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RESEARCH ARTICLE

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Supplier development and its incentives in infrastructure mega-projects: A case study on Hong Kong-Zhuhai-Macao Bridge project

Abstract In this paper the Hong Kong-Zhuhai-Macao Bridge project is taken as a case to analyze supplier development in infrastructure mega-projects. Compared with manufacturing industry, the characteristics of supplier development in infrastructure mega-projects is analyzed in term of development motives, supplier selection, quality management, production mode, owner participation and risks. The critical factors influencing the construction supplier development are identified, which include incentives, collaboration, future market, trust and bilateral communication. Furthermore, focusing on the incentives for the supplier's product quality and production capacity improvement, decision-making framework models are proposed to design the incentive mechanisms.

Keywords infrastructure mega-project, supplier development, critical success factors, incentives, case study

1 Introduction

Infrastructure mega-projects are important measures for improving national sustainable development capacity and comprehensive national strength. These projects are characterized by huge investment, long construction period, high technical and high quality specifications, large resource supply, and extensive influence. For construction suppliers, infrastructure mega-projects raise high requirements in product quality as well as production and delivery capacities. Therefore, to improve the suppliers' capacity is one of the potential challenges in infrastructure mega-projects.

Supplier development concerns how to achieve the accurate and cost-effective resource supply in a timely manner through improving suppliers' quality, production, delivery and cost capacity (Krause and Ellram, 1997). Supplier development is originated from the manufacturing industry practices. For example, in order to help its suppliers achieve Toyota Production System, supplier development is one of the important ways adopted by Toyota Motor to improve the suppliers' product quality and delivery capacities (Dyer and Nobeoka, 2000).

Supplier development also receives much attention from academic research. Scholars have studied the concept, classification, operation process, and critical success factors of supplier development through case study, interview, questionnaire, or literature review. Krause and Ellram (1997) defined supplier development as a measure for the buyer to improve suppliers' performances and capacities, including technology, quality, delivery, and cost capacity, to satisfy the buyer's requirements. They also emphasized the importance of supplier development from the following aspects: (1) Supplier development is instrumental in meeting supply demands, reducing costs, and achieving revenue sharing; (2) It also helps enhance the competitiveness of an enterprise; and (3) helps improve the competitiveness of the entire industry. Supplier development can be divided into two types, namely, reaction and strategic. The former is problem-driven

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supply development that aims at supplier-specific problems and improves suppliers' performance at very limited or least cost. The latter is market-driven supplier development that requires both a buyer and a supplier to invest many resources to enhance the long-term performance of the supplier (Krause et al., 1998). Supplier development generally involves the evaluation of supplier, covering the supplier's technology, quality, delivery, funding, and management, identification of domains that need improvement, formulation of supplier development plans and programs, and assessment of the supplier development effect (Hahn et al., 1990).

The long-term cooperation relationship between a buyer and a supplier is considered one of the key factors for the success of supplier development. Most companies are more inclined to establish long-term strategic relationships with suppliers, in hopes of building lasting competitiveness of both sides, rather than any short-term market advantage (Lascelles and Dale, 1989). Krause et al. (2000) analyzed the factors influencing supplier development from literature review and empirical data. These factors include effective communication, senior management participation, long-term cooperation and purchase volume. For both the perspectives of supplier (Nagati and Rebolledo, 2013) and the buyer (Li et al., 2007), aforementioned factors are all important factors influencing supplier development activities. Especially, the buyer's commitment to long-term cooperation is a key factor for the success of supplier development activities. To urge suppliers to improve their performance and avoid opportunistic behaviors, scholars have also sought for incentives to support training activities, including financial incentives and increasing purchase volume (Toni and Nassimbeni, 2000).

The infrastructure mega-project is usually unique and one time, which significantly differs from the manufacturing industry. Therefore, the relationship between the owner and its supplier is often a short-term partnership. From the perspective of the owner, he/she concerns the short-term interest of the current construction project, e.g., the timely supply of high quality materials. From the perspective of the supplier, he/she pays close attention to the future construction project and all market opportunities in the whole industry, in addition to accomplishing the resource supply of the current construction project. In other word, the supplier gives consideration to both the short-term project income and the long-term market return. Such difference may affect the partnership between the owner and its supplier.

