*})}{\partial V_{SC}} < 0$, $\frac{\partial(X^{C*}-X^{N*})}{\partial \theta} < 0$).

Propositions 3.1 and 3.2 provided basic principles to assess whether DBB outperforms DB in terms of quality improvement. If the designer and the contractor have very limited experience in cooperating with each other, then DBB appears to be more advantageous in terms of quality improvement. Under this condition, to improve performance quality, the owner should allow the designer and the contractor to make decisions independently and take primary responsibilities for balancing the design quality with the construction quality. If the designer and the contractor have a long history of collaboration, then higher-quality buildings can be generated through the project by applying the DB delivery method. As a result, the owner should transfer the coordination work to the DB contractor. The owner should also reduce unnecessary constraints on the internal cooperation between the designer and the contractor.

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Comparison of the total profits of the designer and contractor

Proposition 4: Compared with DBB, if the cooperation efficiency of the DB contractor in the DB method cannot reach the level$\theta > \frac{(p-V_{SC})^2}{P^2}$, then the designer and the contractor cannot receive increased profits. (i.e., $\theta > \frac{(p-V_{SC})^2}{P^2} \Rightarrow \Pi^{C*}_{Cs+Ct} - \Pi^{N*}_{Cs} - \Pi^{N*}_{Ct} < 0$)

In DB, the management cost is passed on to the DB contractor with the transfer of coordination responsibility from the owner to the DB contractor (i.e., the designer and the contractor). Although the internal coordination cost can be partially compensated through the payment mechanism, the owner does not allow a payment increase beyond a certain level. Consequently, the DB contractor will also seek for compensation from the reduction in the design/construction cost. As a result, if the cooperation efficiency is too low, then reducing the design/construction cost will not be able to offset the increase in internal communication/coordination cost. Accordingly, the benefit to the DB contractor (i.e., the designer and the contractor) is negatively affected. When the DB delivery method is applied in a project, the DB contractor should select qualified design and construction teams that have sufficient experience in cooperating with one another, in order to guarantee a favorable level of cooperation efficiency. In addition, effective measures, such as an information management system, should be adopted to reduce the internal communication and coordination costs.

Ranking of DB and DBB methods in different project environments

In this section, we developed a framework that enabled a comparison of the quality-profit points in the DBB and DB methods under different project environments. First of all, we introduce three conditions in this section.

- Condition 1: $(1-\mathrm{r})\cdot \mathrm{F_M}(\mathrm{q}) > \frac{\mathrm{q}\cdot[\theta\cdot \mathrm{p}^2-(\mathrm{p}-\mathrm{V_{SC}})^2]}{8\theta\cdot(\phi_{\mathrm{Cs}}+\phi_{\mathrm{Ct}})}$ (see Proposition 2);
- Condition 2: $\theta < 1-\frac{\mathrm{V_{SC}}}{\mathrm{P}}$ (see Proposition 3.1);
- Condition3: $\frac{\mathrm{q}\cdot[(\mathrm{p}-\mathrm{V_{SC}})^2-\theta\cdot \mathrm{p}^2]}{16\theta\cdot(\phi_{\mathrm{Cs}}+\phi_{\mathrm{Ct}})}-\mathrm{T_{SC}} > 0$ (see Proposition 4).

By evaluating whether or not a given project scenario can meet the aforementioned conditions, we can classify all projects into eight cases (e.g., Case 5 in Table 2). Given that Condition 3 is sufficient to meet Conditions 1 and 2 (i.e., meeting Condition 3 can guarantee the project will satisfy Conditions 1 and 2; we prove this rule in the ***supplementary data, Proof S5***), the three cases that fail to follow this rule (namely, meeting Condition 3 but failing to meet Conditions 1 and 2; meeting Conditions 1 and 3 but failing to meet Condition 2; meeting Conditions 2 and 3 but failing to meet Condition 1) are excluded from the framework. Consequently, we can establish a quality-profit comparison framework that covers all the potential situations (Table 2).

Please place Table 2 here

Case study

To test the application of this study, we presented a real case in which the owner planned to develop a shear wall structure apartment (76 meters, 22 stories) for selling. This apartment was located in the inner ring of Chengdu (a large city in China), and the gross floor area of the building was around 29,100 square meters. This project was close to a business center, and its market price was predicted to be much higher than the average housing price of Chengdu because of its favorable location. Therefore, the potential consumers of this apartment were identified as middle and upper-income groups who could afford the high price. In the marketplace, these potential consumers were typically willing to pay more for better performance quality such as improvements in architectural features, inner functions, and degree of comfort. However, the enhancements of performance quality can significantly increase the total cost of the project. The owner had an internal assessment system for measuring the performance of his projects. In terms of project quality, a higher performance score typically implied an increase in project cost. Consequently, the owner had to make a tradeoff between performance quality and project cost. The main purpose of the owner was to maximize his personal profit achieved from this project. As a small property company, the owner had very limited experience in developing and managing apartment projects. Consequently, the management cost for the owner would be very high in the DBB delivery method because the DBB method required the owner to take the primary responsibilities for managing and coordinating this project. Meanwhile, the contractor and the designer within the project were qualified state-owned companies and had a long history of cooperation. Therefore, by facilitating the internal cooperation/coordination between the designer and the contractor, the total design-construction cost of this project can be significantly reduced.

The data collection of this study was based on interviews and focus group meetings conducted with key participants of the project. These participants included project managers, engineers, and surveyors from the owner (4 participants), the contractor (5 participants), and the designer (4 participants). All participants had direct involvement in this project. The majority of these participants was at or above the managerial level and had more than three years of work experience in their companies to ensure the representativeness and reliability of the collected data. Therefore, they had sufficient knowledge on this project and the business operation of their companies. Prior to the interviews and the focus group meetings, we sent the participants an e-mail that included a brief description of the research purpose and content. The participants were encouraged to review project documents and other materials related to this project. The questions of this survey focused mainly on two aspects: “how to evaluate the model parameters of this project,” and “the values of these parameters.” For example, in the interviews, we asked the project manager “How do you measure the size of this project?” This manager stated, “we use gross floor area to evaluate the size of our project, and this parameter can be found in the master plan.” We then asked him, “Could you check the master plan after this interview and then show us the value of this parameter in the next focus group meeting?” As a result, we acquired related information based on the feedback of this manager. The other parameters associated with this study were evaluated in the same way.

Prior to conducting the following analysis, a few parameters (e.g., cost coefficients and willingness to pay) used in this study were normalized to simplify the calculation process and protect the trade secrets of the property company. It is worth noting that the overall tendency from the data was carefully retained by the authors, because normalization was widely used in previous studies and would not affect the tendency and correlations of the primary data. The values of the key parameters in this case are shown in Table 3.

