Journal of Public Economics 128 (2015) 96–106

Contents lists available at ScienceDirect

Journal of Public Economics

journal homepage: www.elsevier.com/locate/jpube

Bundling decisions in procurement auctions with sequential tasks☆

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ARTICLE INFO

Article history:
Received 25 October 2012
Received in revised form 25 September 2014
Accepted 25 September 2014
Available online 29 October 2014

JEL classification:
D44
D61
D73
H11
H41
H54
H57

Keywords:
Auction
Bundling
Design–bid–build
Design–build
Procurement
Public–private partnerships

ABSTRACT

This paper investigates the principal's bundling decision during a procurement auction for a project consisting of two sequential tasks, in which task externality exists and information arrives sequentially. We show that, although increasing the number of bidders in the market for the second task always tilts the principal's choice toward unbundling, increasing the number of consortiums that can perform both tasks tilts the principal's preference toward bundling if the externality is negative.

1. Introduction

For a typical project with multiple related phases, the owner's decisions about whether to contract with single or separate entities for the different phases represent a critical component of the procurement strategy. For example, recent project delivery methods have witnessed a shift away from design–bid–build (D–B–B) and toward design–build (D–B).[1] The Design-Build Institute of America (DBIA) has reported that D–B projects accounted for more than 30% of the total number of construction in the US in 2001, as compared to just 5% in 1985 (Beard et al., 2001; Tulacz, 2002). In the provision of infrastructure services also, a movement away from conventional short-term contracts has been documented.[2] PPPs are now used extensively across Europe, Canada, the US, and a number of developing countries. Estimates show that 82% of all water projects and 92% of all transport projects undertaken between 1984 and 2002 were PPPs (Oppenheimer and MacGregor, 2004). Furthermore, 30% of all services provided by the larger European Union (EU) governments are delivered through PPPs (Torres and Pina, 2001). Traditionally employed for transportation, energy, and water systems, PPPs have recently penetrated into IT services,

☆ The authors thank the three anonymous referees and David Martimort for their helpful comments and constructive advices. We are also grateful to Malin Arve, Weihua Huang, Doh-Shin Jeon, Patrick Rey, François Salanié, Wilfried Sand-Zantman, Jun Xiao, Bing Ye, Xundong Yin, Jianyu Yu and the participants in the 37th EARIE (European Association for Research in Industrial Economics) conference. The financial supports from the National Natural Science Foundation of China (71303245, 71401034), the Ministry of Education of China (13YJC790174, 13YJC790077), the Fundamental Research Funds for the Central Universities and the Research Funds of Renmin University of China (14XNK006), the Program for Young Excellent Talents (14YQ06) and the Fundamental Research Funds for the Central Universities in UIBE (CXTD4-04) are also acknowledged. All remaining mistakes are our own.

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[1] In D–B–B, separate entities are responsible for the design and construction of a project. However, in D–B, design and construction aspects are contracted with a single entity known as the *design-builder*.

[2] PPP is characterized by long-term contracts between a public sector authority and a private party, in which the tasks of designing, building, and operating are bundled together to form a special purpose vehicle.

http://dx.doi.org/10.1016/j.jpubeco.2014.09.012
0047-2727/

accommodation, leisure facilities, prisons, military purchase,[3] waste management, schools, and hospitals.[4]

The literature on task separation and integration tends to overlook one important dimension: competition among bidders. Competition is a very important factor that determines the principal's bundling decision. Practitioners repeatedly express concerns that public authorities deal with only a small number of large consortia, those which are able to organize bids for the large scale projects involved in PPP contracting. In fact, PPPs are often adopted in public procurement, such as procurement of infrastructure development projects, where competition is limited (Gupta, 2002; Foster, 2005; NAO, 2007). Indeed, Estache and Iimi (2009) found a significant negative relation between the use of bundling and the number of bidders. Concurrent with the move from unbundling to bundling methods in the construction industry during the late twentieth century, there has also been a merger and acquisition (M&A) wave, which indicates that there may be a negative relation between competition and the adoption of the D–B method. In the sample of construction M&A transactions in the US during 1980–2002 analyzed by Choi and Russell (2004), only 5.3% took place in the first four years (1980–1984), while 41.9% occurred during the four-year period between 1995 and 1999. By way of a specific example, while investigating the Los Angeles Unified School District's Belmont project, a D–B project with excessive cost and environmental issues, district attorney Steve Cooley concluded that one problem of the D–B process is that it does not make use of competitive bidding where the prospective builders bid on the same design.[5] As a theoretical guideline, Grimm et al. (2006) presented four main factors that may influence a procurer's bundling-versus-unbundling decision: synergies in production, number of bidders, the degree of heterogeneity of participants and aftermarket trade, and higher cost uncertainty of advanced buying. This paper aims to investigate the effect of competition on the optimal choice between the bundling and unbundling of sequential tasks, and how the effect varies with other factors such as the sign of externality along the sequence.

We begin with some common features shared by these contracting methods. First, auctioning is the primary method used for selection (see e.g., McAfee and McMillan, 1986; Laffont and Tirole, 1987). This suggests that there is information asymmetry between the project principal and its agents. In the absence of asymmetric information, the principal can always do better by selecting the most efficient contractor and using take-it-or-leave-it (TIOLI) offers, without incurring the cost of organizing an auction. Second, activities in the preceding task impact the project quality or operating cost of the succeeding task. Third, bidders can obtain further information, such as the exact size of the project, quality attributes of the infrastructure, quantity and prices of different inputs and available technology. This sequential arrival of information leads to a different information structure under task bundling and unbundling. Costings in the D–B framework are much less accurate than those in the D–B–B framework, while operators in a conventional approach have more accurate estimates of the operating costs that may be incurred with PPPs. For example, Ernzen and Schexnayder (2000) presented an analysis of a company's labor cost risk based on a case study of two similar projects. One project was a typical D–B–B job and the other was a D–B job. They found that there were consistently greater fluctuations in the labor cost in the D–B project. Oztas and Okmen (2004) found that risks, including cost risk, are generally higher in the D–B method than in the D–B–B method. The evidence above suggests that the estimate of labor cost in D–B would be less accurate. Furthermore, Iossa and Martimort (2012) compared PPP and the traditional procurement method. They argued that the mapping between the effort at the design stage and final performance is ex ante uncertain, but new information may come along during operations, thereby suggesting that bidders may hold more information after the planning stage than before it.

