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Invitational bidding and award strategies for technological innovation of public goods: A contest model analysis

ZHOU Jianan, ZHONG Weijun, MEI Shu'e

(School of Economics and Management, Southeast University, Nanjing 211189, China)

Abstract: Invitational bidding is key to encouraging enterprise participation in the technological innovation of public goods. This study develops a contest model that incorporates supplier type (independent or public sector-affiliated), heterogeneous innovation capabilities, and project-specific technical risks. Using limiting-case analysis, we compare two invitational bidding strategies on innovation and efficiency of benefits: inviting only independent suppliers and inviting both independent and affiliated suppliers. We also identify the boundary conditions under which long-term contracts lower the public sector's obligatory award budget. The key findings are as follows: Competition is strengthened when technically strong independent suppliers bid alongside affiliated suppliers; however, competition weakens when independent suppliers lack technical strength. Long-term supply contracts may not necessarily enhance competition and may diminish suppliers' motivation for technological innovation. Innovation and benefit improvement are rarely achieved simultaneously. Both goals can be achieved only when independent suppliers have clear technical advantages, making it optimal for the public sector to invite both independent and affiliated suppliers to bid. When innovation projects involve high technical risks or independent suppliers demonstrate strong innovation capabilities, the public sector may reduce the award budget using long-term contracts as incentives to successfully motivate suppliers.

Key words: technological innovation of public goods; invitational bidding; contest model; procurement contract; award strategy

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The 20th National Congress of the Communist Party of China emphasized the need to enhance independent innovation capabilities through major national science and technology projects. Major projects such as the "Three Gorges Project" and the "Dongfeng-41 Intercontinental Ballistic Missile" are examples of technological innovation of public goods[1]. Technological innovation is both a vital tool for enterprises to strengthen core competitiveness and a crucial means for the government to improve service quality and efficiency in public sectors such as national defense, healthcare[2], and major infrastructure[3-4]. Therefore, as a key area of national technological development, the choice of implementation path and mechanism for technological innovation of public goods is crucial to strengthening the country's overall innovation capability. Within the national system, the state can pool resources to promote major science and technology projects through unified planning and resource integration[5]. This approach not only mobilizes resources efficiently but also provides distinct advantages for achieving technological breakthroughs and innovation[6]. In particular, from the perspective of optimizing new-quality productive forces, the national system accelerates technological innovation in public goods by optimizing and improving the efficiency of new production factors, such as knowledge, technology, and data[7]. This approach preserves the advantages of macro-level planning while enhancing enterprises' technological capabilities. It also positions them as key participants and beneficiaries in optimizing new-quality productive forces[8].

Previous research on technological innovation of public goods has mainly compared enterprise participation mechanisms and bidding procurement. Wang et al.[9], analyzing innovation stages and participation pathways, believe that selecting appropriate participation mechanisms can effectively enhance the role of enterprises in the technological innovation of public goods. Using case studies from the U. S. Department of Defense's acquisition and development competition mechanisms, some scholars have confirmed the feasibility and advantages of the two-stage research and development (R&D) competition mechanism for technological innovation in public goods[10]. Hai et al.[11] have compared auction-based bidding and negotiation-based bidding mechanisms in this context. Some scholars have also examined how technological spillovers influence the government's opti-

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Biographies: ZHOU Jianan (1994—), male, Ph. D. candidate; ZHONG Weijun (corresponding author), male, doctor, professor, zhongweijun@seu. edu. cn.

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mal award levels and favoritism rules[12]. However, these studies emphasize the public sector's subjective favoritism toward bidding enterprises, with less consideration of economic motivations. More recently, scholars have examined incentive contract design considering subcontractors' altruistic preferences[13] and fairness preferences[14] under common risk shocks, using commissioned R&D in technological innovation of public goods as an example.

Although existing research shows that the public sector can effectively promote technological innovation of public goods through competition among cooperative suppliers or direct commissioning, research on invitation bidding remains limited. Invitation bidding, also known as selective bidding, is a procurement or project contracting method positioned between open bidding and direct negotiation[15]. Some "civilian participation in military projects" are effective practices for enterprises to engage in technological innovation of public goods through invitation bidding. For example, the communication components of AVIC's military drones were procured internally until 2021; however, in 2022, AVIC invited Xi'an Yingzhihang Technology Company to bid and later signed a long-term supply contract. Similarly, in the UK's "Future Combat Air System" plan, the UK Ministry of Defense invited BAE Systems and introduced multiple private enterprises, including small technology companies, through competitive mechanisms to acquire advanced artificial intelligence and autonomous control technologies. When technological innovation of public goods projects involves highly complex or specialized technical requirements, only a few suppliers or contractors may be able to meet the demand. By directly inviting these qualified enterprises to bid, procurement efficiency can be improved, and the progress of innovation projects is ensured[16]. In this process, the public sector evaluates innovative products or solutions and awards long-term contracts to the winning suppliers, consistent with the principles of innovation competition.