Please place Table 3 here

According to the data in Table 3, the project meets *Conditions 1 and 2* but fails to meet *Condition 3* (see Case 4). Therefore, in this project, the DB delivery method was better than the DBB mode in terms of performance quality and the project profit of the owner. However, if the DB method was selected in this case, the total profit of the contractor and the designer would be adversely affected. The owner only aimed to maximize his own profit, and thus the DB delivery method was chosen as a reasonable alternative. The optimal intensity of incentive for quality improvement was $\mathrm{Pay}^{C*} = \frac{P+V_{SC}}{2} = 55$ Yuan/m^2, and the expected level of performance quality reached $X^{C*} = \frac{\mathrm{Pay}-V_{SC}}{2\theta\cdot(\phi_{Cs}+\phi_{Ct})}$ =3.52. The expected cost of the owner was $q \cdot X_{Ct} \cdot \mathrm{Pay} + F_M(q) \cdot r$= 7,375,307.81 Yuan, and the optimal profit of the owner was $\Pi_I^C = q \cdot p \cdot X_{Ct} - q \cdot X_{Ct} \cdot \mathrm{Pay} - F_M(q) \cdot r$= 2,855,160.94 Yuan. By selecting the DB delivery method instead of DBB, the owner could achieve an additional profit of $\Pi_I^C - \Pi_I^N$=$\frac{q\cdot(p-V_{SC})^2}{8\theta\cdot(\phi_{Cs}+\phi_{Ct})} - F_M(q) \cdot r - \left(\frac{q\cdot p^2}{8\cdot(\phi_{Cs}+\phi_{Ct})} - F_M\right)$ =4,136,785.94 Yuan at the quality-profit equilibrium point. Meanwhile, the performance quality of the project was improved from 3.13 to 3.52.

As a result, in the project plan, selecting the DB delivery method and setting the

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performance quality target to 3.52 were reasonable for the owner. In the project budget of the owner, 7,375,307.81 Yuan was an ideal cost objective and 2,855,160.94 Yuan was an expected profit target. In the project contacts, the owner should set the incentive intensity to 55 Yuan/m^2 for the DB contractor, and the total contract price for the DB contractor was $\mathrm{q} \cdot \mathrm{X}_{\mathrm{Ct}} \cdot \mathrm{Pay} = 5{,}256{,}757.81$ Yuan. In summary, by employing the findings of this study, the owner can optimize his project profit as well as the performance quality of the project through setting a reasonable delivery method, performance quality target, incentive intensity, and cost budget.

Meanwhile, the DB contractor had to take the coordination responsibility in this project. To obtain more personal profit, the DB contractor should also set the quality target to 3.52 and balance the construction quality with the design quality (see Proposition 1). In addition, effective measures should be taken to reduce the communication/coordination cost. In this project, an information management system was established as an effective communication channel to facilitate the coordination between the designer and the contractor within the DB contractor.

Sensitivity analysis and the importance of cooperation efficiency

In consideration of the uncertainties in real projects, sensitivity analysis was conducted to investigate the key factors that could significantly affect the quality-profit comparisons between DB and DBB. In practice, variations of these factors can determine the final decision on delivery method selection. Therefore, their effects must be quantified and simulated during the decision-making stage. Data collected from the case study were selected as the basic scenario that provided a baseline for the quality-profit comparisons. The results of the sensitivity analysis are presented in Fig. 3 to 5. The horizontal axes of these figures denote the variations of the key factors. The vertical axes of these figures denote the performance gaps between DB and DBB (i.e.,$\mathrm{X}^{\mathrm{C}*}-\mathrm{X}^{\mathrm{N}*}$, $\Pi_{\mathrm{I}}^{\mathrm{C}*}-\Pi_{\mathrm{I}}^{\mathrm{N}*}$, and $\Pi_{\mathrm{Cs+Ct}}^{\mathrm{C}*}-\ \Pi_{\mathrm{Cs}}^{\mathrm{N}*}-\ \Pi_{\mathrm{Ct}}^{\mathrm{N}*}$). If a performance gap exceeds 0, then DB is better than DBB. If this gap equals to 0, then DB and DBB can achieve the same performance. If this gap is lower than 0, then DBB is better than DB.

Please place Fig. 3 here

Based on the sensitivity analysis, parameter θ was indentified as the most important factor that could determine the quality comparison between DB and DBB (see Fig. 3). The quality gap between the two delivery methods could be reduced to a negative level if the increase of θ was higher than 12% of the basic scenario. Although other factors such as P and V_{SC} could also affect this quality gap, none of these factors could change this gap from “+” to “-”. Consequently, variations of these key factors (excluding θ) cannot affect the results on quality comparison. In this project, if the owner attempted to achieve good quality by selecting a favorable delivery method, then the increase of θ should be viewed as the most critical source of risks that could adversely affect performance quality.

Please place Fig. 4 here

Fig. 4 shows that the owner of this project could always benefit by selecting the DB method. The key factors analyzed in the sensitivity analysis could affect the gap of the profit of the owner between DBB and DB. However, these factors failed to change this profit gap from a positive value to a negative value. Therefore, DB was always better than DBB in terms of the project profits of the owner. Compared with other factors, θ had the most significant effect on the profits of the owner (see Fig. 4). In summary, the owner of this project should reasonably assess the value of θ to achieve good quality and profits. In practice, θ denotes the cooperation efficiency between a designer and a contractor. Consequently, the owner should pay sufficient attention in the evaluation of the partnership between the designer and the contractor. These selections of key project participants should be based primarily on their experience in cooperating with one another. The results shown in Fig.5 also support this argument. In this project, higher cooperation efficiency could benefit the owner and provide better profits for the designer and contractor because it could help lower the design-construction cost of the designer and contractor. In DB method (this case is a DB project), favorable cooperation efficiency can achieve the following: 1) Facilitate the improvement in project quality, 2) Increase the project profit of the owner, 3) Reduce the design/construction cost of the designer and contractor. Consequently, a high cooperation efficiency can encourage participants of a project to use the DB delivery method in practice.

Please place Fig. 5 here

Lessons learned

Please place Fig. 6 here

Based on the case study, we summarized three key steps to help practitioners apply our economic model in their projects (see Fig. 6). First, the key parameters in the model (variables in Table 3) should be evaluated according to the knowledge of project participants and project documents. Empirical tools such as interview, focus group, and questionnaire, can be used to collect related data. Second, the quality-profit performance of DB and DBB should be assessed by considering of the specific context of the project. The quality-profit performance of DB and DBB can be ranked using the findings in Table 2. A favorable delivery method can be selected according to the analysis of our model. Finally, sensitivity analysis must be conducted to test and identify critical factors that can significantly influence the comparison between DB and DBB (see Fig. 3 to 5). Effective measures must be taken to manage and control these critical factors. In summary, our model can help practitioners form reasonable decisions on delivery method selection between DB and DBB.