For the purpose of illustration, we consider a project as comprising two sequential tasks. Tasks 1 and 2 are, respectively, designing and building (as in the case of the project delivery methods debate), or building and operating (as in the scenario for PPPs). Any cost-reducing activity is non-observable and non-contractible, which typically raises the moral hazard problem. We assume that task externality exists – that is, the activity in task 1 has an impact on the operation cost of task 2. Furthermore, information regarding agents' cost type for task 2 arrives only in period 2; agents only know their cost type for task 1 during period 1.

To minimize the expected total payment to agents, the principal can choose between two regimes – the bundling or unbundling of tasks. Under the bundling regime, a single prospective consortium is selected to perform both tasks through competitive bidding for an incentive contract, as opposed to the unbundling regime, where the contractors for the two tasks are selected through two sequential auctions. In this paper, we consider the first-price, sealed-bid auction. For the sake of simplicity, we only examine linear contracts as in McAfee and McMillan (1986). The linearity assumption leads to a moral hazard problem, and the winner's effort increases with the slope of the linear contract, which we term “the power of incentives” in the paper.[6]

In procurement, some tasks can only be performed by a few firms, while other tasks could be performed by many firms. We assume that N_1 firms can perform task 1 and N_2 firms can perform task 2, with $N_1 < N_2$. For example, for the construction industry, building firms outnumber designing firms. In the bundled auction, a designer and a builder have to form a consortium before participating in the auction. As a result, the number of consortiums is equal to N_1. We define N_2 as the competitiveness in the market for task 2 and N_1 as the competitiveness in the market of joint-tasks.

There are two crucial differences that determine the relative advantage and disadvantage of the two procurement regimes in our model. The first is the externality internalization. In the auction organized in period 1, agents have private information on the cost of task 1 under both regimes. Hence, the winner earns information rent, which increases with the share of the cost of task 1 borne by that firm. Consequently, there is a trade-off between providing incentives and reducing the winner's information rent in the auctions. In the presence of positive task externality, a higher cost-reduction effort in task 1 leads to a lower operation cost for task 2. Hence, bundling serves as a device for internalizing task externality and mitigating the agency problem of task 1. For negative externality, the agent is more reluctant to exert cost-control measures due to internalization in period 1; this aggravates the agency problem. Consequently, whether externality internalization biases the principal's choice toward bundling or unbundling depends on whether the externality is positive or negative.

The second difference between the two regimes is the presence of sequential information. The assumption that agents can only observe their cost related to task 2 in period 2 has two effects. First, unlike in unbundling, in which the most efficient agent for task 2 is chosen, the consortium chosen in the bundled auction is only associated with the average cost of performing task 2, an efficiency loss with bundling for period 2. Second, unlike in bundling, agents have private information; therefore, information rent should be given to the winner while auctioning task 2 in the unbundled regime. As competition in task 2 increases, the efficiency loss of bundling increases and the information

[3] For example, Lyon (2000, 2006) conducted an empirical analysis on procurement for tactical missiles in American defense policy and compared the pricing of competition and bundling. See Grimm et al. (2006), “Division into lots and competition in procurement”, Chapter 7, *Handbook of Procurement*, edited by Dimitri et al.

[4] See Iossa and Martimort (2013) for more detailed examples of PPP.

[5] http://da.lacounty.gov/pdf/BLC_Final_Report.pdf, “Los Angeles DA, Steve Cooley final Investigate report on Belmont”.

[6] If we consider optimal contracting as in Laffont and Tirole (1987), then the model belongs to the category of “false moral hazard models”, since the possibility to contract on overall costs makes effort de facto contractible.

rent given to the agent in unbundling decreases. Hence, the principal's choice is biased toward unbundling.

The sign of externality is crucial in determining the effect of joint-task competition on the principal's bundling decision.[7] For positive externality, the winner is rewarded with a lower power of incentive in the first period under bundling than under unbundling. This is because externality internalization already gives the winner some first-period incentive. An increase in the joint-task market competition implies that the winner's first-period information rent are reduced in both regimes. The deduction of information rent, as shown in the current paper, is smaller in the bundling regime; consequently, unbundling becomes relatively more favorable. For negative externality, the winner is rewarded with a higher power of incentive in the first period under bundling than under unbundling. This is because externality internalization weakens the winner's first-period incentive and thus the principal must provide higher-power incentives in the first period. An increase in the joint-task market competition implies that the winner's first-period information rents are reduced in both regimes. The deduction of information rent is larger in the bundling regime due to the fact that the first-period power of incentives is higher under bundling. Consequently, bundling becomes more favorable.