Organizing suppliers through innovation competitions is a major source of technological innovation for public sectors and enterprises in many countries. The main reason is that innovative product procurement often cannot specify procurement requirements or design verifiable procurement indicators, whereas innovation competitions can provide stronger incentives to tap suppliers' innovation potential[17]. Domestic and foreign research on innovation competitions has mainly addressed issues related to enterprise project outsourcing or public procurement. Research can be grouped into the following categories: (1) Minimizing procurement costs. Loertscher et al. [18] show that buyers can sustain supplier competitiveness by establishing multi-channel cooperation. Chen et al. [19] find that supplier costs can be reduced through "cost-reduction investigations," helping buyers achieve near-optimal procurement performance. (2) Awards and number of participants. Terwiesch et al. [20] examine the number of participants in innovation competitions and find that buyers can benefit from a larger participant pool. Bi et al. [21] find that the optimal award value increases monotonically with task complexity and novelty, that winner-takes-all is the optimal award allocation, and that one-step markup is the optimal markup method. Dietzenbacher et al. [22] show that the relationship between the scale of rewards and the size of the crowd follows an "inverted U-shape," implying that moderate rewards maximize crowd size. (3) Information feedback and disclosure. Mihm et al. [23] discuss how buyers can improve competition outcomes by designing feedback mechanisms to establish the best information structure. Lemus et al. [24] show that, in some cases, larger prizes or a greater number of participants may reduce the degree of information disclosure. (4) Joint procurement. Fan et al. [25] distinguish the procurement of innovative products into sequential design and manufacturing stages, showing that different strengths of commitment mechanisms generate distinct incentives for innovation effort and shape firms' allocation of production resources. Chen et al. [26] demonstrate that the novelty of procurement innovation, the size of the supplier base, and the cost of integrating components largely determine whether buyers should procure integrated systems or individual components.

A synthesis of earlier research on technological innovation of public goods and innovation contests highlights several limitations: (1) few studies use competition models to examine the public sector's strategy selection in invitation bidding; (2) most focus on the award effect of competitions, while overlooking the impact of long-term supply contracts on competition incentives and award budgets; (3) they fail to consider the affiliation relationship between suppliers and the public sector, thus overlooking the possibility that the public sector may obtain additional rents through affiliated enterprises. Building on the research by Breig et al. [27] and Chen et al. [17], this study combines supplier heterogeneity in innovation capabilities and technical uncertainty to construct a competition model. It systematically analyzes the innovation output and benefit levels under two invitation bidding strategies and further examines the role of long-term contracts in designing competition and award budgets. The core research issues are as follows: (1) Under what conditions should the public sector choose the independent supplier competition strategy to better foster innovation, and when is competition between independent and affiliated suppliers more effective? (2) In what circumstances can pre-commitment to long-term supply contracts intensify competition among suppliers? (3) Can the public sector simultaneously promote technological innovation and enhance overall benefit levels through competition strategy selection? (4) Under what conditions can the public sector balance award incentives with long-term contract benefits by reducing competition awards?

The main contributions of this study are as follows: First, contest theory is extended by incorporating supplier affiliations, capability heterogeneity, and technical risks into a unified model, providing a more realistic framework for analyzing public procurement strategies. Second, the dual role of long-term contracts is revealed: in addition to offering stability, they create a "selective bias" in the public sector, thereby deepening understanding of contractual incentives. Third, the model identifies the conditions for achieving cost-effectiveness by reducing awards and offers a quantitative basis for optimizing procurement policies.

1 Problem and Assumptions

1.1 Problem description

To strengthen national defense capabilities, the public sector uses invitation bidding to procure new military drones, set quality thresholds, and combine long-term contract incentives to prevent low-price, low-quality competition. This approach ensures military modernization and national defense security. Given the unique nature of the product, innovation quality must be prioritized to ensure the equipment's technological advancement and reliability. Fig. 1 shows the bidding process. To compare the two bidding strategies and how public sector intervention influences the bidding results, the following assumptions are made.

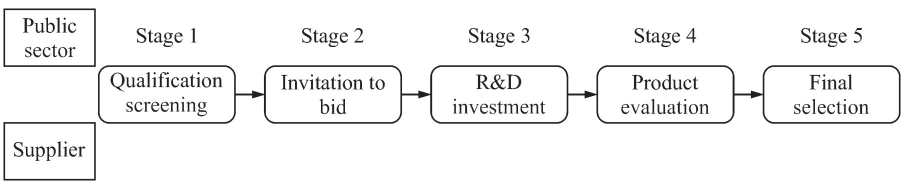

Fig. 1 Event sequence

1.2 Basic assumptions

Assumption 1 Assume that both the public sector and participating suppliers are risk-neutral. The independent supplier (without subordinate ties to the public sector) is denoted as subscript 1, while the affiliated supplier (with a subordinate relationship, such as a government controlling interest) is denoted as subscript 2.

Assumption 2 The award A is a one-time R&D subsidy granted in the R&D competition to incentivize suppliers' investment in prototype innovation. The winning supplier receives the entire award.

Assumption 3 The winning supplier receives both the award and benefits from long-term cooperation. To simplify the model, we assume that the exogenous variable $b_i = b > 0, i = 1, 2$ represents the benefits that suppliers derive from long-term supply contracts.

Assumption 4 Assume that the cost coefficient of supplier i is c, and the R&D cost is a quadratic function of R&D effort:

$$c(e_i) = ce_i^2/2 \tag{1}$$

The profit of supplier i winning is $(A + b) - c(e_i)$, and the loss of failure is $-c(e_i)$.

Assumption 5 Assume that the innovation output of supplier i is

$$v_i = re_i + \xi_i \tag{2}$$

where r is the supplier's R&D utility coefficient; the random variable ξ_i is private information, representing external uncertain factors unrelated to the supplier's effort.

Assumption 6 Assume that $\Delta\xi = \xi_1 - \xi_2$ represents the difference in supplier output uncertainty. It follows a normal distribution with mean μ and variance σ^2, i. e., $\Delta\xi \sim N(\mu, \sigma^2)$; with density function $g_{\Delta\xi}(x)$ and cumulative distribution function $G_{\Delta\xi}(x)$. Here, μ reflects the innovation capabilities of both suppliers. If $\mu > 0$, the independent supplier has strong innovation capabilities or technical advantages; $\sigma > 0$ represents the technical risk associated with the innovation project.