If the technical level or production capacity of the supplier does not meet the project specifications, the supplier needs to invest a large amount of manpower, materials, and funds in technology research, production equipment upgrading and personnel training. Such investments may be difficult to recover through the undertaken project. Therefore, incentive mechanism is considered as an important means to enhance cooperation and supplier development (Mead and Gruneberg, 2013). Besides, leadership, training, coordination, and other measures are also important for forming cooperative relations in construction projects (Tang et al., 2006; Bresnen and Marshall, 2000).

In general, the studies on supplier development are almost concentrated in the manufacturing industry, while the studies on supplier development and its incentive mechanisms in construction industry is very scattered (Ross and Goulding, 2007). The purpose of the paper is to further explore the critical factors influencing construction supplier development according to the construction project characteristics. In particular, considering the quality improvement and production capacity improvement in construction supplier development, the paper will analyze the incentives for supplier development and propose decision-making framework models to design incentive mechanisms. We hope the study can provide managerial insights for infrastructure mega-project supplier development practices.

The reminder of the paper is structured as follows. First, the supplier development case of Hong Kong-Zhuhai-Macao Bridge (hereinafter referred to as HZMB) project is introduced and the characteristics of construction supplier development are analyzed in Section 2. Then, in Section 3, the factors influencing the construction supplier development and its conceptual model are introduced. In the subsequent Section 4, the incentives for construction supplier development are analyzed and decision-making framework models for incentive mechanism design are proposed. Conclusions are drawn in Section 5.

2 Supplier development case study: The HZMB project

2.1 Brief introduction

The HZMB, a cross-sea bridge under construction, is a huge bridge connecting Hong Kong, Zhuhai, and Macao. The natural environment of the construction site is very bad, such as complicated ocean current, hydrological, and weather conditions. The construction site is on the busy shipping lines. Meanwhile, the quality specifications of the project is very high, e.g., the service life of the bridge is 120 years, which is far above that of common construction projects in China. To meet the high quality standards and specifications and reduce the impacts of complex construction environmental conditions, the HZMB project introduces the prefabricated construction method, with main works of the bridge, including piers, steel box girders, hybrid girders and immersed tube tunnels prefabricated in their respective factories and delivered to the construction site for installation.

In the HZMB project, plenty of new technologies and advanced equipment were used in the manufacturing and assembling of the prefabricated components. For example, in the section of the deep-water non-navigable bridge, large cantilever type single-box dual-cell girder structures were first adopted in China. To guarantee the quality and supply of such steel box girders, three major steel box girder suppliers in China were selected by the HZMB authority at the beginning of the project. However, their existing production capacities or product quality failed to meet the construction specifications. The HZMB authority, as the owner, took various measures to improve the suppliers' production capacities and quality levels, including joint commitment to national science and technology support programs, preferential steel box girder price, personnel training, etc.

2.2 Characteristics of construction supplier development

To investigate the differences between supplier development in construction and that in the manufacturing industry, the HZMB project is taken as a case to analyze the characteristics of construction supplier development from the aspects of development motives, supplier selection, quality management, production mode, owner participation and risks.

2.2.1 Development motives

In the manufacturing industry, supplier development may be reactive or problem driven, which emphasizes on a short-term partnership between suppliers and buyers to solve the existing problems of supply capacities, product quality, etc. Supplier development may also be strategic or market driven, pursuing the future long-term market competitiveness (Krause et al., 1998).

Unlike that in the manufacturing industry, supplier development in infrastructure mega-project is often one time and temporary due to the particularities of infrastructure mega-project such as its temporary organization, unique products, etc. The owner and its suppliers cannot form a long-term partnership, so supplier development is reactive based on a short-term partnership. Like the example of HZMB, this kind of bridge project is very rare in the world, and the partnership between the owner and its suppliers only lasts during the project period. It is worthy to mention that it is possible to establish a long-term partnership in the regular construction projects, for example, the real estate developers can establish long-term relationship with their suppliers as they are going to do the same kind of projects over and over.

Infrastructure mega-project has higher requirements in technical, quality and production capacity. These require the suppliers to invest in their capacity improvement. The cost effectiveness may be low for the suppliers if they only consider the short-term return on investment from the one-time construction project. In practice, the supplier's decision on whether to participate in the construction is usually not only dependent on the short-term gains from the current project, but also the long-term market competitiveness and development opportunities. On the other side of the owner, the owner of infrastructure mega-project often represents government to exercise project management duties and has a mission to improve competitiveness of the whole industry.

With the aim to improve the manufacturing level of the Chinese steel box girder industry, the HZMB authority takes various measures, including joint commitment to national science and technology support programs, preferential price of steel box girder, personnel training, etc. To enhance the future market competitiveness, the steel box girder suppliers upgrade their production equipment, improve production capacity and management level. Through the supplier development activities, the suppliers are awarded the relevant international quality system certification and their international market competitiveness is enhanced.