Our model is applicable to other fields apart from infrastructure procurement, such as scientific research (for which tasks 1 and 2 can be respectively recognized as basic research and applied R&D activities). Our results are consistent with empirical evidence showing that both integration and separation exist in practice. For example, in the German Research Center for Artificial Intelligence, the same scientists conduct basic research, applied R&D, and product transfer (Wahlster, 2002). On the other hand, a successful software development process is characterized by the separation of R&D and production activities (Royce, 2002).[8]

This paper contributes to the literature on task separation and integration in the presence of the agency problem. Earlier work by Holmstrom and Milgrom (1991) showed that tasks should be bundled (unbundled) if they are complements (substitutes). Similar results can be found in the literature on optimal ownership structures in PPPs. For example, Martimort and Pouyet (2008) studied the PPP problem in the context of moral hazard and found that whether bundling is preferable depends only on the sign of the externality between two tasks (see also Hart (2003); Hoppe and Schmitz (2010); Chen and Chiu (2010); Iossa and Martimort (2013)). Bennett and Iossa (2006) also studied two successive stages in public procurement – “building” and “management” – by which they examined the ownership arrangement of the project in the presence of either positive or negative externality between the two stages. Bennett and Iossa's (2006) study lies in the realm of incomplete contract à la Grossman and Hart (1986).[9] However, our paper belongs to the realm of complete contract, as in Martimort and Pouyet (2008). While analyzing the relationship between the government and the operator, operating costs are readily observable and often used to contract upon for service provision. In this case, the complete contracting method is more appropriate. Moreover, all these previous studies assumed that only one agent exists for each period. The current study, however, considers the more common situation in which several potential agents exist and an auction is organized for selecting contractors; moreover, information arrives sequentially. Considering the case of an auction allows for a discussion of how competitiveness in the market affects the bundling decision of the principal.

We borrow extensively from McAfee and McMillan (1986), who studied the problem of bidding for incentive contracts. Laffont and Tirole (1987) also studied the problem of auctioning an incentive contract. However, none of the scenarios considered by these authors have been related to the bundling choice.

Another area of the literature related to our paper is that of multi-object auctions (Palfrey, 1983; Chakraborty, 1999; Armstrong, 2000; Jehiel et al., 2007; Manelli and Vincent, 2006). The key difference between multi-object auctions and multitask auctions is that the extent of externality between two objects (i.e., the degree of complementarity or substitutability) is exogenously given, while the extent of externality between two tasks (i.e., how much effort to exert) is endogenously determined and affected by the contract provided by the principal. Most previously published papers assume that bidders know their individual information when the auction takes place. Jeitschko and Wolfstetter (2002) and Grimm (2007) consider sequential multi-object auctions with the same timing of information revelation as in our paper. However, only adverse selection problem was considered in these previous studies, while our paper incorporates both adverse selection and moral hazard.

2. The model

Suppose a principal wishes to procure a project comprising two sequential tasks. To facilitate expression, we focus on the case of D–B–B vs. D–B (i.e., with the two tasks determined as *designing* and *building* throughout the paper).[10] We assume that the fixed benefit is so large that the principal will always want to implement it. The principal's objective is to minimize the total implementation costs paid to the agents. Our major concern is whether the principal contracts with single or separate agents for the two tasks.

A total of N_1 firms can design and N_2 firms can build, with $N_1 < N_2$.[11] In an unbundled auction, the designers and builders are separate entities. However, in a bundled auction, a designer and builder have to form a consortium before participating. This is common during procurement auctions in which bidders are required to prove their ability to implement the tasks, and where the number of consortiums is equal to N_1. We denote the competitiveness in the building market by N_2 and the competitiveness in the joint-task market by N_1. All the agents and the principal are risk neutral.

In period 1, the agent exerts effort to complete the task of designing and the cost is

$$c_1 = \theta_1 - e_1 \tag{1}$$

where θ_1 denotes the cost type of the agent that has been selected for the design task and e_1 denotes his cost-reducing effort. Let $\theta_1^{n_1}$ be the cost type of agent $n_1 \in \{1, 2, \ldots, N_1\}$. We assume that $\theta_1^{n_1}s$ are drawn independently from the same distribution with a cumulative distribution function $F_1(\cdot)$ on the interval $[\underline{\theta}_1, \overline{\theta}_1]$ and a differentiable density f_1.

In period 2, the agent exerts effort to complete the task of building and the cost is

$$c_2 = \theta_2 - e_2 - \delta e_1 \tag{2}$$

where θ_2 is the cost type of the agent selected to build and e_2 denotes his cost-reducing effort in this task. Similarly, let $\theta_2^{n_2}$ be the cost type of agent $n_2 \in \{1, 2, \ldots, N_2\}$, and assume that $\theta_2^{n_2}s$ are drawn independently from the same distribution with a cumulative distribution function $F_2(\cdot)$ on the interval $[\underline{\theta}_2, \overline{\theta}_2]$ and a differentiable density f_2. Moreover, $\theta_1^{n_1}$s and

[7] Hopefully our modeling results in negative externality between sequential tasks may complement the established findings of Grimm et al. (2006, Chapter 7) on task-synergy, that is, positive externality, in which the tasks are simultaneous or parallel.

[8] See Schmitz (2005) for more examples.

[9] Here, the setting is that no contract can be written and only ex post negotiation between the government and the operator and/or builder is feasible; hence, inefficiencies arise because of the hold-up problem. The efficiency depends on the threat points defined by the ownership structure.

[10] Of course, one can also view the two tasks as building and operating, as in conventional contracting vs. PPPs.

[11] The case in which $N_1 > N_2$ will be discussed below, where we show that our main insights still hold for this scenario.

$\theta_2^{n_2}$s are independent. As in the standard literature, $F_t(\theta_t^{n_t})$ satisfies the monotone hazard rate property: $\frac{F_t(\theta_t^{n_t})}{f_t(\theta_t^{n_t})}$ is increasing, for $t = 1, 2$.

Exerting effort e_t costs $\psi(e_t)$, with $\psi'(e_t) > 0$, $\psi''(e_t) > 0$, $\psi'''(e_t) \geq 0$ for all $e_t > 0$ and $t = 1, 2$. Assume that $\psi(0) = 0$, $\psi'(0) = 0$ and $\psi''(0) = 0$. In the regime of task bundling, these disutility functions are additive, that is, the effort cost is $\psi(e_1) + \psi(e_2)$.

Following the literature, we assume that $\theta_1^{n_1}$ and $\theta_2^{n_2}$ represent private information of agents n_1 and n_2, respectively, and that e_t is neither observable nor contractible, while c_t is observable and contractible, for $t = 1, 2$.