Assumption 7 Unlike the assumption in Chen et al.[17], if the affiliated supplier wins, the public sector does not participate in the award A sharing; however, it obtains certain cost benefits, such as reduced procurement costs for long-term contracts. Assume that the rent received by the public sector is kb where $k \in [0, 1]$ is the public sector's shareholding ratio in the affiliated supplier. The larger the shareholding ratio, the greater the cost benefits obtained from future procurement.

Assumption 8 While obtaining rents, the public sector must internalize part of the affiliated supplier's R&D

costs. The utility function is

$$\Pi = E[\max\{v_1, v_2 + kb\}] - A - kc(e_2) \tag{3}$$

The utility functions of the two suppliers are

$$\pi(e_1) = (A + b)\Pr(v_1 > kb + v_2) - c(e_1) \tag{4}$$

$$\pi(e_2) = (A + b)\Pr(v_2 + kb > v_1) - c(e_2) \tag{5}$$

where $\Pr(v_1 > kb + v_2)$ is the winning probability of the independent supplier, and $\Pr(v_2 + kb > v_1)$ is the winning probability of the affiliated supplier.

2 Supplier's R&D Effort

First, solve the Nash equilibrium under the public sector's strategy of choosing independent and affiliated suppliers to compete, and then compare the suppliers' R&D efforts under the two scenarios of $k > 0$ and $k = 0$. At this time, both suppliers independently choose their R&D investments to maximize their expected profits:

$$e_1^* \in \arg\max \pi_1(e_1;\ e_2^*) = (A + b)\Pr(v_1 > kb + v_2) - c(e_1) \tag{6}$$

$$e_2^* \in \arg\max \pi_2(e_2;\ e_1^*) = (A + b)\Pr(v_2 + kb > v_1) - c(e_2) \tag{7}$$

Solve the supplier's R&D decision e_i^* according to Eq. (6):

$$\pi(e_1) = (A + b)\Pr(re_1 + \xi_1 > kb + re_2 + \xi_2) - ce_1^2/2 \tag{8}$$

Substituting $\Delta\xi = \xi_1 - \xi_2$ into Eq. (8), we obtain

$$\pi(e_1) = (A + b)\Pr(re_1 + \Delta\xi > kb + re_2) - ce_1^2/2 \tag{9}$$

Since e_1, e_2 are completely symmetric, $re_1 = re_2$, let the first-order partial derivative of Eq. (9) with respect to e_1 be zero:

$$\partial\pi(e_1)/\partial e_1 = r(A + b)g_{\Delta\xi}(kb) - ce_1 = 0 \tag{10}$$

From Eq. (10), we can obtain the second-order conditions: $\partial^2\pi(e_1)/\partial e_1^2 = -c < 0$, which implies that the equilibrium solution is unique. Let $\phi(x)$ be the probability density function of the standard normal distribution, $\Phi(x)$ be the cumulative distribution function, and standardize $g_{\Delta\xi}(kb)$:

$$g_{\Delta\xi}(kb) = \frac{\exp - \frac{1}{2}\left(\frac{re_2 - re_1 - kb - \mu}{\sigma}\right)^2}{\sqrt{2\pi}\,\sigma} = \frac{1}{\sigma}\phi\left(\frac{kb - \mu}{\sigma}\right) \tag{11}$$

Substituting the result of Eq. (11) into Eq. (10), we obtain the unique symmetric Nash equilibrium:

$$e_i^* = \frac{r(A + b)}{c\sigma}\phi\left(\frac{kb - \mu}{\sigma}\right) \tag{12}$$

Proposition 1 When $k = 0$, e_i^0 is positively correlated with b; when $k > 0$, only when $0 < b < [\mu - Ak + \sqrt{(Ak + \mu)^2 + 4\sigma^2}\,]/(2k)$, e_i^* is positively correlated with b.

Proof When $k = 0$, there is a competition between independent suppliers. The supplier's R&D effort e_i^0 is

$$e_i^0 = \frac{r(A + b)}{c\sigma}\phi\left(\frac{\mu}{\sigma}\right) \tag{13}$$

It follows that e_i^0 is positively correlated with b.

The partial derivative of e_i^* with respect to b is

$$\frac{\partial e_i^*}{\partial b} = \frac{r\left\{\sigma^2 - [k(A + b)(kb - \mu)]\right\}}{c\sigma^3}\phi\left(\frac{kb - \mu}{\sigma}\right) \tag{14}$$

Represent $\sigma^2 - [k(A + b)(kb - \mu)]$ as a function of b:

$$f(b) = Ak\mu + bk\mu + \sigma^2 - Abk^2 - b^2k^2 \tag{15}$$

The solution that satisfies $f(b) > 0$ is

$$\frac{\mu - Ak - \sqrt{(Ak + \mu)^2 + 4\sigma^2}}{2k} < b < \frac{\mu - Ak + \sqrt{(Ak + \mu)^2 + 4\sigma^2}}{2k}$$

Obviously, $\frac{\mu - Ak - \sqrt{(Ak + \mu)^2 + 4\sigma^2}}{2k} < 0$, so when $0 < b < \frac{\mu - Ak + \sqrt{(Ak + \mu)^2 + 4\sigma^2}}{2k}$, $\frac{\partial e_i^*}{\partial b} > 0$.