2.2.2 Supplier selection

The number of suppliers in the manufacturing sector is usually large. The corresponding evaluation system for suppliers may be established on the basis of their historical performance data. Bidding is usually used for the selection of the suppliers. Besides, the manufacturer also uses the means of founding stockholding or joint-stock company with the suppliers.

Due to the high technical and quality specifications for infrastructure mega-projects, usually very few suppliers possess the required capacities on the market. For example, three major Chinese steel box girder suppliers were selected by bidding at the beginning of the project, and each supplier undertook one bid package of the steel box girders supply. To ensure the production capacity and quality level of steel box girder meet the required construction specifications, mandatory requirements for the suppliers' production equipment and management system are listed in the tender documents.

2.2.3 Product quality management

In the manufacturing industry, the type and quantity of components are usually large. Therefore, sampling test is usually adopted in the product quality inspection.

While in the construction project, the type of prefabricated component is often onefold and the quantity is relatively smaller, but at very high unit price. Full inspection is often adopted in the quality inspection. For example, the HZMB authority hired an independent consultant group to supervise the quality of the prefabricated components. To guarantee the quality of each prefabricated component, the first-article inspection and full inspection are adopted in the quality inspection of prefabricated steel box girders and immersed tubes.

2.2.4 Production mode

In contrast to the diversification of production methods in the manufacturing industry, distributed production mode is often adopted in construction. This is due to the restriction on transportation of large and heavy prefabricated components in infrastructure mega-projects. In the HZMB example, all the three suppliers of steel box girders set up their own assembly plants in Zhongshan city in close proximity to the construction site, in addition to their production bases of steel box girder segments in other cities.

2.2.5 Owner participation

In the manufacturing industry, buyers directly involved in the production process. Furthermore, they can provide technical guidance and personnel training for the suppliers, in addition to funding support to supplier development.

The owner in construction project is mainly responsible for the organization and coordination of the entire project management, but does not directly engage in production. Therefore, the owner mainly supports its suppliers in the form of funding, helps them establish sound management systems, and provides technical support for suppliers with the aid of technical advisory bodies.

2.2.6 Risks

In regular construction project, e.g., the house building project, prefabrication construction may be cheaper than conventional construction due to the mass production of standardized prefabricated components. But in infrastructure mega-projects the prefabricated components are usually customized and non-standardized, like the prefabricated steel box girders and immersed tubes in HZMB project are produced under customized specifications. Thus the prefabricated components for infrastructure mega-projects are generally costly, with longer production cycle. Meanwhile, the site assembly of such components is subject to natural environment conditions. The assembly of the prefabricated steel box girders and immersed tubes in the HZMB project has to be completed offshore. The assembly must be carried out in the optimal time window, which is seriously affected by oceanic currents, typhoons, and other natural environmental factors. Thus, higher requirements in the production, delivery and warehousing of such prefabricated components are put forward, and the suppliers should dynamically adjust their production plan according to the assembly plan. Any failure in timely production or supply may cause a delay of the entire project and bring about a huge loss. Therefore, the risks are often great in infrastructure mega-project.

3 Analysis of factors influencing the supplier development in infrastructure mega-projects and its conceptual model

3.1 Analysis of factors influencing the supplier development in infrastructure mega-projects

From the comparative analysis in the previous section, the differences between the construction industry and manufacturing industry are analyzed. To take advantage of supplier development in construction, it is important to identify the drivers and barriers of the construction supplier development according to the aforementioned characteristics of construction project.

1) Incentives

In infrastructure mega-project, the suppliers need to invest considerable money and labor to improve the quality and the production capacity and enhance their market competitiveness. However, the suppliers' huge investments in the supplier development may not be necessarily recovered from the construction project because of uncertainties of the future market. Therefore, the owner's incentives to improve the supplier's willingness to participate in the supplier development are considered as effective measures to encourage the suppliers to actively participate in the supplier development activities (Mead and Gruneberg, 2013). The owner's incentives are the key driving factor for supplier development.