The sign of δ determines the sign of the externality between the two tasks[12]. Positive δ indicates positive externality, while negative δ indicates negative externality. Positive externality between the two tasks is well documented in the second-sourcing literature. One example is that the designer can make monetary investments that lower the cost in the second period.[13] Negative externality happens, for example, when agents make innovations in the design technology that reduce the design cost. However, such innovations may require agents to learn new job processes and lead to increases in the building cost (see Martimort and Pouyet (2008)). It could also be the case that the beauty of the blueprint itself may give the designer some extra benefit[14] due to peer effect[15]. However, a beautiful blueprint is always too sophisticated and causes drastic increases in building costs. A designer might exert too much effort on such dimensions if he or she fails to consider the externality for the subsequent task. To ensure the effort in the first period is socially desirable, the externality δ should not be excessively negative.

Assumption 1. $\delta > -1$.

Assume that agent n_1 observes $\theta_1^{n_1}$ privately in period 1. $\theta_2^{n_2}$ can only be observed by agent n_2 in period 2. In the DBB vs. DB case, the estimation of the building cost requires certain information, such as the exact size of the project, the quality attributes of the infrastructure, the quantity and prices of inputs, and the available technology at the time of construction. This is only available at the end of the design period. Hence, we reasonably assume that the cost of building can only be determined after completion of the design.

We focus on mechanisms that are commonly used in practice: bundling or unbundling. In the bundling, the principal auctions the two tasks to one single firm; in the unbundling, the two tasks are auctioned separately. The auction format we consider is the first-price sealed-bid auction. In this format, the one with the lowest bid wins the auction and is rewarded the contract.

The timing is as follows:[16]

1) The principal chooses the regimes between bundling and unbundling.
   Bundling
2) Then, designers and builders join to form design-builders for bidding. A design-builder only knows the cost parameter for the design.
3) The principal organizes an auction for bundled tasks. The winner of the contract is chosen from among the bidders.
4) The winner undertakes the design, and the costs for the first period are realized.
5) At this point, the design-builder is privately informed about the cost parameters for the building portion of the project and then begins to complete the second task (building).
6) Building costs are realized, and the contract is executed.

Unbundling

For the unbundling scenario, the series of steps starting with step 2 unfold in the following fashion:

2) Designers become privately informed. The principal organizes an auction for designing. All designers bid and the winner obtains a designing contract.
3) The winning designer undertakes the design, and costs in the first period are realized with the execution of the design contract.
4) Builders become privately informed. The principal organizes an auction for building. All builders bid and the winner obtains a building contract.
5) Building costs are realized and the building contract is executed.

2.1. Contracts

Following McAfee and McMillan (1986), we consider only linear contracts, which are the most commonly used.[17] In the unbundling case, the contract in period t is given by

$$t(b_t, c_t) = b_t + \alpha_t c_t$$

where b_t is the bid of the winner, c_t is the realized cost and $t(b_t, c_t)$ is the transfer given to the winner in period t, $t = 1, 2$.[18] In addition to the winner's bid, the principal also pays a share of the realized cost: if $\alpha_t = 0$, the contract is a fixed-price contract; if $\alpha_t = 1$, the contract is a cost-plus contract. In the literature on incentive theory, the share $1 - \alpha_t$ is called the power of incentive since the agent's effort increases as the share increases, as we will see later. Throughout the paper, we impose the condition $\alpha_t \leq 1$. Otherwise, the agent's net payoff would increase according to the realized cost and, thus, he or she would always inflate the cost. Note that we allow $\alpha_t < 0$. In that case, the contract is called a super-powered contract (Lewis and Sappington, 1997).

Furthermore, note that the contracts are short term since the payment of the winner in the first period does not depend on the realized cost in the second period. Although this is beneficial for the principal, it may not be feasible when payments cannot be delayed because of the well-known limited commitment of local government[19].

Under bundling, the contract is given by

$$t(b, c_1, c_2) = b + \alpha_1 c_1 + \alpha_2 c_2$$

where b is the winner's bid and c_t is the realized cost in period t, $t = 1, 2$.

2.2. Complete information benchmark

Suppose efforts e_1 and e_2 as well as the private information θ_1 and θ_2 can be observed and contracted upon. The principal then can implement the first-best outcome. That is, he chooses unbundling and selects the agent with the lowest type of cost θ_t in order to perform task t. He or she then uses forcing contracts to implement first-best efforts. The chosen agents are awarded fixed fees that cover their respective effort costs. The first-best efforts e_1^* and e_2^* are determined by equalizing the marginal cost and marginal benefit of each effort:

$$\psi'(e_1^*) = 1 + \delta \tag{3}$$

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[12] Here, although we assume that activities in two tasks are cost reducing, it is straightforward to view the activities during the first period as improving quality, as in the literature related to PPP.

[13] Of course the setup, as in Laffont and Tirole (1988), is then a little bit different: $c_1 = \theta_1^{n_1} - e_1 + d(i)$ and $c_2 = \theta_2^{n_1} - e_2 - i$. An agent will invest too little if he fails to consider the impact of such investment on the succeeding task. Using this method of modeling, positive externality will generate the same prediction as in our model, as we will argue below.

[14] An extra benefit equates to a reduction in designing cost.

[15] That is, the designer's peers may have a more positive impression of his or her design ability.

[16] Under unbundling, the principal is potentially better off if he can ask all the builders to pay a fixed payment in the first period that permits the auction that will be organized for the second period. By doing so, he extracts all the information rent of the builders. This requires that i) the principal can commit to an auction that is to be organized at some undetermined time, potentially far into the future; and ii) firms are not cash-constrained. These two requirements may not be attainable in many circumstances.

[17] Our results are robust for optimal contracts. Proof available upon request.

[18] McAfee and McMillan (1986) argue that a more general form $t(b, c) = F + \alpha_1 c + \alpha_2 b$ can be reduced to the form we have used in the paper.