Proposition 1 shows that when independent suppliers compete, long-term contract commitments enhance competition; however, when affiliated and independent suppliers compete, the public sector's commitment to long-term procurement contracts does not necessarily foster competition. Let $A = 1, r = 2, c = 1, \mu = 1, \sigma = 1$, then Fig. 2 shows the nonlinear impact of b on e_i^n under different values of k. Compared with the baseline case where $k = 0$, it is observed that within a certain range, the long-term contract b can intensify the competition between independent and affiliated suppliers when $k > 0$. However, when b becomes excessively large, it weakens such mixed competition, reflecting how the implicit advantages of affiliated suppliers reduce competition intensity. The reason is that if $b > [\mu - Ak + \sqrt{(Ak + \mu)^2 + 4\sigma^2}\,]/(2k)$, the rent kb substantially affects the public sector's utility, as captured in Eq. (3). Driven by economic motivation, the public sector exhibits a strong selective bias due to the high rent kb, and the independent supplier's probability of winning ($v_1 > kb + v_2$) becomes small; therefore, it weakens competition and discourages supplier's innovation investment. Proposition 1 not only analyzes the advantages and disadvantages of the public sector's commitment to long-term contracts but also supplements and extends the findings of Fan et al. [25].

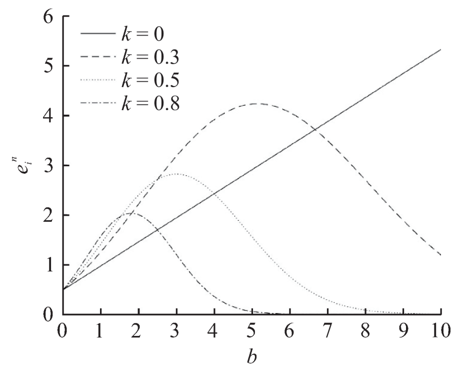

Fig. 2 Impact of b on e_i^*

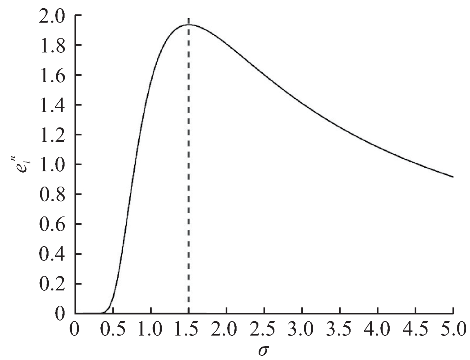

Fig. 3 Impact of σ on e_i^n

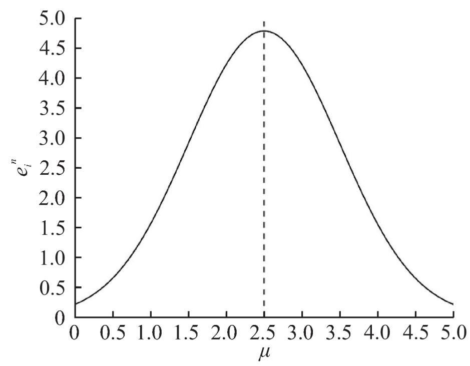

Fig. 4 Impact of μ on e_i^n

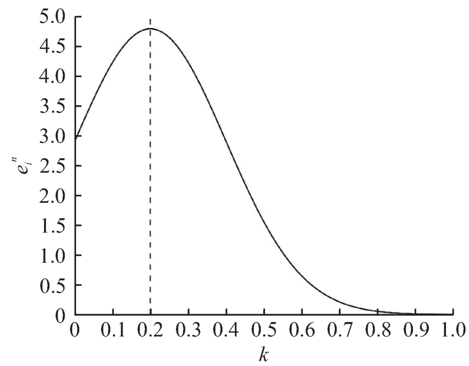

Fig. 5 Impact of k on e_i^n

Proposition 2 For any $k > 0$, there exists: (1) When $\sigma < |kb - \mu|$, e_i^* is positively correlated with σ; (2) When $\mu < kb$, e_i^* is positively correlated with μ; (3) When $\mu > kb$, e_i^* is positively correlated with k.

Proof The partial derivative of e_i^* with respect to σ is

$$\frac{\partial e_i^*}{\partial \sigma} = \frac{r(A+b)\left[(kb-\mu)^2 - \sigma^2\right]}{c\sigma^4}\phi\left(\frac{kb-\mu}{\sigma}\right) \quad (16)$$

Only if $(kb-\mu)^2 - \sigma^2 > 0$, $\sigma < |kb-\mu|$, $\partial e_i^*/\partial\sigma > 0$.

The partial derivatives of e_i^* with respect to μ, k are

$$\frac{\partial e_i^*}{\partial \mu} = \frac{r(A+b)(kb-\mu)}{c\sigma^3}\phi\left(\frac{kb-\mu}{\sigma}\right) \quad (17)$$

$$\frac{\partial e_i^*}{\partial k} = \frac{rb(A+b)(\mu-kb)}{c\sigma^3}\phi\left(\frac{kb-\mu}{\sigma}\right) \quad (18)$$

When $kb - \mu > 0$, $\partial e_i^*/\partial\mu > 0$; when $kb - \mu < 0$, $\partial e_i^*/\partial k > 0$.