2) Collaboration

Construction supplier development reflects a partnership between the owner and its suppliers. The collaboration between the owner and its suppliers is considered as a key factor for the success of supplier development. The collaboration of supplier development can be divided into collaborative strategy, collaborative operation and collaborative support layers. The collaborative strategy layer is at the highest level, which includes the collaborative management policies and coordination mechanisms of supplier development. In detail, supplier selection, contract and incentive mechanisms design, profit sharing and conflict resolution, mutual trust and win-win culture, etc. are included the layer. The collaborative operation layer is the embodiment of the collaborative strategy layer, which covers measures to improve the suppliers' product quality and production capacities, achieve coordination of construction plan and resource supply plan, and enhance collaborative quality management. To support the efficient collaboration of supplier development, the collaborative support layer is used to achieve the information and knowledge sharing and

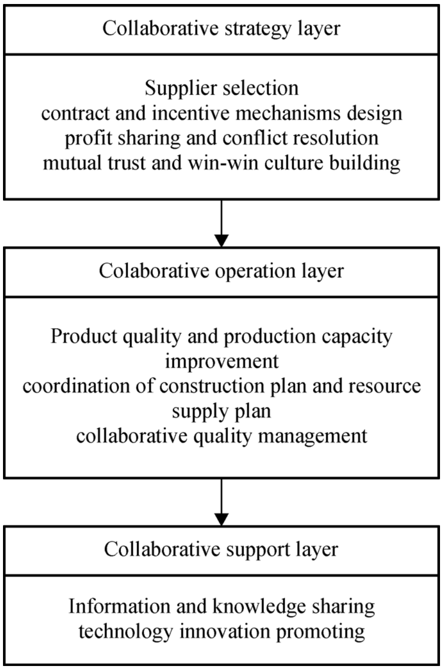

Fig. 1 Collaboration between the owner and the supplier in the supplier development

technology innovation during the process of supplier development. Figure 1 shows the collaboration between the owner and the supplier in the supplier development.

There exist differences between the perspectives of the owner and its suppliers in construction supplier development. From the perspective of the owner, he/she mainly pays attention to the performance improvement of construction quality, progress, and cost through supplier development. However, the supplier does not only focus on ensuring the resource supply, but also takes into account the influences of the future market through supplier development. If the future market demand is large, then the supplier is more willing to participate in supplier development, in hopes of improving their competitiveness and return on investment in the future market. For example, in the HZMB project, the three steel box girder suppliers map out different investment plans for improving their respective production capacities according to their own judgments of the future market demand. Some suppliers newly build their production capacities, including setting up new factories of small segments of steel box girders at the production bases, purchasing land near the construction site and opening new assembly plants of large segments of steel box girders. Other suppliers just upgrade their old production lines at the production bases and lease

Table 1 Summary of drivers and barriers of construction supplier development

Factors	Drivers	Barriers	Study
Incentives	The owner's incentives motivate the suppliers to actively participate in the supplier development, thereby ensuring the resource supply and enhancing the suppliers' competitiveness.		Krause et al., 2000; Toni and Nassimbeni, 2000; Mead and Gruneberg, 2013
Collaboration	Collaboration at the strategy, operation and support layer enables the organization and conduct of supplier development activities.	The owner and its suppliers have to pay high attention to collaboration from high level leaders to executive level and this requires heavy investment on manpower, material and financial resources.	Krause et al., 2000; Nagati and Rebolledo, 2013; Li et al., 2007
Future market	To improve the competitiveness in the future market is one of important factors for the suppliers to take part in the supplier development program.	Uncertainties and risks of the future market affect the supplier's return on investment and willingness to participate in the supplier development.	Mead and Gruneberg, 2013
Trust	The mutual trust between the owner and the supplier can build a good cooperative partnership and help facilitate the conduct of supplier development activities.	Different interests among the participants often hinder the achievement of their mutual trust.	Handfield et al., 2000; Li et al., 2007; Sako, 2004
Bilateral communication	The effective bilateral communication can accurately identify the requirements of supplier development, detect problems during the supplier development process and improve the efficiency of the supplier development activities.	The poor communication between the owner and the supplier often leads to deviations or inefficiencies during the supplier development process.	Krause et al., 2000; Nagati and Rebolledo, 2013; Li et al., 2007; Krause, 1999
Suppliers' competitiveness	Suppliers' own abilities, including product quality, productivity, and management capacity, affect the owner's supplier selection and supplier development method and input.		Hahn et al., 1990; Mahapatra et al., 2012; Modi and Mabert, 2007

land near the construction site to assemble large segments of steel box girders. Therefore, the perception of the future market demand will influence the strategy chosen by the supplier, furthermore, the successive supplier development activities (Nagati and Rebolledo, 2013).