[19] See Laffont and Tirole (1993, chapter 8) and Martimort and Pouyet (2008).

and

$$\psi'(e_2^*) = 1 \tag{4}$$

Under complete information, the principal will never choose bundling because of its efficiency loss. Since information on θ_2 is still unavailable and, it is impossible for the principal to choose the most efficient builder in the first period.

3. The bundling decision

In this section, we first solve the principal's optimal linear contracts of unbundling and bundling separately, and then we compare the expected total payments under the two regimes.

3.1. Unbundling

3.1.1. Agents' optimization

In period 1, the utility of an agent with cost parameter θ_1 who has been selected for task 1, can be written as

$$\begin{aligned}\pi_1(\theta_1, b_1) &= b_1 + \alpha_1 c_1 - c_1 - \psi(e_1)\\ &= b_1 - (1-\alpha_1)\theta_1 + (1-\alpha_1)e_1 - \psi(e_1)\end{aligned} \tag{5}$$

Maximizing over e_1 gives $\psi'(e_1) = 1 - \alpha_1$, and hence $e_1 = \psi'^{-1}(1 - \alpha_1)$. Thus, the principal's choice of sharing ratio α_1 determines the agent's choice of cost-reduction activity. The larger the share of costs paid by the principal, the smaller the effort expended in lowering costs.

The contract is awarded by means of a first-price, sealed-bid auction. In this bidding, the symmetric Nash equilibrium always exists (see McAfee and McMillan, 1986), and each agent's bid function is $B_1(\cdot)$, which is strictly monotonic. Consider an agent who has cost parameter θ_1 and makes the bid, b_1. Given that all other bidders follow the bid function $B_1(\cdot)$, the probability that this bidder is submitting the lowest bid equals $\left[1-F_1\left(B_1^{-1}(b_1)\right)\right]^{N_1-1}$. Thus, this agent's ex-ante expected utility is

$$E\pi_1(\theta_1, b_1) = \left[1-F_1\left(B_1^{-1}(b_1)\right)\right]^{N_1-1}\pi_1(\theta_1, b_1)$$

In equilibrium, we can write $b_1 = B_1(\theta_1)$.We then obtain the following bidding strategy:

$$\begin{aligned}B_1(\theta_1) = (1-\alpha_1)&\left((1-F_1(\theta_1))^{-(N_1-1)}\int_{\theta_1}^{\bar{\theta}_1}(1-F_1(s))^{N_1-1}ds + \theta_1\right)\\ &+(\psi(e_1)-(1-\alpha_1)e_1),\end{aligned} \tag{6}$$

where $e_1 = \psi'^{-1}(1 - \alpha_1)$.[20]

It is easy to verify that the bid function given by Eq. (6) is strictly monotonic in θ_1, as required. The first term of the bidding strategy, which reflects the adverse selection effect, is decreasing in α_1; bidders will bid more aggressively if the principal pays a larger share of the cost. The second part reflects the benefit that the agent can obtain from the cost-reduction activity. Each bidder anticipates this term; hence, competition enables the principal to extract it fully.

In the second period, the auction is merely a repetition of that in the first period. Hence, by using the same technique as above (details in the Appendix A), we can obtain the equilibrium's expected utility and bidding functions as

$$\pi_2(\theta_2) = (1-\alpha_2)(1-F_2(\theta_2))^{-(N_2-1)}\int_{\theta_2}^{\bar{\theta}_2}(1-F_2(s))^{N_2-1}ds \tag{7}$$

$$\begin{aligned}B_2(\theta_2) = (1-\alpha_2)&\left((1-F_2(\theta_2))^{-(N_2-1)}\int_{\theta_2}^{\bar{\theta}_2}(1-F_2(s))^{N_2-1}ds + \theta_2\right)\\ &+(\psi(e_2)-(1-\alpha_2)e_2)-\delta(1-\alpha_2)e_1\end{aligned} \tag{8}$$

where $e_1 = \psi'^{-1}(1 - \alpha_1)$ and $e_2 = \psi'^{-1}(1 - \alpha_2)$.

The additional part $\delta(1 - \alpha_2)e_1$ stems from the fact that the effort in the first period has an externality on the cost in the second period. Note that e_1 is fully determined by the contracts in the first period. Since contracts are public, each bidder can correctly deduce e_1, even though it is not observable. Consequently, they will reduce their bids by this fixed part so that the one with cost parameter $\bar{\theta}_2$ still earns zero utility.

3.1.2. Optimal linear contract

If the agent with cost parameter θ_t wins, the payment of the principal is $B_t(\theta_t) + \alpha_t c_t$. The total expected payment of the principal in period t is

$$\tau_t = N_t\int_{\underline{\theta}_t}^{\bar{\theta}_t}(b_t(\theta_t) + \alpha_t c_t)(1-F_t(\theta_t))^{(N_t-1)}f_t(\theta_t)d\theta_t \quad \text{for } t = 1, 2 \tag{9}$$

Lemma 1. *The total payment in unbundling is given by the following expression*

$$\begin{aligned}\tau^u &\equiv \tau_1 + \tau_2\\ &= \textstyle\sum_{t=1}^2 E\theta_{t\min} + \sum_{t=1}^2(1-\alpha_t)E\frac{F_t}{f_t}(\theta_{t\min})\\ &\quad -\{(1+\delta)e_1 - \psi(e_1) + e_2 - \psi(e_2)\}\end{aligned} \tag{10}$$

where $\theta_{t\min} = \min\left(\theta_t^1 \ldots \theta_t^{N_t}\right)$, $t = 1, 2$, $e_1 = \psi'^{-1}(1 - \alpha_1)$ *and* $e_2 = \psi'^{-1}(1 - \alpha_2)$.

Proof. See the Appendix.

The total payment includes three parts. The first part is the expected exogenous cost of the winner. The second is the expected information rent of the winner. Because agents have private information, this part should be strictly positive. The third part is the benefit of cost-reduction activities. The competition between bidders enables the principal to extract the total payment.