Proposition 2 shows how suppliers' R&D efforts respond to technical risk σ, independent supplier's technological advantage μ, and public ownership k under mixed competition. First, when technical risk is high ($\sigma > |kb-\mu|$), outcome uncertainty dampens suppliers' incentive to invest, resulting in reduced R&D effort as σ increases. Conversely, when technical risk is negligible ($\sigma \to 0$), kb offsets μ ($|kb-\mu| \approx 0$); therefore, both parties perceive competition as fair and intense and thus increase R&D effort ($\partial e_i^*/\partial\mu > 0$). Second, if the independent supplier faces a significant technological disadvantage ($\mu < kb$), its low winning probability weakens competition and reduces R&D effort. Finally, when the independent supplier holds a technological advantage ($\mu > kb$) and the public sector's share k is large, institutional preference for the affiliated supplier (kb) forces the independent supplier to deliver significantly better output ($v_1 > kb + v_2$) to win. This intensifies competition and raises both parties' R&D efforts ($\partial e_i^*/\partial k > 0$). Assigning specific parameter values yields Figs. 3-5, which illustrate visually the results stated in Proposition 2 (Fig. 3: $A = 1, r = 2, c = 1, b = 5, k = 0.5, \mu = 1$; Fig. 4: $A = 1, r = 2, c = 1, b = 5, k = 0.5, \sigma = 1$; Fig. 5: $A = 1, r = 2, c = 1, b = 5, \sigma = 1, \mu = 1$).

3 Innovation Output

Proposition 2 (3) proves that competition between independent and affiliated suppliers can increase the supplier's innovation investment under certain conditions. However, given the impact of rent, will the public sector ultimately favor inferior innovations for economic reasons? To address this, we must compare the innovation output under the two bidding strategies. Let $\psi(k;\ e_1^*, e_2^*)$ denote the innovation output of the final procurement product under the competition between independent and affiliated suppliers:

$$\psi(k;\ e_1^*, e_2^*) = E\left[v_1 + (v_2 - v_1)1_{\{v_1 < kb + v_2\}}\right] \quad (19)$$

Proposition 3 For any $k > 0$, only when $\mu > 0$, $\psi(k;\ e_1^*, e_2^*)$ is positively correlated with k.

Proof Organize Eq. (19):

$$\partial\psi(k;\ e_1^*, e_2^*) = re_i^* + E[\xi_1] - kbG_{\Delta\xi}(kb) + \int_{-\infty}^{kb} G_{\Delta\xi}(x)\,\mathrm{d}x \tag{20}$$

The partial derivative of Eq. (20) with respect to k is

$$\frac{\partial\psi(k;\ e_1^*, e_2^*)}{\partial k} = -\frac{b[bck\sigma + r^2(kb-\mu)(A+b)]}{c\sigma^2}\phi\left(\frac{kb-\mu}{\sigma}\right) \tag{21}$$

According to Eq. (21), when $k = 0$,

$$\frac{\partial\psi(0;\ e_1^*(0), e_2^*(0))}{\partial k} = \frac{br^2\mu(A+b)}{c\sigma^2}\phi\left(\frac{\mu}{\sigma}\right) \tag{22}$$

For any $k > 0$, only when $\frac{br^2\mu(A+b)}{c\sigma^2}\phi\left(\frac{\mu}{\sigma}\right) > 0$, $\mu > 0$, $\frac{\partial\psi(k;\ e_1^*, e_2^*)}{\partial k} > 0$ holds.

Corollary 1 For any $k \in [0, 1]$, when $\mu > 0$, $k^* > 0$; when $\mu \leqslant 0$, $k^* = 0$.

Proof Let $\frac{\partial\psi(k;\ e_1^*, e_2^*)}{\partial k} = 0$, we can get $k^* = \frac{(A+b)r^2\mu}{b(Ar^2 + br^2 + c\sigma)}$, because $\frac{(A+b)r^2}{b(Ar^2 + br^2 + c\sigma)} > 0$, and $k \in [0, 1]$, so when $\mu > 0$, $k^* > 0$; when $\mu \leqslant 0$, $k^* = 0$.

Proposition 3 and Corollary 1 show that when independent suppliers hold technical advantages ($\mu > 0$), inviting both independent and affiliated suppliers to compete ($k^* > 0$) can increase innovation output and achieve innovation maximization; otherwise, competition among independent suppliers is more favorable ($k^* = 0$). In other words, when independent suppliers have strong innovation capabilities, the public sector's strategy of inviting both independent and affiliated suppliers to compete is better than inviting only independent suppliers; otherwise, the strategy of inviting independent suppliers alone is better than inviting both independent and affiliated suppliers. When independent suppliers have stronger innovation capabilities than affiliated suppliers, owing to the impact of rent kb on the public sector's utility, independent suppliers must invest more R&D effort to win. This intensifies competition and enhances innovation output; in contrast, as Proposition 2 proves, if independent suppliers do not have strong innovation capabilities, their low winning probability weakens competition.

As shown in Fig. 6 (the black shaded region indicates no equilibrium solution), the "Independent + Affiliated" strategy is preferred in the region where $\mu > 0$, whereas the "Independent + Independent" strategy dominates in the region where $\mu < 0$. The shaded and unshaded areas in the figure depict the distribution of these strategy choices in the (μ, σ) plane. When the independent supplier's relative capability is high, introducing an affiliated supplier can broaden competition and increase the public sector's rent extraction potential. Conversely, when the independent supplier's capability is weak, the public sector tends to favor competition between two independent suppliers to achieve stronger innovation outcomes.