Discussion

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Contribution to the body of knowledge

Inconsistent conclusions were observed from previous quality comparisons between the DBB and DB delivery methods. The complexity of project quality and the inconsistency of evaluation systems can easily cause ambiguous results. Contrary to existing comparative analyses that focused on empirical studies (e.g., Balson et al. 2012; Park et al. 2015), economic theories were introduced in this research to compare the performance quality and project profits of the DBB and DB methods. These economic theories have been widely used in other research areas such as product design (e.g., Chen 2001) and logistics management (e.g., Shi et al. 2013). The present study extended the application of these models to the field of construction project management. The practical value of this research was tested through the use of a case study. The results indicated that economic models related to performance quality can support the decision-making for key participants in DBB or DB projects.

Compared with the supporters of DBB (e.g., Balson et al. 2012) and of DB (e.g., Park et al. 2015), we argued in this study that neither DB nor DBB was always better than the other in terms of project quality (at least the dimension of performance quality). The reason is that project specifics (e.g., experience of cooperation) can affect the operational efficiency of the two delivery methods. Thus, we developed four propositions to judge the project conditions under which one certain delivery method is better than the other with regards to performance quality and project profits. Key factors, such as cooperation efficiency, cost coefficients, and communication cost, were examined to show their impacts on the quality-profit performance of DBB and DB projects.

Finally, compared with previous studies that focused on conformance quality (e.g., Konchar and Sanvido 1998), this study shed lights on performance quality that emphasizes delivering additional value for consumers. Given that the construction industry pays increasing attentions to the consumers in the marketplace (Maloney 2002), additional investigations on performance quality should be made in the future.

Limitations

The model developed in this study was based on a few economic assumptions. Although these assumptions were widely accepted by scholars and considered to be reasonable under most conditions, some gaps may emerge between these assumptions and real cases. For example, in some projects, the main purpose of the owner was not to maximize his personal profit but to maximize the total profit of all the potential stakeholders. Consequently, when practitioners attempt to use these models for decision-making, they should pay attention to the applicable scope of this study. They should also test whether the conditions of their projects can meet the assumptions of this study or not. However, this limitation did not diminish the contribution of this study, because a wide range of projects in practice can fall into the applicable scope. In further study, economic models based on other reasonable assumptions can be developed to improve the findings of the present research. Another limitation is that the practical value of this study was not examined using large sample data. In future research, more DBB and DB projects should be investigated to test the robustness

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of this study.

Conclusions

In this study, we developed an economic model to compare the performance quality and project profits of the DBB and DB delivery methods. By calculating and analyzing the model, we obtained the following findings:

- The balance between the design scheme and the construction processes is quite important for the coordinator to maximize his personal profit.
- Choosing between DBB and DB can influence the performance quality and the profits of the key participants of a project. The quality-profit comparison of DBB and DB should depend on the market environment of the project (e.g., the preference for quality of the end consumers), design/construction efficiency (e.g., the cost curve of the designer), and management efficiency (e.g., the management cost of the owner).
- Under certain conditions, a project can reach a win-win solution, in which all the participants can achieve relatively higher profits and the performance quality is improved, by selecting a suitable delivery method (e.g., Case 1, DBB).
- A win-win solution is sometimes impossible. Therefore, decision-makers must make tradeoffs between performance quality and profits (e.g., Case 3). In addition, the profit conflict between the owner and other participants may arise as well (e.g., Case 2).

Propositions were developed to identify project conditions under which a specific delivery method was better than the other in terms of performance quality and profits. To facilitate the application of these findings, we ranked the quality-profit performance of the DB and DBB delivery methods in different scenarios. A real case in Chengdu was also presented to test the practical value of this research. Based on the study of this case, we highlighted the importance of cooperation efficiency and summarized three key steps (i.e., data collection, performance evaluation and comparison, and sensitivity analysis) to help practitioners apply our model in their projects. The findings of this study can be referred to optimize the decision-making of project participants in DBB or DB projects.

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Notation

The following symbols are used in this paper:

C= design-build;

Cs= designer;

Ct= contractor;

$\mathrm{F_M}$= management cost for the owner (implication: the costs of managing the project and coordinating various design/construction activities);

I= owner;

N= design-bid-build;

P=unit value coefficient of the project (implication: the end consumers' willingness to pay for project quality);

$\mathrm{Pay_i}$= payment coefficient for designer or contractor (implication: the willingness of the owner to pay for quality improvement in the project);

Q= project quantity (implication: the size of the project);

R= modified coefficient of the management cost of owner, when delivery method changes from design-bid-build to design-build (implication: the degree to which the owner can save his/her management cost by selecting design-build instead of design-bid-build, i.e., transferring the cooperation/coordination responsibility from the owner to the design-build contractor);

T= the total costs for facilitating the cooperation/coordination between the designer and contractor in the design-build method;

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T_{SC}= fixed cost of the cooperation/coordination between the designer and contractor in the design-build method (implication: the costs for developing internal cooperation/coordination channels between the contractor and designer in the design-build method, e.g., costs for developing an information management system);

UC_i= the unit cost for completing the work of a participant (designer or contractor);

V_{SC}= unit variable cost of the cooperation/coordination between the designer and contractor in the design-build method (implication: the costs related to the frequency of (internal cooperation/coordination) channel use in the design-build method, e.g., costs for conducting meetings);

X_i= the amount of quality that the designer or the contractor offered to the project (implication: the design quality or the construction quality of the project);

Π_i^j= in a delivery method (design-bid-build or design-build), the total profit that a participant (owner, designer or contractor) can receive from the project;

θ= modified coefficient of the total design-construction cost, when delivery method changes from design-bid-build to design-build (implication: in the design-build method, the degree to which the designer and contractor can save their design-construction cost by facilitating the internal cooperation between the parties);

*= equilibrium solutions of the economic model developed in this study.

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Supplementary Data

Proof S1

***Proposition 1**:*

i In DBB:

The designer's objective function is $\Pi_{\mathrm{Cs}}^{\mathrm{N}} = \mathrm{q} \cdot \mathrm{X}_{\mathrm{Cs}} \cdot \mathrm{Pay}_{\mathrm{Cs}} - \mathrm{q} \cdot \phi_{\mathrm{Cs}} \cdot \mathrm{X}_{\mathrm{Cs}}^{2}$ and the contractor's is given by $\Pi_{\mathrm{Ct}}^{\mathrm{N}} = \mathrm{q} \cdot \mathrm{X}_{\mathrm{Ct}} \cdot \mathrm{Pay}_{\mathrm{Ct}} - \mathrm{q} \cdot \phi_{\mathrm{Ct}} \cdot \mathrm{X}_{\mathrm{Ct}}^{2}$. Their first-order condition is easy to achieve by $\begin{cases} \frac{\mathrm{d}\ \Pi_{\mathrm{Cs}}^{\mathrm{N}}}{\mathrm{d}\ \mathrm{X}_{\mathrm{Cs}}} = \mathrm{q} \cdot \mathrm{Pay}_{\mathrm{Cs}} - 2\mathrm{q} \cdot \phi_{\mathrm{Cs}} \cdot \mathrm{X}_{\mathrm{Cs}} = 0 \\ \frac{\mathrm{d}\ \Pi_{\mathrm{Ct}}^{\mathrm{N}}}{\mathrm{d}\ \mathrm{X}_{\mathrm{Ct}}} = \mathrm{q} \cdot \mathrm{Pay}_{\mathrm{Ct}} - 2\mathrm{q} \cdot \phi_{\mathrm{Ct}} \cdot \mathrm{X}_{\mathrm{Ct}} = 0 \end{cases}$. Since $\begin{cases} \frac{\mathrm{d}^2\Pi_{\mathrm{Cs}}^{\mathrm{N}}}{\mathrm{d}\ \mathrm{X}_{\mathrm{Cs}}^{2}} = -2\mathrm{q} \cdot \phi_{\mathrm{Cs}} \leq 0 \\ \frac{\mathrm{d}^2\Pi_{\mathrm{Ct}}^{\mathrm{N}}}{\mathrm{d}\ \mathrm{X}_{\mathrm{Ct}}^{2}} = -2\mathrm{q} \cdot \phi_{\mathrm{Ct}} \leq 0 \end{cases}$, the optimal quality solution is $\begin{cases} \mathrm{X}_{\mathrm{Cs}}^{\mathrm{N}*} = \frac{\mathrm{Pay}_{\mathrm{Cs}}}{2\phi_{\mathrm{Cs}}} \\ \mathrm{X}_{\mathrm{Ct}}^{\mathrm{N}*} = \min\left\{\frac{\mathrm{Pay}_{\mathrm{Ct}}}{2\phi_{\mathrm{Ct}}}, \frac{\mathrm{Pay}_{\mathrm{Cs}}}{2\phi_{\mathrm{Cs}}}\right\} \quad (\mathrm{s.t.} \mathrm{X}_{\mathrm{Ct}} \leq \mathrm{X}_{\mathrm{Cs}}) \end{cases}$. Consequently, the objective function of the owner can be transformed into $\Pi_{\mathrm{I}}^{\mathrm{N}} = \mathrm{q} \cdot \mathrm{p} \cdot \min\left\{\frac{\mathrm{Pay}_{\mathrm{Ct}}}{2\phi_{\mathrm{Ct}}}, \frac{\mathrm{Pay}_{\mathrm{Cs}}}{2\phi_{\mathrm{Cs}}}\right\} - \mathrm{q} \cdot \frac{\mathrm{Pay}_{\mathrm{Cs}}}{2\phi_{\mathrm{Cs}}} \cdot \mathrm{Pay}_{\mathrm{Cs}} - \mathrm{q} \cdot \min\left\{\frac{\mathrm{Pay}_{\mathrm{Ct}}}{2\phi_{\mathrm{Ct}}}, \frac{\mathrm{Pay}_{\mathrm{Cs}}}{2\phi_{\mathrm{Cs}}}\right\} \cdot \mathrm{Pay}_{\mathrm{Ct}} - \mathrm{F}_{\mathrm{M}}(\mathrm{q})$. The owner can control the level of the design and construction quality by adjusting the payment mechanism$\mathrm{Pay}_{\mathrm{Cs}}$ and $\mathrm{Pay}_{\mathrm{Ct}}$. Under some conditions, a poor payment mechanism can lead to an imbalance between the design and the construction (i.e., $\frac{\mathrm{Pay}_{\mathrm{Ct}}}{2\phi_{\mathrm{Ct}}} \neq \frac{\mathrm{Pay}_{\mathrm{Cs}}}{2\phi_{\mathrm{Cs}}}$). We can prove that the imbalance will hinder the owner from maximizing profit (namely, when $\frac{\mathrm{Pay}_{\mathrm{Ct}}}{2\phi_{\mathrm{Ct}}} \neq \frac{\mathrm{Pay}_{\mathrm{Cs}}}{2\phi_{\mathrm{Cs}}}$, there must be a $\mathrm{Pay}^{\#}{}_{\mathrm{Ct}}$ and a $\mathrm{Pay}^{\#}{}_{\mathrm{Cs}}$that can increase the profit for the owner).

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1 If the optimal construction quality is restricted by the optimal design quality (i.e., $\frac{\mathrm{Pay}_{\mathrm{Ct}}}{2\phi_{\mathrm{Ct}}} > \frac{\mathrm{Pay}_{\mathrm{Cs}}}{2\phi_{\mathrm{Cs}}}$), let $\mathrm{Pay}^{\#}{}_{\mathrm{Ct}} = \frac{\phi_{\mathrm{Ct}} \cdot \mathrm{Pay}_{\mathrm{Cs}}}{\phi_{\mathrm{Cs}}}$ and $\mathrm{Pay}^{\#}{}_{\mathrm{Cs}} = \mathrm{Pay}_{\mathrm{Cs}}$, then it is easy to prove that $\Pi_{\mathrm{I}}^{\mathrm{N}\#} - \Pi_{\mathrm{I}}^{\mathrm{N}} = \mathrm{q} \cdot \mathrm{X}_{\mathrm{Ct}} \cdot \left(\mathrm{Pay}_{\mathrm{Ct}} - \mathrm{Pay}^{\#}{}_{\mathrm{Ct}}\right) > 0$.

2 If the optimal construction quality fails to reach the optimal design quality (i.e., $\frac{\mathrm{Pay}_{\mathrm{Ct}}}{2\phi_{\mathrm{Ct}}} < \frac{\mathrm{Pay}_{\mathrm{Cs}}}{2\phi_{\mathrm{Cs}}}$), let $\mathrm{Pay}^{\#}{}_{\mathrm{Cs}} = \frac{\phi_{\mathrm{Cs}} \cdot \mathrm{Pay}_{\mathrm{Ct}}}{\phi_{\mathrm{Ct}}}$ and $\mathrm{Pay}^{\#}{}_{\mathrm{Ct}} = \mathrm{Pay}_{\mathrm{Ct}}$, then it is easy to prove that $\Pi_{\mathrm{I}}^{\mathrm{N}\#} - \Pi_{\mathrm{I}}^{\mathrm{N}} = \mathrm{q} \cdot \mathrm{X}_{\mathrm{Cs}} \cdot (\mathrm{Pay}_{\mathrm{Cs}} - \mathrm{Pay}^{\#}{}_{\mathrm{Cs}}) > 0$.