The principal's problem is[21]

$$\min_{\{\alpha_1 \le 1, \alpha_2 \le 1\}} \tau^u$$

Let α_1^u and α_2^u be the solutions to the above minimization problem. The following are the first-order conditions:[22]

$$0 = \frac{\alpha_1^u + \delta}{\psi''(\psi'^{-1}(1-\alpha_1^u))} - E\frac{F_1}{f_1}(\theta_{1\min}) \tag{11}$$

$$0 = \frac{\alpha_2^u}{\psi''(\psi'^{-1}(1-\alpha_2^u))} - E\frac{F_2}{f_2}(\theta_{2\min}) \tag{12}$$

For the RHS of both Eqs. (11) and (12), the first term is called the moral hazard effect, and the second term is called the information rent effect[23]. To understand the moral hazard effect, note that the social return of the agent's activity e_1 is $(1 + \delta)e_1 - \psi(e_1)$. Differentiating the social return with respect to α_1 (note that $e_1 = \psi'^{-1}(1 - \alpha_1)$), we obtain the first term of the RHS of Eq. (11). Since this part is uniform for all agents, regardless of their cost types, the principal can extract all of it. The information rent effect stems from the fact that, all other things being equal, the winner's information rent is smaller if the principal pays a larger share of the realized cost. Hence, there is a tradeoff in

[20] The detailed calculation of the agent's bidding strategy is given in the Appendix.

[21] Throughout the paper, we assume the discount factor is zero. A non-zero discount factor will not change our main results.

[22] It is easy to check that τ^u is convex in α_1 and α_2; hence the S.O.C. is satisfied.

[23] It is called the bidding-competition effect in McAfee and McMillian(1986).

providing incentives, which requires α_t to be small, and reducing information rent, which requires α_t to be large.[24]

We summarize our findings in the following proposition:

Proposition 1. *Under unbundling, the optimal power of incentive is determined by Eqs. (11) and (12), and the optimal efforts in both periods are downwardly distorted:* $e_1^u < e_1^*$ *and* $e_2^u < e_2^*$.

Proof. Immediate from Eqs. (11), (12), and that $\psi'(e_1^*) = 1 + \delta$ and $\psi'(e_2^*) = 1$.

3.2. Bundling

3.2.1. Agents' optimization

The winning agent with cost type θ_1 has expected utility

$$\begin{aligned}\pi^b(\theta_1, b) &= E[t(b, c_1, c_2) - c_1 - c_2 - \psi(e_1) - \psi(e_2)] \\ &= b - (1-\alpha_1)\theta_1 + [1-\alpha_1 + \delta(1-\alpha_2)]e_1 - \psi(e_1) \\ &\quad - (1-\alpha_2)E\theta_2 + (1-\alpha_2)e_2 - \psi(e_2)\end{aligned}$$

where the expectations are taken with respect to θ_2 since the agents have no information on θ_2 at the time of auction. Maximizing $\pi^b(\theta_1, b)$ over e_1 and e_2 yields $e_2 = \psi'^{-1}(1 - \alpha_2)$ and $e_1 = \psi'^{-1}(1 - \alpha_1 + \delta(1 - \alpha_2))$. Note that once the contract is awarded, the choice of e_2 does not depend on θ_2. Hence, the optimal effort in the second period remains unchanged after the winner obtains additional information on θ_2.

Similar to the case of unbundling, the bundled contract is awarded by using a first-price, sealed-bid auction among N_1 consortiums. Applying the same technique (details in the Appendix), we obtain the following equilibrium bidding functions:

$$\begin{aligned}B(\theta_1) = (1-\alpha_1)&\left((1-F_1(\theta_1))^{-(N_1-1)}\int_{\theta_1}^{\bar{\theta}_1}(1-F_1(s))^{N_1-1}ds + \theta_1\right) \\ &+\psi(e_1) - [1-\alpha_1 + \delta(1-\alpha_2)]e_1 + \psi(e_2) - (1-\alpha_2)e_2 \\ &+(1-\alpha_2)E\theta_2\end{aligned}$$

where $e_1 = \psi'^{-1}(1 - \alpha_1 + \delta(1 - \alpha_2))$ and $e_2 = \psi'^{-1}(1 - \alpha_2)$.

3.2.2. Optimal linear contract

If the consortium with cost parameter θ_1 wins, the payment made by the principal is $B(\theta_1) + \alpha_1 c_1 + \alpha_2 c_2$. Thus, the total expected payment of the principal is:

$$\tau^b = N_1\int_{\underline{\theta}_1}^{\bar{\theta}_1}(B(\theta_1) + \alpha_1 c_1 + \alpha_2 c_2)(1-F_1(\theta_1))^{(N_1-1)}f_1(\theta_1)d\theta_1 \tag{13}$$

Lemma 2. *The total payment in bundling is given by*

$$\begin{aligned}\tau^b &= E\theta_{1\,\min} + E\theta_2 + (1-\alpha_1)E\frac{F_1}{f_1}(\theta_{1\,\min}) \\ &\quad +\psi(e_1) - (1+\delta)e_1 + \psi(e_2) - e_2\end{aligned} \tag{14}$$

where $e_1 = \psi'^{-1}(1 - \alpha_1 + \delta(1 - \alpha_2))$ *and* $e_2 = \psi'^{-1}(1 - \alpha_2)$.

Proof. See the Appendix.