4) Trust, bilateral communication and suppliers' competitiveness

Apart from the above-mentioned factors, the mutual trust between the owner and the supplier (Handfield et al., 2000; Li et al., 2007; Sako, 2004), bilateral communication (Krause, 1999), and competitiveness of the supplier (Hahn et al., 1990; Mahapatra et al., 2012; Modi and Mabert, 2007) may influence supplier development.

Table 1 summarizes the drivers and barriers of construction supplier development.

3.2 Conceptual model of construction supplier development

From the analysis on the drivers and barriers of construction supplier development, the owner' incentives, collaboration, supplier selection, suppliers' competitiveness and future market demand are considered as the key factors influencing the supplier development. Nagati and Rebolledo (2013) gave a concept model of the supplier development, which investigates the role of trust, preferred customer status and dynamism of the environment on suppliers' participation in supplier development activities and their impact on suppliers' operational performance improvement. Based on the concept model of supplier development in manufacturing industry, a conceptual model of construction supplier development is proposed in Fig. 2, which emphasizes the aforementioned critical factors.

1) Suppliers' competitiveness, future market, and supplier selection

Suppliers' competitiveness is one of the most important factors to supplier selection. Due to the high requirements for the suppliers' capacities in the infrastructure mega-project, the owner is more inclined to select the most competitive suppliers. The future market demand and long-term development strategies are considered as the important factors to the suppliers.

2) Incentives, supplier selection, collaboration, and supplier development activities

The owner can motivate suppliers to improve their production capacities and product quality levels by various incentives such as purchasing price subsidies and cost sharing. The collaboration between the owner and its suppliers can improve their mutual trust and promote the supplier development activities. The selection of appropriate suppliers can lay a good foundation for the supplier development activities.

3) Supplier development activities and suppliers' performance improvements

The goal of supplier development activities is to achieve the improvement of suppliers in the production capacity, quality and cost control, etc.

4 Incentives for the supplier development for infrastructure mega-projects

From the above analysis, the owner's incentives are the key influencing factors and measures for the supplier development. To design the incentives to promote the supplier development in infrastructure mega-projects, decision-making framework models are proposed based on the theory of incentive mechanism design.

4.1 Analysis of the incentives for construction supplier development

To motivate the suppliers to participate in the supplier development, e.g., production quality improvement and/or product capacity improvement, it is important to design the contract and incentive mechanisms for the owner and its suppliers. In construction project, the owner often plays a dominant role and determines the product quality specification, delivery time, etc. In other word, the owner often has a dominant position in the negotiation of the supply contract with the suppliers. Therefore, the incentive mechanisms design for the construction supplier development should be considered under the structure of hierarchical decision making. Two commonly used

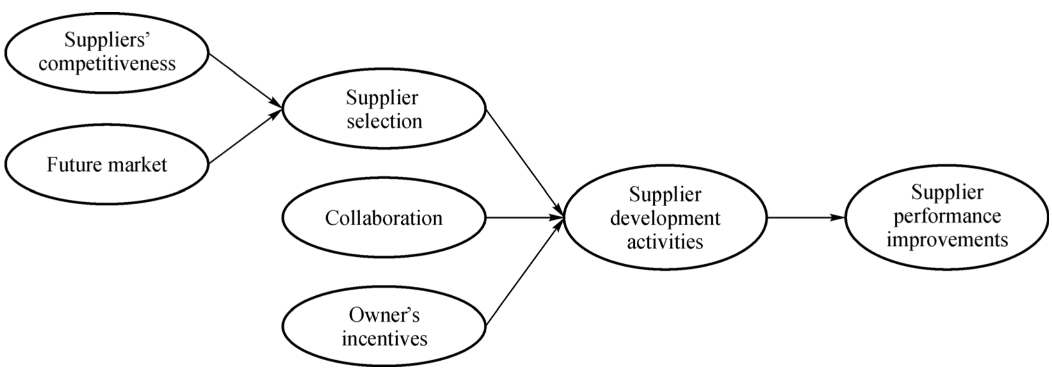

Fig. 2 Conceptual model of construction supplier development

methods are applied in incentive mechanism design. One is principal-agent theory (Laffont and Martimort, 2002). The relationship of the owner and its supplier is regarded as a kind of principal-agent relationship. In detail, the mission of resource supply is awarded to the supplier by the owner who is the principal. The interests between the owner and its suppliers are not entirely consistent, because as an agent the suppliers seek to maximize their own interests. Incentive mechanisms may be used to align the interests of the agent with those of the principal. The other one is Stackelberg game (Basar and Olsder, 1982) which is a framework to analyze situations in which two or more rational individuals make decisions that will influence one another's interests and at the same time there is a predefined sequence in which the individuals must take their decisions. In the construction, as the Stackelberg leader the owner offers an incentive contract to its supplier who is the Stackelberg follower. Both sides try to maximize its own interests and a solution for the game is reached at the Stackelberg equilibrium, i.e., the incentive contract is accepted by both sides.