Consequently, in the DBB method, the owner will always tend to let $\frac{\mathrm{Pay}_{\mathrm{Ct}}}{2\phi_{\mathrm{Ct}}}$ equal to $\frac{\mathrm{Pay}_{\mathrm{Cs}}}{2\phi_{\mathrm{Cs}}}$ in order to obtain a better profit. Therefore, we can achieve $\mathrm{X}_{\mathrm{Cs}}^{\mathrm{N}*} = \mathrm{X}_{\mathrm{Ct}}^{\mathrm{N}*} = \frac{\mathrm{Pay}_{\mathrm{Ct}}}{2\phi_{\mathrm{Ct}}} = \frac{\mathrm{Pay}_{\mathrm{Cs}}}{2\phi_{\mathrm{Cs}}}$.

ii In DB:

The DB contractor's objective function is given by $\Pi_{\mathrm{Cs+Ct}}^{\mathrm{C}} = \mathrm{q} \cdot \mathrm{Pay} \cdot \mathrm{X}_{\mathrm{Ct}} - \mathrm{q} \cdot \theta \cdot (\phi_{\mathrm{Cs}} \cdot \mathrm{X}_{\mathrm{Cs}}^2 + \phi_{\mathrm{Ct}} \cdot \mathrm{X}_{\mathrm{Ct}}^2) - \mathrm{T}_{\mathrm{SC}} - \mathrm{q} \cdot \mathrm{X}_{\mathrm{Ct}} \cdot \mathrm{V}_{\mathrm{SC}}$. If $\mathrm{X}_{\mathrm{Cs}} > \mathrm{X}_{\mathrm{Ct}}$, let $\mathrm{X}_{\mathrm{Cs}}^{\#} = \mathrm{X}_{\mathrm{Ct}}$ and $\mathrm{X}_{\mathrm{Ct}}^{\#} = \mathrm{X}_{\mathrm{Ct}}$, then $\Pi_{\mathrm{Cs+Ct}}^{\mathrm{C}\#} - \Pi_{\mathrm{Cs+Ct}}^{\mathrm{C}} = \mathrm{q} \cdot \theta \cdot (\mathrm{X}_{\mathrm{Cs}}^2 - \mathrm{X}_{\mathrm{Ct}}^2) > 0$. Consequently, as a rational decision-maker, the DB contractor will always let $\mathrm{X}_{\mathrm{Cs}} = \mathrm{X}_{\mathrm{Ct}}$. Therefore, we can achieve $\mathrm{X}_{\mathrm{Cs}}^{\mathrm{C}*} = \mathrm{X}_{\mathrm{Ct}}^{\mathrm{C}*}$. Q.E.D.

Equilibrium Points:

In DBB

According to Proposition 1, since $\mathrm{X}_{\mathrm{Cs}}^{\mathrm{N}*} = \mathrm{X}_{\mathrm{Ct}}^{\mathrm{N}*} = \frac{\mathrm{Pay}_{\mathrm{Ct}}}{2\phi_{\mathrm{Ct}}} = \frac{\mathrm{Pay}_{\mathrm{Cs}}}{2\phi_{\mathrm{Cs}}}$ in DBB, the objective of the owner can be transformed into $\Pi_{\mathrm{I}}^{\mathrm{N}} = \mathrm{q} \cdot \mathrm{p} \cdot \frac{\mathrm{Pay}_{\mathrm{Ct}}}{2\phi_{\mathrm{Ct}}} - \mathrm{q} \cdot \frac{\mathrm{Pay}_{\mathrm{Ct}}}{2\phi_{\mathrm{Ct}}} \cdot \frac{\phi_{\mathrm{Cs}} \cdot \mathrm{Pay}_{\mathrm{Ct}}}{\phi_{\mathrm{Ct}}} - \mathrm{q} \cdot \frac{\mathrm{Pay}_{\mathrm{Ct}}}{2\phi_{\mathrm{Ct}}} \cdot \mathrm{Pay}_{\mathrm{Ct}} -$

$F_M(q)$. Since $\frac{d\ \Pi_I^N}{d\ \mathrm{Pay}_{Ct}} = \frac{q\cdot p}{2\phi_{Ct}} - \frac{q\cdot\phi_{Cs}\cdot \mathrm{Pay}_{Ct}}{{\phi_{Ct}}^2} - \frac{q\cdot \mathrm{Pay}_{Ct}}{\phi_{Ct}}$ and $\frac{d^2\ \Pi_I^N}{d\ {\mathrm{Pay}_{Ct}}^2} = -\frac{q\cdot\phi_{Cs}}{{\phi_{Ct}}^2} - \frac{q}{\phi_{Ct}} < 0$, we can achieve the optimal payment mechanism $\mathrm{Pay}_{Ct}^{N*} = \frac{p\cdot\phi_{Ct}}{2\cdot(\phi_{Cs}+\phi_{Ct})}$, $\mathrm{Pay}_{Cs}^{N*} = \frac{p\cdot\phi_{Cs}}{2\cdot(\phi_{Cs}+\phi_{Ct})}$ in DBB. We can also achieve the optimal level of project quality $X_{Cs}^{N*} = X_{Ct}^{N*} = X^{N*} = \frac{p}{4\cdot(\phi_{Cs}+\phi_{Ct})}$ and the following profits for every participant $\begin{cases} \Pi_I^{N*} = \frac{q\cdot p^2}{8\cdot(\phi_{Cs}+\phi_{Ct})} - F_M \\ \Pi_{Cs}^{N*} = \frac{q\cdot p^2\cdot\phi_{Cs}}{16\cdot(\phi_{Cs}+\phi_{Ct})^2} \\ \Pi_{Ct}^{N*} = \frac{q\cdot p^2\cdot\phi_{Ct}}{16\cdot(\phi_{Cs}+\phi_{Ct})^2} \end{cases}$.

In DB

In DB, since $X_{Cs}^{C*} = X_{Ct}^{C*}$, let $X = X_{Cs}^{C} = X_{Ct}^{C}$ the objective function of the DB contractor can be transformed into$\Pi_{Cs+Ct}^{C} = q\cdot \mathrm{Pay}\cdot X - q\cdot\theta\cdot X^2\cdot(\phi_{Cs}+\phi_{Ct}) - T_{SC} - q\cdot X\cdot V_{SC}$. It is easy to achieve that $X^{C*} = X_{Cs}^{C*} = X_{Ct}^{C*} = \frac{\mathrm{Pay}-V_{SC}}{2\theta\cdot(\phi_{Cs}+\phi_{Ct})}$. Consequently, the objective function of the owner can be given as $\Pi_I^C = q\cdot p\cdot\frac{\mathrm{Pay}-V_{SC}}{2\theta\cdot(\phi_{Cs}+\phi_{Ct})} - q\cdot \mathrm{Pay}\cdot\frac{\mathrm{Pay}-V_{SC}}{2\theta\cdot(\phi_{Cs}+\phi_{Ct})} - F_M(q)\cdot r$. It is easy to achieve the optimal payment $\mathrm{Pay}^{C*} = \frac{P+V_{SC}}{2}$. Therefore, the quality is $X^{C*} = \frac{P-V_{SC}}{4\theta\cdot(\phi_{Cs}+\phi_{Ct})}$ (P> V_{SC}) and the profits for each participants are $\begin{cases} \Pi_I^{C*} = \frac{q\cdot(p-V_{SC})^2}{8\theta\cdot(\phi_{Cs}+\phi_{Ct})} - F_M(q)\cdot r \\ \Pi_{Cs+Ct}^{C*} = \frac{q\cdot(p-V_{SC})^2}{16\theta\cdot(\phi_{Cs}+\phi_{Ct})} - T_{SC} \end{cases}$.