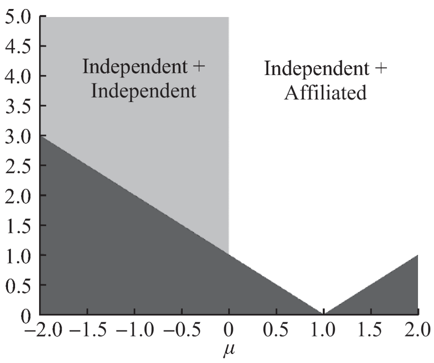

Fig. 6 Invitation bidding strategy based on innovation output under μ, σ constraints

4 Public Sector Benefit Level

As a representative of the public, improving the public sector's benefit level not only means more efficient public resource allocation but also promotes resource allocation to more urgent social needs, thereby maximizing social benefits and improving overall social welfare. We now compare the public sector's benefit levels under the two invitation bidding strategies. We expand Eq. (3) to obtain the public sector's utility function under competition between independent and affiliated suppliers:

$$\Pi(k) = r(e_i^*) + E[\max\{\Delta\xi, kb\}] + E[\xi_2] - A - kc(e_i^*) \tag{23}$$

Proposition 4 For any $k > 0$, there exist thresholds $\underline{\mu}$, $\bar{\mu}$ and $\bar{\sigma}$, satisfying $\mu < \underline{\mu}$, $\mu > \bar{\mu}$ or $\sigma > \bar{\sigma}$, $\Pi(k)$ is positively correlated with k; when $\underline{\mu} < \mu < \bar{\mu}$, $\Pi(k)$ is negatively correlated with k.

Proof The first-order partial derivative of Eq. (23) with respect to k is

$$\frac{\partial\Pi(k)}{\partial k} = \frac{\partial r(e_i^*)}{\partial k} - c(e_i^n) - k\frac{\partial c(e_i^*)}{\partial k} + b(1 - G_{\Delta\xi}(kb)) \tag{24}$$

According to Eq. (24), when $k = 0$,

$$\frac{\partial\Pi(0)}{\partial k} = \frac{(A+b)r^2\phi\left(\frac{\mu}{\sigma}\right)\left[2b\frac{\mu}{\sigma} - (A+b)\phi\left(\frac{\mu}{\sigma}\right)\right]}{2c\sigma^2} + b\left(1 - \Phi\left(\frac{\mu}{\sigma}\right)\right) \tag{25}$$

For any $k > 0$, if $\frac{\partial\Pi(k)}{\partial k} > 0$, it must satisfy

$$\frac{(A+b)r^2\phi\left(\frac{\mu}{\sigma}\right)\left[2b\frac{\mu}{\sigma}-(A+b)\phi\left(\frac{\mu}{\sigma}\right)\right]}{2c\sigma^2}+b\left(1-\Phi\left(\frac{\mu}{\sigma}\right)\right)>0 \tag{26}$$

Organizing Eq. (26) yields

$$\phi\left(\frac{\mu}{\sigma}\right)\left(\frac{2\mu}{\sigma}-\frac{A+b}{b}\phi\left(\frac{\mu}{\sigma}\right)\right)>-\frac{2c\sigma^2}{(A+b)r^2}\left(1-\Phi\left(\frac{\mu}{\sigma}\right)\right) \tag{27}$$

Let the left-hand side of Eq. (27) be M and the right-hand side be N. Then we obtain: (1) $\lim\limits_{\mu\to+\infty} M > \lim\limits_{\mu\to+\infty} N$; $\lim\limits_{\mu\to-\infty} M = 0 > -\frac{2c\sigma^2}{(A+b)r^2} = \lim\limits_{\mu\to-\infty} N$; (2) $\lim\limits_{\sigma\to+\infty} M = -\frac{1}{2\pi} > -\infty = \lim\limits_{\sigma\to+\infty} N$. According to the intermediate value theorem, (1) there exist thresholds $-\infty < \underline{\mu} < 0$, $0 < \bar{\mu} < +\infty$, when $\mu < \underline{\mu}$ or $\mu > \bar{\mu}$, $M > N$; (2) when $\underline{\mu} < \mu < \bar{\mu}$, $M < N$; and (3) there exists a threshold $0 < \bar{\sigma} < +\infty$, for any $\sigma > \bar{\sigma}$, $M > N$.

Proposition 4 shows that when innovation capabilities differ significantly between suppliers ($\mu < \underline{\mu}$ or $\mu > \bar{\mu}$) or when the technical risk is high ($\sigma > \bar{\sigma}$), competition between independent and affiliated suppliers can improve the public sector's benefit level; if the independent supplier's technical advantage is not significant ($\underline{\mu} < \mu < \bar{\mu}$), the public sector cannot benefit from this strategy, then the strategy of inviting independent suppliers to bid is preferable. When affiliated suppliers hold clear technical advantages, their probability of winning is high, allowing the public sector to extract additional rent kb and increase expected benefits. Conversely, when independent suppliers have significant technical advantages, their innovation output must be higher than that of affiliated suppliers to win ($v_1 > kb + v_2$). In this case, affiliated suppliers have low winning probability and invest little effort, thus reducing the R&D costs borne by the public sector and improving both the innovation and benefit levels of the final procurement product. When technical risk is high ($\sigma \to +\infty$), suppliers make less effort to reduce the loss of innovation failure. The probability of affiliated suppliers winning is high. Compared with inviting independent suppliers, the public sector gains additional rent and improves its benefit level. However, innovation remains low; therefore, the strategy fails to achieve both innovation promotion and benefit.

Setting $\bar{\mu} = 1.5$, $\underline{\mu} = -0.5$, $\bar{\sigma} = 4$, we obtain Fig. 7. In regions where $\mu < -0.5$, $\mu > 1.5$, or $\sigma > 4$ (i. e., when capabilities largely differ or risk is high), the "Independent + Affiliated" strategy is preferred, as the affiliated supplier can provide complementary technology, rent returns, or additional security under high-risk conditions. Conversely, in the region where $-0.5 < \mu < 1.5$ and $\sigma < 4$ (i. e., when capability differences are few and risk is low), the "Independent + Independent" strategy is preferred, leveraging competition among independent suppliers to stimulate innovation while reducing reliance on affiliated relationships.