Following the above-mentioned theory of incentive mechanism design, two scenarios of the owner's dominance in the supplier development will be studied. On the one hand, the owner has a dominant position and tries to maximize its own benefits, while the supplier has to choose whether to accept the supplier development. To motivate suppliers to participate in the supplier development program, the owner gives the supplier the lowest incentives, thus making the suppliers' income during his participation in the supplier development not less than theirs without participating in the supplier development. This scenario can be represented by a principal–agent model under which the owner acts as the principal and the supplier serves as agents (Laffont and Martimort, 2002). In the principal-agent model, the individual rationality constraint (IR) of the supplier is that his/her profit gained through the supplier development should be larger than the profit gained when he/she does not take part in the supplier development. Being subject to the IR constraint, the owner determines the incentive intensity and maximizes his profit. On the other hand, the owner first offers the contract terms with incentives to the supplier, and then the supplier determine his investment in the supplier development. Each side wants to maximize its own benefit and eventually reach a Stackelberg equilibrium. This scenario can be represented by a Stackelberg game model under which the owner acts as the Stackelberg leader and the supplier serves as the Stackelberg follower (Basar and Olsder, 1982). In the Stackelberg game model, the owner determines the incentive intensity to motivate the supplier to participate the supplier development and maximize his profit, while the supplier determines the investment in the supplier development program to maximize his profit.

Improvements of supplier's product quality and production capacity are two main goals of supplier development. In the paper two common used incentives in the construction practices, namely, the investment cost sharing and the purchase price incentive, are considered. In detail, the owner may share a certain proportion of the supplier's investment on the improvement of product quality and production capacity, i.e. the cost-sharing incentive for supplier development. The owner may offer different purchase price according to the supplier's product quality level, namely, the purchase price incentive.

4.2 Mathematical representation of construction supplier development

4.2.1 Mathematical representation of construction supplier development in quality improvement

1) Quality level

The product quality is described by a series of attribute vector indexes such as reliability, persistence, and appearance. Similar to Banker et al., (1998), the quality level as a one-dimensional variable is a collective of a series of quality attributes in this paper. Assume that the initial product quality level is $x_0(>0)$, the improved quality level is $x(>0)$ and x is continuous. The greater the value, the better the product quality is.

2) Quality improvement cost

When the supplier invests in quality improvement with the initial quality level x_0 improved to x, the cost function is assumed as $(f+\varepsilon(x-x_0))Q+k(x-x_0)^2$. Here, the supplier's production cost can be divided into two parts. Part I $f+\varepsilon(x-x_0)$ refers to the supplier's unit production cost. Where f represents part of the unit variable cost that is unrelated to the quality; ε represents the unit variable cost that is related to the quality, and $\varepsilon>0\,(\varepsilon<0)$ represents an increase or decrease in the variable production cost with the quality improvement; and Q represents the purchase volume. It is worthy to mention that the demand for construction materials is usually certain for a construction project. Part II $k(x-x_0)^2$ refers to the investment in technology research and development, equipment, education and training, quality management promotion, etc. Without loss of generality, the quality investment cost is expressed as the quadratic function for the quality level improvement $(x-x_0)$ (Banker et al., 1998). Where k represents the fixed cost parameter for the supplier's quality improvement, and the smaller the value of k is, the greater the quality improvement under the same investment is.

3) Owner's incentives

For the cost sharing, assume that the proportion of the supplier in the cost of the fixed investment in quality is $\theta\,(\theta\in[0,1])$, while that of the owner is $(1-\theta)$. The cost of the supplier's investments in quality is $k\theta(x-x_0)^2$, while that of the owner's is $k(1-\theta)(x-x_0)^2$. Thus, $\theta = 1$ means the supplier bears all the investment in quality improvement, and $\theta = 0$ means the owner bears all the investment in quality improvement.

The owner's purchase price incentive is expressed by $p_0 + \delta(x-x_0)$, where p_0 represents the market price with the initial product quality level, and $\delta(\geqslant 0)$ represents the incentive parameter of the purchase price. The higher the quality level improved, the greater incentives the owner gives in the purchase price.