Proof S2

Proposition 2:

i $\Pi_I^{C*} - \Pi_I^{N*} = \frac{q\cdot[(p-V_{SC})^2-\theta\cdot p^2]}{8\theta\cdot(\phi_{Cs}+\phi_{Ct})} + (1-r)\cdot F_M(q) \Longrightarrow\ \Pi_I^{C*} - \Pi_I^{N*} > 0 \Leftrightarrow (1-r)\cdot F_M(q) > \frac{q\cdot[\theta\cdot p^2-(p-V_{SC})^2]}{8\theta\cdot(\phi_{Cs}+\phi_{Ct})}$

ii $\frac{\partial\ (\Pi_I^{C*}-\Pi_I^{N*})}{\partial\ \theta} = -\frac{q\cdot(p-V_{SC})^2}{8\theta^2\cdot(\phi_{Cs}+\phi_{Ct})} < 0$; $\frac{\partial\ (\Pi_I^{C*}-\Pi_I^{N*})}{\partial\ V_{SC}} = -\frac{q\cdot(p-V_{SC})}{4\theta\cdot(\phi_{Cs}+\phi_{Ct})} < 0$

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Q.E.D.

Proof S3

***Proposition 3.1**:*

Since $X^{C*} - X^{N*} = \frac{P - V_{SC} - \theta\cdot p}{4\theta\cdot(\phi_{Cs}+\phi_{Ct})}$, we can prove that $X^{C*} > X^{N*} \Leftrightarrow P - V_{SC} - \theta \cdot p > 0 \Leftrightarrow 1 - \frac{V_{SC}}{P} > \theta$. Q.E.D.

***Proposition 3.2**:*

$$\frac{\partial(X^{C*} - X^{N*})}{\partial V_{SC}} = -\frac{1}{4\theta\cdot(\phi_{Cs}+\phi_{Ct})} < 0, \frac{\partial(X^{C*} - X^{N*})}{\partial \theta} = -\frac{P - V_{SC}}{4\theta^2\cdot(\phi_{Cs}+\phi_{Ct})} < 0$$

Q.E.D.

Proof S4

***Proposition 4**:*

$$\Pi_{Cs+Ct}^{C*} - \Pi_{Cs}^{N*} - \Pi_{Ct}^{N*} = \frac{q\cdot[(p - V_{SC})^2 - \theta\cdot p^2]}{16\theta\cdot(\phi_{Cs}+\phi_{Ct})} - T_{SC}.$$

$$\theta > \frac{(p - V_{SC})^2}{P^2} \Longrightarrow \frac{q\cdot[(p - V_{SC})^2 - \theta\cdot p^2]}{16\theta\cdot(\phi_{Cs}+\phi_{Ct})} < 0.$$

Since $T_{SC} > 0$, we can prove that $\Pi_{Cs+Ct}^{C*} - \Pi_{Cs}^{N*} - \Pi_{Ct}^{N*} < 0$ (if $\theta > \frac{(p - V_{SC})^2}{P^2}$)

Q.E.D.

Proof S5

Ranking of DB and DBB methods under Different Project Environments

If Condition 3 is true $\frac{q\cdot[(p-V_{SC})^2-\theta\cdot p^2]}{16\theta\cdot(\phi_{Cs}+\phi_{Ct})}-T_{SC}>0$, we can achieve $[(p-V_{SC})^2-\theta\cdot p^2]$>0. $\Longrightarrow\frac{q\cdot[\theta\cdot p^2-(p-V_{SC})^2]}{8\theta\cdot(\phi_{Cs}+\phi_{Ct})}<0\Longrightarrow(1-r)\cdot F_M(q)>\frac{q\cdot[\theta\cdot p^2-(p-V_{SC})^2]}{8\theta\cdot(\phi_{Cs}+\phi_{Ct})}$. Consequently, Condition 3 is sufficient to Condition 1.

In addition, $[(p-V_{SC})^2-\theta\cdot p^2]$ >0$\Longrightarrow(1-\frac{V_{SC}}{P})^2>\theta$. Since $0<1-\frac{V_{SC}}{P}$<1, we can achieve $1-\frac{V_{SC}}{P}>(1-\frac{V_{SC}}{P})^2>\theta$. Therefore, Condition 3 is also sufficient to Condition 2.

The comparison of Cases 1,2,3,4, and 5 is based on Propositions 3.1, 4.1, and 5.1.

Q.E.D.