The principal chooses α_1 and α_2 to minimize his or her total payment τ^b. Let α_1^u and α_2^u be the solutions to the minimization problem. The first-order conditions are

$$0 = \frac{\alpha_1^b + \delta\alpha_2^b}{\psi''\left(\psi'^{-1}\left(1-\alpha_1^b + \delta(1-\alpha_2^b)\right)\right)} - E\frac{F_1}{f_1}(\theta_{1\,\min}) \tag{15}$$

$$\begin{aligned}0 &= \frac{\alpha_2^b}{\psi''\left(\psi'^{-1}(1-\alpha_2^b)\right)} + \frac{\left(\alpha_1^b + \delta\alpha_2^b\right)\delta}{\psi''\left(\psi'^{-1}\left(1-\alpha_1^b + \delta(1-\alpha_2^b)\right)\right)} \\ &= \frac{\alpha_2^b}{\psi''\left(\psi'^{-1}(1-\alpha_2^b)\right)} + \delta E\frac{F_1}{f_1}(\theta_{1min})\end{aligned} \tag{16}$$

where the last equality uses Eq. (15). The RHS of Eq. (15) comprises the moral hazard and information effects, as in the case of unbundling. The difference is that the marginal effect of an increase in the power of incentive $1 - \alpha_1$ on the effort e_1 now depends on the power of incentive during the second period since the agent internalizes the externality between the two tasks. This difference is reflected in the first term of the moral hazard effect. However, the RHS of Eq. (16) does not include the information effect. This is because, at the time of contracting, agents have no information on the building cost and hence earn no information rent on it. An increase in the power of incentive during the second period increases both effort during the second period and effort during the first period, as reflected in the first and second terms of the RHS of Eq. (16).

Our assumptions that $\psi'(0) = 0$ and $\psi''(0) = 0$ imply $1/\psi''(\psi'^{-1}(0)) = +\infty$. This guarantees that the solutions α_1^u, α_2^u and α_2^b to the first-order conditions (11), (12) and (16) are smaller than 1; hence we can focus on an interior solution. For $\delta < 0$, it can also be shown that $\alpha_1^b < 1$ is guaranteed. To ensure $\alpha_1^b < 1$ for $\delta > 0$, we impose the following additional assumption:

Assumption 2. $E\frac{F_1}{f_1}(\theta_{1min}) < M$. M is determined by the equation

$$M = h_1\left(1 + \delta h_2^{-1}(-\delta M)\right)$$

where $h_1(x) = \frac{x}{\psi''\left(\psi'^{-1}(1+\delta-x)\right)}$ and $h_2(x) = \frac{x}{\psi''\left(\psi'^{-1}(1-x)\right)}$.[25]

Proposition 2. *Compared to unbundling*

(1) *The power of incentive is smaller (larger) during the first period, if the externality is positive (negative):* $1 - \alpha_1^b \le 1 - \alpha_1^u$ *iff* $\delta \ge 0$;
(2) *The power of incentive is larger (smaller) during the second period if the externality is not too negative (negative enough):* $1 - \alpha_2^b \ge 1 - \alpha_2^u$ *iff* $\delta \ge \hat{\delta}$, *where* $\hat{\delta} = -\frac{E\frac{F_2}{f_2}(\theta_{2min})}{E\frac{F_1}{f_1}(\theta_{1min})} < 0$;
(3)
  i) *The optimal efforts during the first period under the two regimes are equal and downwardly distorted:* $e_1^u = e_1^b < e_1^*$;
  ii) *The optimal effort during the second period is larger (smaller) if the externality is not too negative (negative enough):* $e_2^b \ge e_2^u$ *iff* $\delta \ge \hat{\delta}$;
  iii) *The optimal effort during the second period is upwardly (downwardly) distorted if the externality is positive (negative):* $e_2^b \ge e_2^*$ *iff* $\delta \ge 0$.

Proof. See the Appendix.

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[24] One can also see that the optimal α_2^u is independent of the choice of α_1^u. This is because we assume that effort e_1 in the first period affects the cost in the second period in a deterministic and additive manner. The additive assumption ensures that more effort in the first period does not affect the marginal returns of effort in the second period. The deterministic assumption ensures that the condition of asymmetric information will not be changed by the effort in the first period. Relaxing any one of the two assumptions makes α_2^u dependent on α_1^u (See Piccione and Tan (1996); Chen and Chiu (2010)).

[25] The reason is that ψ'' and ψ'^{-1} are increasing functions, h_1 and h_2 are monotonously increasing. Eqs. (15) and (16) are equivalent to $h_1\left(\alpha_1^b + \delta\alpha_2^b\right) = E\frac{F_1}{f_1}(\theta_{1min})$ and $h_2\left(\alpha_2^b\right) = -\delta E\frac{F_1}{f_1}(\theta_{1min})$. Because $h_1(1+\delta) = \frac{1+\delta}{\psi''\left(\psi'^{-1}(0)\right)} = +\infty$, we must obtain $\alpha_1^b + \delta\alpha_2^b < 1 + \delta$, which implies $\alpha_1^b < 1 + \delta(1 - \alpha_2^b)$. For $\delta < 0$ we obtain $\alpha_1^b < 1$ because $\alpha_2^b < 1$. To ensure $\alpha_1^b < 1$ for $\delta > 0$, it is sufficient to assume that $E\frac{F_1}{f_1}(\theta_{1min}) < h_1\left(1 + \delta\alpha_2^b\right)$. Indeed, if this condition holds, then we obtain $h_1\left(\alpha_1^b + \delta\alpha_2^b\right) = E\frac{F_1}{f_1}(\theta_{1min}) < h_1\left(1 + \delta\alpha_2^b\right)$, which implies $\alpha_1^b + \delta\alpha_2^b < 1 + \delta\alpha_2^b \Rightarrow \alpha_1^b < 1$. Notice that $h_1(1 + \delta\alpha_2^b)$ is a decreasing function of $E\frac{F_1}{f_1}(\theta_{1min})$, because $h_1(1 + \delta\alpha_2^b)$ is increasing in α_2^b, and that α_2^b is decreasing in $E\frac{F_1}{f_1}(\theta_{1min})$. Thus, the condition $E\frac{F_1}{f_1}(\theta_{1min}) < h_1\left(1 + \delta\alpha_2^b\right)$ is equivalent to $E\frac{F_1}{f_1}(\theta_{1min}) < M$.