4) Future market demand

Assume that the demand D is determined by the product price p and the quality x, $D = \alpha + \lambda x - \gamma p$, where α represents the intrinsic demand potential parameter for the product, λ represents the demand responsiveness to the product quality, and γ represents the demand responsiveness to the product price p.

5) Profit functions of the owner's and its supplier

After the supplier development, the supplier's product quality level is improved to x. Assume that the supplier adopts the same quality level in the future. The supplier's incomes come from its current project and future market. The supplier's profit from the current project is

$$\Pi_{\mathrm{sc}}^{\mathrm{D}} = [p_0 + \delta(x-x_0) - (f + \varepsilon(x-x_0))]Q - k\theta(x-x_0)^2. \tag{1}$$

The supplier's future profit is

$$\Pi_{\mathrm{sf}}^{\mathrm{D}} = \rho[p - (f + \delta(x-x_0))](\alpha + \lambda x - \gamma p). \tag{2}$$

Combining Eqs. (2) and (3) and considering the discount ρ of the future profit, the supplier's total profit $\Pi_{\mathrm{S}}^{\mathrm{D}}$ is

$$\Pi_{\mathrm{S}}^{\mathrm{D}} = \Pi_{\mathrm{sc}}^{\mathrm{D}} + \Pi_{\mathrm{sf}}^{\mathrm{D}} = [p_0 + \lambda(x-x_0) - (f + \delta(x-x_0))]Q$$

$$-k\theta(x-x_0)^2 + \rho[p - (f + \delta(x-x_0))](\alpha + \lambda x - \gamma p). \tag{3}$$

Similarly, when the supplier improves the quality level by itself without participating in supplier development, the supplier's profit is $\Pi_{\mathrm{S}}^{\mathrm{N}}$. The detailed expression is omitted here.

Assume that the utility brought about for the owner after product quality improvement is $a(x-x_0)Q$. The owner's total profit is the utility after transfer payment and shared cost. Therefore, the expected utility function of the supplier is

$$\Pi_b = a(x-x_0)Q - (1-\theta)k(x-x_0)^2 - [p_0 + \lambda(x-x_0)]Q. \tag{4}$$

4.2.2 Mathematical representation of construction supplier development in production capacity improvement

The production capacity refers to the quantity of products made in unit time. For the supplier, its under-capacity may cause the delay of construction project and penalty from the owner. However, over-capacity may increase the supplier's production and warehousing costs, etc. For the owner, the supplier's enough production capacity may ensure construction delivery on schedule.

1) Production capacity improvement cost

Assume that the supplier's initial production capacity is q_0, the production capacity is improved to $q(q>0)$, and q is continuous, then the improved production capacity is $(q-q_0)$. Assume that the investment cost per unit production capacity is k, and the cost of investments in improving the production capacity is $k(q-q_0)$ (Cachon and Lariviere, 2001)

2) Owner's incentives

Similarly, the owner adopts two incentives for the supplier, namely, the investment cost sharing and the purchase price incentive. The proportion of the supplier in the investment cost sharing is $\theta(\theta \in [0,1])$, while that of the owner is $(1-\theta)$. For the owner, he only require the supplier's production capacity to satisfy the purchase volume Q, and overcapacity is not necessary. When the supplier's production capacity is larger than required, the supplier will bear a penalty $h(q-Q)$, where h is the penalty per unit over-capacity. Assume that the purchase price incentive is δ when the supplier improves its production capacity to satisfy the supply requirement, then the purchase price that the owner offers the supplier is $p_0 + \delta$.

3) Market demand risk

It is exactly due to the non-deterministic market demand, it is nontrivial to make the decision on the production capacity. If the realized demand is low, the suppliers risk the burden of over-capacity, or under-capacity if the realized demand is high (Tomlin, 2003). Therefore, different from the assumption of the market demand D, here assume that the market demand D is random, the demand possibility density function is $f(\cdot)$, and the cumulative distribution function is $F(\cdot)$, which has an increasing generalized failure rate (IGFR).

Because the market demand is random, the supplier's attitude to risk should be taking into account. Assume that the supplier is risk aversion and adopts the value at risk (VaR) model to measure the supplier's risk attitude (Tapiero, 2005). Let Π_0 represent the supplier's reservation utility obtained from the future market, represent the supplier's risk aversion parameter, namely, the supplier's confidence level measured by the VaR model, then the supplier's risk attitude is modeled as $P(\Pi_{\mathrm{sf}} \leqslant \Pi_0) \leqslant \tau$.