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Figure list

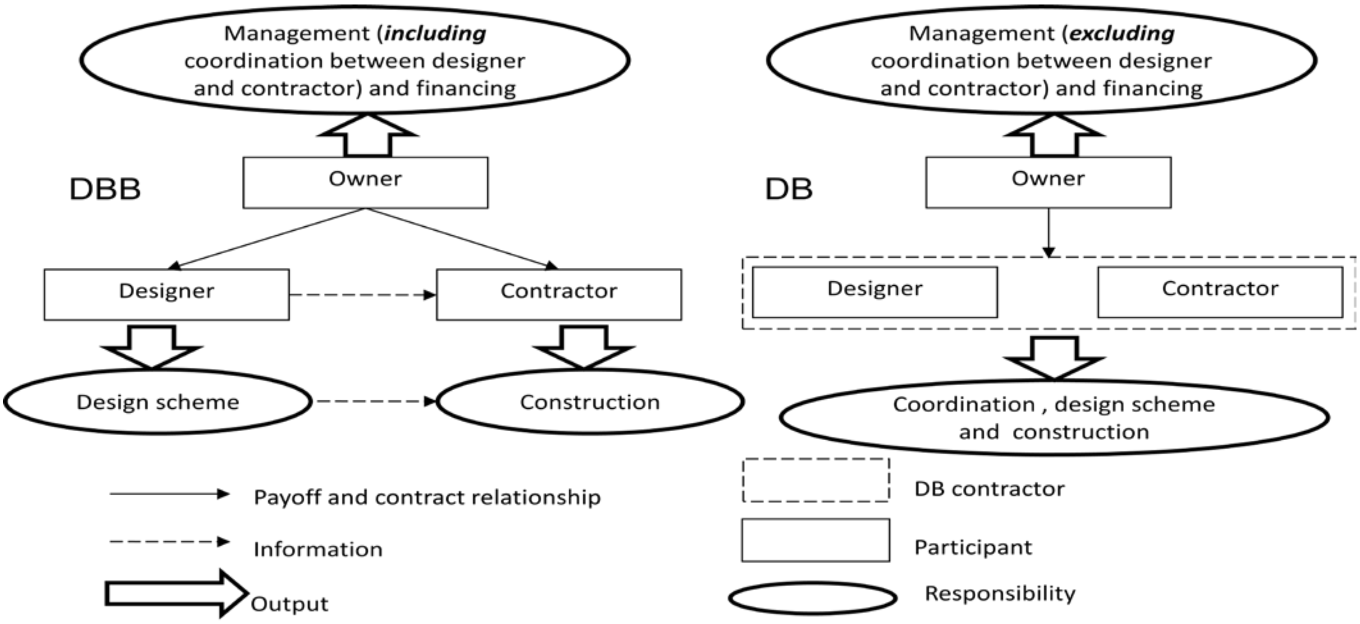

Fig.1. Conceptual model of the DBB and DB methods

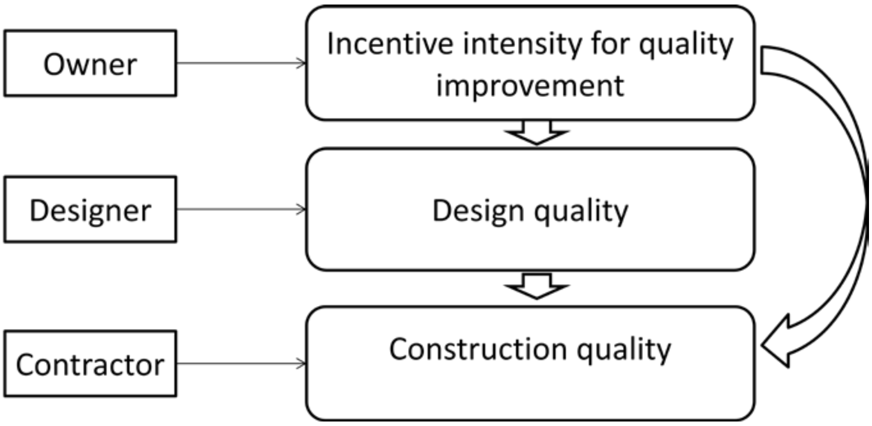

Fig. 2. Decision-making process of the key participants

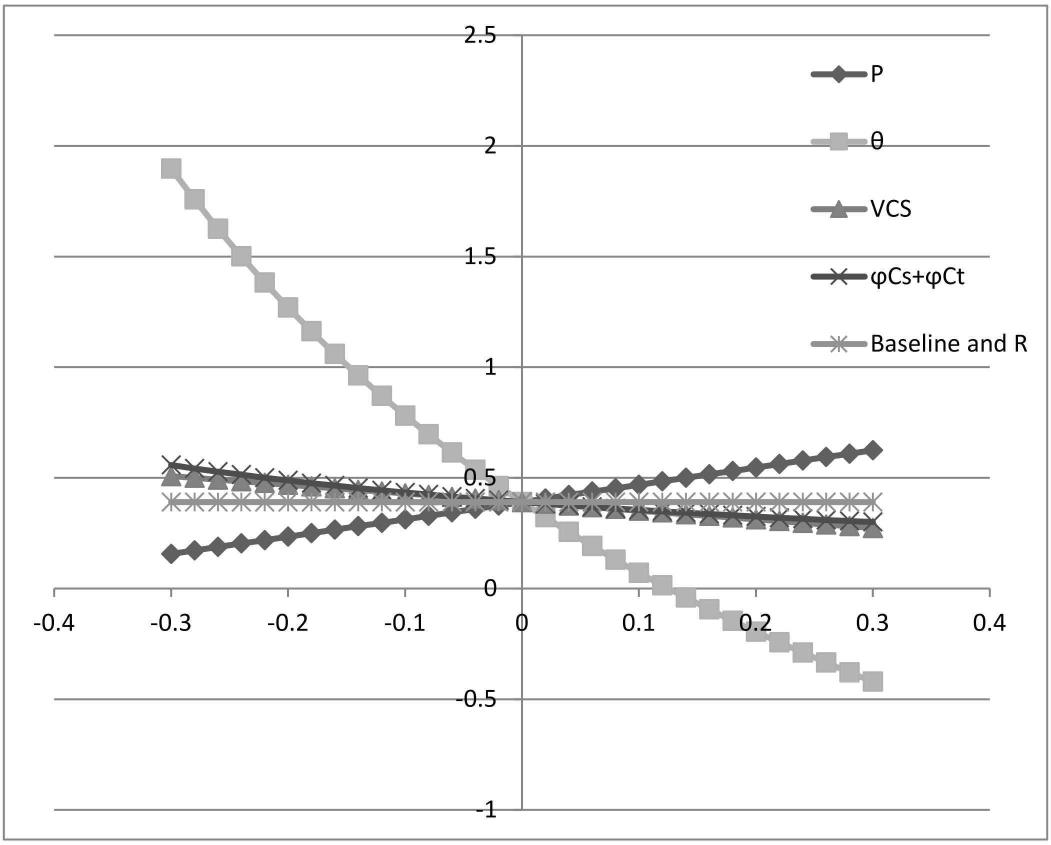

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Fig.3. Sensitivity analysis for quality comparison

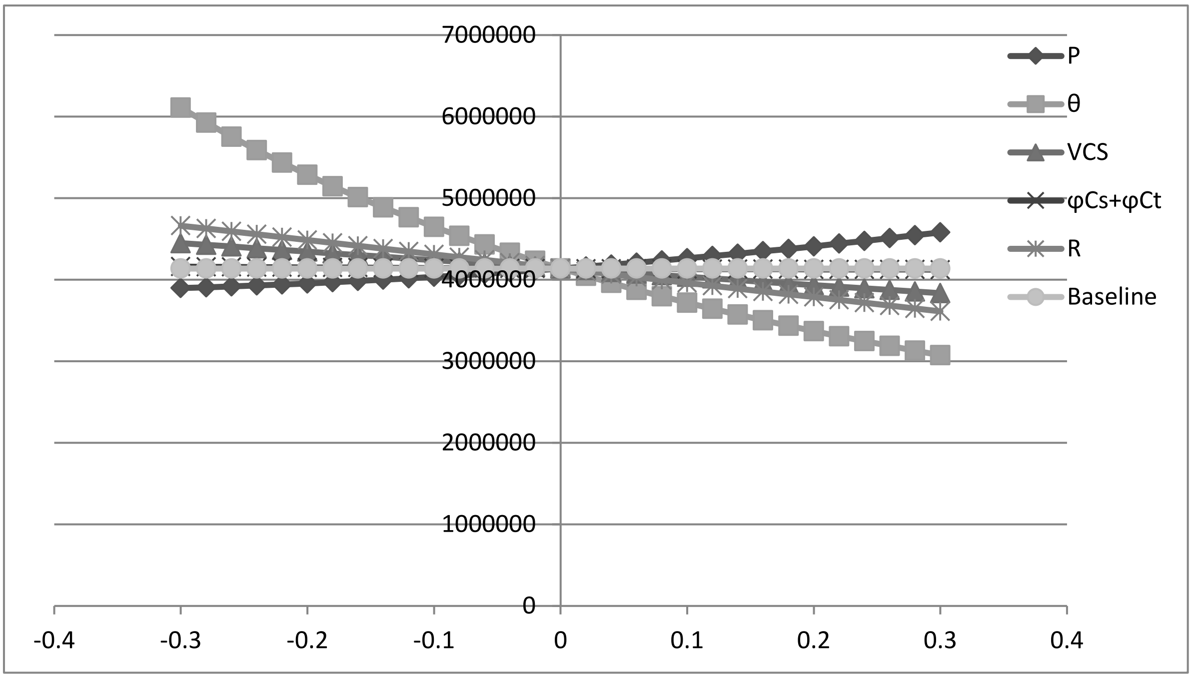

Fig.4. Sensitivity analysis for profit comparison (profit of the owner)