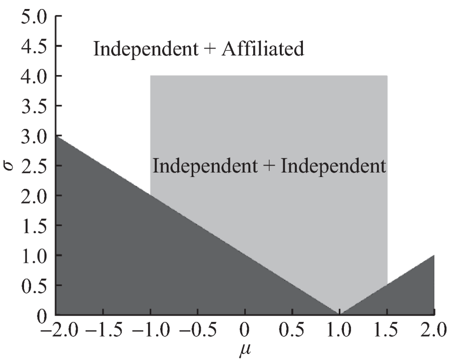

Fig. 7 Invitation bidding strategy based on benefit level under μ, σ constraints

Corollary 2 Promoting innovation and improving benefits are often difficult to achieve simultaneously. Only if independent suppliers have strong innovation capabilities (i. e., μ is large enough) can competition between independent and affiliated suppliers promote innovation and improve the public sector's benefit level. A strategy of inviting independent and affiliated suppliers to compete is better than inviting only independent suppliers.

Based on the dual dimensions of innovation output and public sector efficiency, the analysis indicates that when disparities in suppliers' innovation capabilities are substantial or when technological risks are high, the adoption of affiliated suppliers (the "Independent + Affiliated" strategy) ensures higher innovation success rates while generating potential rental income for the public sector. Conversely, when capability gaps are minimal and risks are manageable, the "Independent + Independent" strategy is more effective in optimizing innovation outcomes and operational efficiency through robust market competition incentives. This indicates that public sector procurement strategies should balance technological risk exposure and supplier capability differentiation to maximize innovation achievements and institutional returns.

5 Award Endogeneity Analysis

The public sector optimizes the award budget in procurement competitions to improve fiscal fund efficiency and prevent resource waste. By reasonably adjusting the award, repeated incentives can be avoided and the balance between competition awards and long-term contract benefits maintained. This encourages suppliers to focus more on R&D investment and long-term cooperation profits.

Proposition 5 For any $k \in [0, 1]$, there exists an optimal award A^* that maximizes the public sector's benefit level.

Proof According to Eq. (3), the public sector's benefit level is

$$\Pi = re_i^* + E[\xi_1] - kbG_{\Delta\xi}(kb) + \int_{-\infty}^{kb} G_{\Delta\xi}(x)\mathrm{d}x - A - kc(e_i^*) \quad (28)$$

Substitute e_i^* to obtain

$$\Pi = r\frac{r(A+b)}{c\sigma}\phi\left(\frac{kb-\mu}{\sigma}\right) + E[\xi_1] - kbG_{\Delta\xi}(kb) + \int_{-\infty}^{kb} G_{\Delta\xi}(x)\mathrm{d}x - A - k\frac{c}{2}\left[\frac{r(A+b)}{c\sigma}\phi\left(\frac{kb-\mu}{\sigma}\right)\right]^2 \quad (29)$$

Let the first-order partial derivative of Π with respect to A be zero:

$$\frac{\partial \Pi}{\partial A} = \frac{\exp - \dfrac{(bk-\mu)^2}{2\sigma^2} r^2}{c\sqrt{2\pi}\,\sigma} - \frac{(A+b)\exp - \dfrac{(bk-\mu)^2}{\sigma^2} kr^2}{2c\pi\sigma^2} - 1 = 0 \quad (30)$$

Solve Eq. (30) to obtain the optimal award A^*:

$$A^*(b) = \frac{E(k)\sqrt{2\pi}\,r^2\sigma - 2cE^2(k)\pi\sigma^2}{kr^2} - b \quad (31)$$

where $E(k) = \exp\dfrac{(bk-\mu)^2}{2\sigma^2}$.

Proposition 6 For any $k > 0$, there exist thresholds $kb < \bar{\mu} < +\infty$ and $0 < \bar{\sigma} < +\infty$, when $\mu > \bar{\mu}$ or $\sigma > \bar{\sigma}$, $\dfrac{\partial A^*}{\partial b} < 0$.

Proof The partial derivative of A^* with respect to b is

$$\frac{\partial A^*}{\partial b} = (bk-\mu)\left(\frac{E(k)\sqrt{2\pi}}{\sigma} - \frac{4cE^2(k)\pi}{r^2}\right) - 1 \quad (32)$$

For any $k > 0$, according to Eq. (32), there exist $\lim\limits_{\mu \to +\infty} \dfrac{\partial A^*}{\partial b} < 0$, $\lim\limits_{\sigma \to +\infty} \dfrac{\partial A^*}{\partial b} < 0$.

When independent and affiliated suppliers compete ($k > 0$), the public sector can reduce the award budget A in two situations: (1) When independent suppliers have strong R&D capabilities, their probability of winning is high. Then, the incentive for independent suppliers comes from award A and long-term contract b. As the future income of the long-term contract becomes an important incentive, the marginal incentive effect of the award is relatively weakened. (2) When the output uncertainty is high (σ is large), the randomness of the competition outcomes increases, and the presence of rent kb significantly reduces the probability of independent suppliers winning. This leads to a reduction in suppliers' expected income from the award A and weakens overall competitiveness. In this case, the award cannot effectively increase competition intensity, and the public sector can optimize fiscal expenditure by reducing its budget. In summary, under these situations, the future stable income stream b strengthens the supplier's motivation to win the competition; therefore, they accept a lower award A while still actively competing. When competition is fierce, even if the short-term award is low, long-term cooperation remains an important incentive for suppliers.