4) Profit functions of the owner and its supplier

When the supplier participates in the owner's project, the supplier's production capacity must meet the construction project specifications, that is $q \geqslant Q$. Furthermore, assume that in the future market the supplier produces according to the production capacity after supplier development, then the supplier's profit is the sum of the current construction profit and the future market profit. The supplier's profit from the current construction is

$$\Pi_{sc} = (p+\delta-f)Q - h(q-Q) - \theta k(q-q_0). \quad (5)$$

The supplier's profit from the future market is

$$\Pi_{sf} = (p-f)\min(D,q) - h(q-D)^+. \quad (6)$$

Combining Eqs. (5) and (6), the supplier's total profit is

$$\Pi_S^D = (p+\delta-f)Q - h(q-Q) - \theta k(q-q_0) + \rho[(p-r)\min(D,q) - h(q-D)^+]. \quad (7)$$

Similarly, when the supplier does not undertake the current project, the profit from the future market is given as Π_S^N. The detailed expression is omitted here.

The owner's total profit is

$$\Pi_b = [a(q-q_0) - (p+\delta)]Q - (1-\theta)k(q-q_0). \quad (8)$$

4.3 Decision-making framework model of incentives for construction supplier development

According to aforementioned the principal–agent model and the Stackelberg game model, the decision-making framework model of incentives for construction supplier development is given as follows. The principal–agent model of supplier development is

$$\text{Max } E[\Pi_b], \quad (9)$$

$$\text{s.t. } E[\Pi_S^D] \geqslant E[\Pi_S^N], \quad (10)$$

$$\text{or s.t.} \begin{cases} E(\Pi_S) \geqslant E(\Pi_{S0}^N) \\ q \geqslant Q \\ P(\Pi_{sf} \leqslant \Pi_0) \leqslant \tau \end{cases}, \quad (11)$$

where Eq. (9) represents the maximizing the owner's expected profit $E[\Pi_b^D]$, Eq. (10) is the IR constraint of the supplier development in quality improvement, and Eq. (11) includes the IR constraint of the supplier development in production capacity improvement, production capacity constraint and risk constraint. Under the assumption of symmetric information, the incentive-compatibility constraint is not considered.

In the principal-agent model, the owner determines the incentive intensity, i.e., purchase price incentive δ and cost sharing proportion θ, and quality level x or production capacity q, to maximize his/her expected profit.

The Stackelberg game model of supplier development is

$$\text{Max } E[\Pi_b], \quad (12)$$

$$\text{Max } E[\Pi_S^D], \quad (13)$$

$$\text{s.t.} \begin{cases} q \geqslant Q \\ P(\Pi_{sf} \leqslant \Pi_0) \leqslant \tau \end{cases}, \quad (14)$$

where Eq. (3) represents maximizing the owner's expected profit, Eq. (4) represents maximizing the supplier's expected profit, and Eq. (14) represents the production capacity constraint and risk constraint in the case of production capacity improvement.

In the Stackelberg model, the owner determines the incentive intensity, i.e., purchase price incentive δ and cost sharing proportion θ, to maximize his/her expected profit, while the supplier determines the quality level x or production capacity q to maximize his/her expected profit.

Through solving the two decision-making models, it is possible to analyze how the owner's incentives affect the supplier's quality level and production capacity improvement. By the parametric sensitivity analysis, the influences of purchase volume, production costs and market demand on the incentives and the quality level and production capacity improvement can be analyzed. These analyses can provide decision-making supports for incentive mechanism design in supplier development.

5 Conclusions

Supplier development is one of the major challenges for the infrastructure mega-projects. This paper takes the supplier development in the HZMB project as a case. Comparative analysis shows that there are obvious differences between the supplier development in construction with that in manufacturing industry in the term of development motives, supplier selection, quality management, production mode, owner participation and risks. The drivers and barriers of construction supplier development are further analyzed. Incentives, collaboration, future market, trust, bilateral communication, and suppliers' competitiveness are critical factors for the success of the supplier development. On this basis, the conceptual model of construction supplier development is proposed. Following the principal-agent theory and Stackelberg game, the decision-making framework models of incentives for construction supplier development in quality level and production capacity improvement are also given.

This research is an empirical study on construction supplier development mainly based on the HZMB project. Supplier development practices should be further studied in other infrastructure mega-projects to verify the factors influencing construction supplier development in the conceptual model and analyze the incentive mechanisms for construction supplier development through numerical analysis and examples.

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