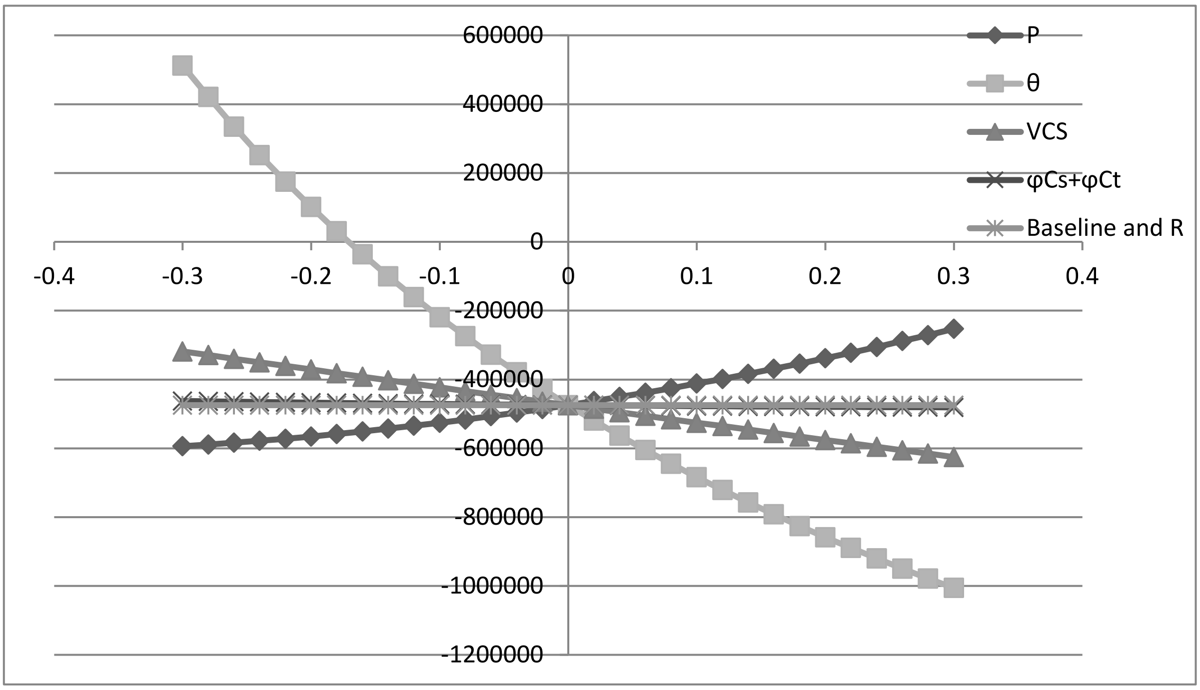

Fig.5. Sensitivity analysis for profit comparison (profit of the designer and contractor)

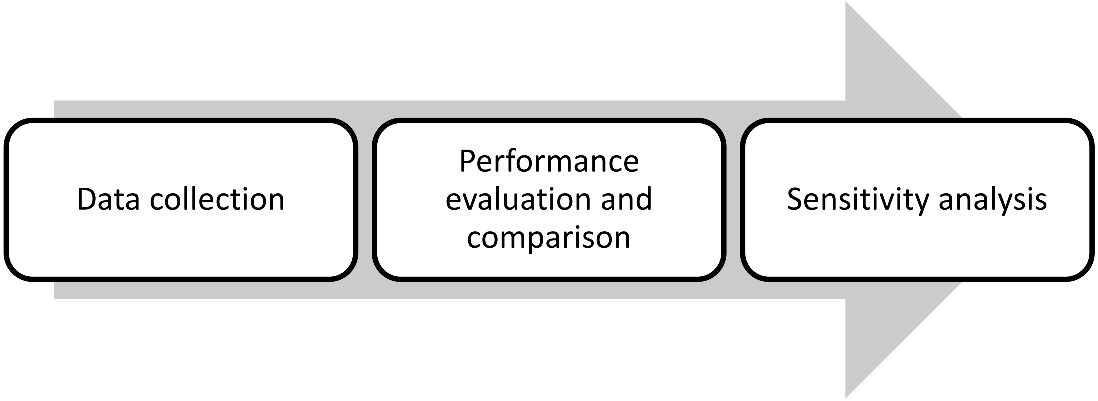

Fig.6. Application of the economic model developed in this study

Table 1. Comparison between the DB and DBB delivery methods

	DB	**DBB**
1 Mode of payment	The owner pays the DB contractor.	The owner pays the designer and the contractor, respectively.
2 Degree of cooperation between the designer and the contractor	High	Low
3 Responsibility and involvement of the owner	Low	High

4 Responsibility and involvement of the designer and the contractor	High	Low
5 Risks for the owner	Low	High
6 Risks for the designer and the contractor	High	Low
7 Design/construction costs for the designer and the contractor	Uncertain	Uncertain
8 Coordination/communication costs for the designer and the contractor	High	Low
9 Management costs for the owner	Low	High

Table 2. Scenarios Comparing the Quality-profit Equilibrium for DBB and DB

Case NO.	Descriptions of Project Conditions	Performance Quality	Profit of the Owner	Profit of the Designer and Contractor
1	Failure to meet Conditions 1, 2, and 3.	DBB is better	DBB is better	DBB is better
2	Able to meet Condition 1, but failure	DBB is better	DB is better	DBB is better

	to meet Conditions 2 and 3.			
3	Able to meet Condition 2, but failure to meet Conditions 1and 3.	DB is better	DBB is better	DBB is better
4	Able to meet Conditions 1 and 2, but failure to meet Condition 3.	DB is better	DB is better	DBB is better
5	Able to meet Conditions 1, 2, and 3.	DB is better	DB is better	DB is better

Table 3. Values of the key parameters

Parameter	**Value**	**Parameter**	**Value**
Q	29, 100 m^2	R	0.3
P	100 Yuan/m^2	θ	0.8
ϕ_{Cs}	3	T_{SC}	503, 000 Yuan
ϕ_{Ct}	5	V_{SC}	10 Yuan/m^2

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F_M	5, 828, 500 Yuan