By setting $\bar{\mu} = 1$, $\bar{\sigma} = 2$, Fig. 8 is derived, showing the boundary conditions under the μ, σ constraints for reducing the award budget. In the shaded area, the public sector can reduce the contest award in proportion to the strength of the long-term contract incentive.

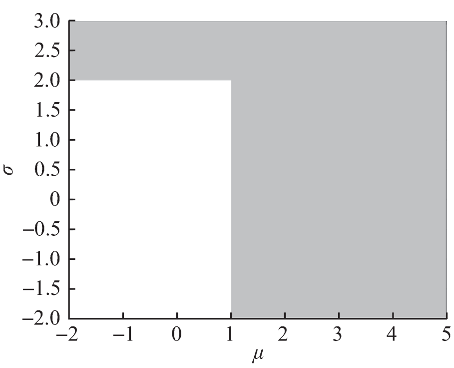

Fig. 8 Award strategy under μ, σ constraints

In summary, when $\mu > \bar{\mu}$ or $\sigma > \bar{\sigma}$, the long-term contract provides suppliers with sufficient incentive to substitute for part of the short-term award. This allows the public sector to reduce A^* accordingly to optimize expenditure. This outcome highlights the substitutability between short-term awards and long-term contracts under different circumstances.

6 Conclusions and Implications

This study examines optimal invitation bidding strategies for public sector innovation procurement using a formal competition model. The main findings are as follows: (1) Strategy depends on independent suppliers' technical capability. A hybrid "Independent + Affiliated" bidding strategy enhances both innovation output and public benefits when independent suppliers have a significant technical advantage; conversely, if they are technologically weak, this strategy hinders competition. (2) Long-term contracts are a double-edged sword. While they provide stable expectations, they may also weaken suppliers' motivation for sustained innovation, requiring careful trade-offs; (3) Award budgets can be substituted with long-term contracts. When projects involve high technical risk or if independent suppliers are highly capable, a suitable reduction of the award budget allows for better use of long-term contract incentives; (4) Flexible strategy adjustment is crucial. Public sectors should avoid a one-size-fits-all approach and instead formulate bidding and incentive strategies flexibly, based on supplier capabilities and project risks.

A relevant example is the procurement of critical components for China's LEO satellite internet constellation. During the initial technology phase, the responsible agency adopted a typical "Independent + Affiliated" invitational bidding strategy, inviting both a private company with proprietary phased array chip technology and a traditional state-owned aerospace research institute. This strategy successfully stimulated innovative designs that surpass conventional solutions. As technology advanced into the engineering and cost-reduction phase, the public buyer increasingly adopted an "Independent + Independent" strategy, fostering competition among several proficient private firms to effectively control system costs. This case clearly shows the core principle that the public sector should dynamically adjust its bidding strategy based on suppliers' relative technical capabilities. Furthermore, combining "R&D subsidies with future volume commitments," the project's contract design supports the substitution relationship between long-term contracts and contest awards in high-technical-risk scenarios, offering strong real-world support for the theoretical propositions of this study.

Drawing on these findings and case insights, several management implications emerge: (1) In bid inviting bids, priority should be given to independent suppliers with strong technological capabilities, while affiliated suppliers can be introduced to ensure effective competition; (2) Although long-term contracts provide stability, they should be supported by dynamic performance evaluation mechanisms to prevent supplier complacency and sustain continuous innovation; (3) Confirm whether the primary project goal is a technological breakthrough or cost-effectiveness. The hybrid bidding strategy enhances both innovation and benefits when independent suppliers have significant advantages; (4) For projects characterized by high technical risks or when suppliers have strong innovation capabilities, appropriately reducing the award budget allows the public sector to fully leverage the incentives of long-term contracts and optimize fund allocation.

However, the assumptions and conclusions of this study have certain limitations. For example, will bidding competitions generate technology spillovers, information sharing, or other benefits among participating suppliers? How can the public sector provide R&D subsidies to suppliers to improve innovation performance? These questions warrant further studies.

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公共产品技术创新邀请招标与奖金策略——基于竞赛模型的分析

周佳楠， 仲伟俊， 梅姝娥

（东南大学经济管理学院，南京 211189）

摘要：邀请招标是推动企业参与公共产品技术创新的重要机制。基于供应商隶属关系（独立或隶属于公共部门），并结合其创新能力的异质性与创新项目的技术风险，构建竞赛模型，从创新产出和效益水平2个维度，运用极限分析方法比较2种邀标策略：一是公共部门仅邀请独立供应商竞标，二是同时邀请独立供应商与附属供应商竞标。此外，进一步探讨了长期合同降低公共部门奖金预算的边界条件。结果表明：邀请具有显著技术优势的独立供应商与附属供应商共同参与竞标，可有效激发竞争；反之，若独立供应商技术实力不足，其参与可能反而削弱市场竞争效果。预先承诺长期供应合同未必能增强竞争，反而可能削弱供应商技术创新的动力。促进创新与提升效益通常难以同步实现，只有在独立供应商拥有明显技术优势的情况下，公共部门采用独立与附属供应商竞标的策略，才能同时兼顾二者目标。当创新项目存在较高的技术风险，或独立供应商具备较强创新能力时，公共部门可依据长期合同所发挥的激励作用，适当降低奖金预算，以更有效地激励供应商。

关键词：公共产品技术创新；邀请招标；竞赛模型；采购合同；奖金策略
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