To understand Eq. (1), note that, for positive externality and same power of incentive under the two regimes in the first period, effort in the first period is higher in bundling because of the internalization of the externality between the two tasks. Bundling mitigates the agency problem in the first period; hence, the principal does not need to provide a high first-period power of incentive. Consider a marginal increase in the power of incentive: $d(1-\alpha_1)$. The marginal benefit, which is the resulting increased efficiency caused by the increased effort in the first period, is smaller in bundling for two reasons. First, the increased effort is smaller under bundling since $de_1 = \frac{1}{\psi''(e_1)}d(1-\alpha_1)$ is decreasing in e_1. Second, with a marginal increase in effort e_1, the resulting increased marginal efficiency is smaller in bundling since the efficiency $(1+\delta)e_1 - \psi(e_1)$ is concave in e_1. On the other hand, the marginal cost, which is the resulting increased information rent, is the same under the two regimes. At the optimum, the principal chooses the power of incentive, so the marginal benefit and the marginal cost are equal. Consequently, the optimal power of incentive is smaller under bundling. The result is reversed for negative externality.

The logicality for Eq. (2) can be explained in the following manner. In unbundling, because of the tradeoff between providing an incentive and reducing the winner's information rent, the principal has to pay a strictly positive share of c_2, which is independent of the externality δ. In bundling, the agents are uninformed; hence there is no information rent on their cost in the second period at the time of auctioning. If there is no externality (i.e., $\delta = 0$), it is optimal to let the agent bear the whole share of c_2 (i.e., $1-\alpha_2 = 1$). In the presence of positive externality, instead of letting the agent bear the entire share of c_2, the principal prefers to increase $1-\alpha_2$ slightly by an amount $d(1-\alpha_2)$ and decrease $1-\alpha_1$ by $\delta d(1-\alpha_2)$, simultaneously. By doing so, the incentive in the first period will not be altered. Moreover, the efficiency in the second period is diminished only by a second-order term $\psi''(e_2)(d(1-\alpha_2))^2$ since 1 is the level of the power of incentive that maximizes the efficiency in the second period. Hence, the total loss of efficiency will be only a second-order term. However, the reduced $1-\alpha_1$ saves the expected information rent left to the agent in the first period to the first-order $\delta E\frac{F_1}{f_1}(\theta_{1min})d(1-\alpha_2)$. Thus, at the optimum, the principal gives a super-powered incentive in the second period (i.e., $1-\alpha_2 > 1$), thereby implying that the principal bears a negative share of the cost in the case of positive externality. In negative externality, the result is reversed, and the principal would bear a strictly positive share of c_2, which increases according to the extent of externality. If the extent is not too large, the share in bundling is still smaller than that in unbundling. However, the share in bundling will be larger than that in unbundling when the extent is very large. The argument also explains Eq. (3) ii) and iii) since the effort in the second period is determined solely by the power of incentive in the second period under both regimes.

This proposition also indicates that the agent's effort during the first period is the same under both bundling and unbundling. Although the agent in the first period does not internalize the externality between the two tasks in unbundling, the principal can correct this by letting him or her bear a larger share of c_1.

3.3. Bundling or unbundling?

The principal will choose unbundling iff $\tau^u \le \tau^b$. Combining Eqs. (10) and (14), we obtain

$$\tau^u - \tau^b = \underbrace{\{E\theta_{2\min} - E\theta_2\}}_{-} + \left\{ \underbrace{\left(\alpha_1^b - \alpha_1^u\right) E\frac{F_1}{f_1}(\theta_{1\min})}_{+/-} + \underbrace{\left(1-\alpha_2^u\right) E\frac{F_2}{f_2}(\theta_{2\min})}_{+} \right\} - \underbrace{\left\{ e_2^u - \psi\left(e_2^u\right) - \left(e_2^b - \psi\left(e_2^b\right)\right)\right\}}_{+/-} \quad (17)$$

The RHS of the above equation comprises three parts representing three differences between bundling and unbundling. The first difference is allocation efficiency. Unbundling enables the principal to allocate the contract to the agents with the lowest θ_2, while bundling does not since the agents have no information on θ_2 at the time of auction. The second difference is the information rent given to agents. The principal has to pay the winner information rent for the agents' private information θ_1 under both bundling and unbundling. A difference arises here because the principal pays a different share of c_1 under the two regimes. Moreover, the principal needs to pay information rent on θ_2 under unbundling, while he or she does not need to do so under bundling since the agents are uninformed about θ_2 at the time of auction. The third difference is the benefit generated by the agent's cost-reducing activity. By Proposition 2, the agent exerts the same effort in the first period under the two regimes. Thus, the difference in this part vanishes. However, the efforts in the second period are different, as we have shown in Proposition 2.

From Eq. (17), it is evident that the expected total payment under unbundling can be either larger or smaller than bundling. The following proposition shows how the externality and competitiveness in the second-period market affects the relative attractiveness of bundling and unbundling.

Proposition 3.

(1) *If the externality is positive (negative), increasing the extent of externality tilts the principal's choice toward bundling (unbundling).*
(2) *Increasing the competitiveness in the building market tilts the principal's choice toward unbundling.*

Proof. See the Appendix. □

Proposition 3(1) reflects findings by Bennett and Iossa (2006) and Martimort and Pouyet (2008). Proposition 3(2) is straightforward. As the competitiveness in the building market becomes more intense, the principal's payoff does not change in bundling, while it increases in unbundling. One disadvantage of bundling is that it does not make use of the competition in the second period. A real-world example is the Los Angeles Unified School District's Belmont project. This project was procured through a bundling method, and it led to excessive costs. After investigating this project, Los Angeles district attorney Steve Cooley concluded in his report that one problem in the D–B process is that it does not utilize competitive bidding, in which prospective builders bid on the same design.

Note that Proposition 3(2) also holds for the case where $N_2 < N_1$. If $N_2 < N_1$, the number of bidders in the bundling auction is N_2. Obviously, the principal's payoff is independent on N_1 under bundling and strictly increasing in N_1 under unbundling. Increasing N_1 increases the first-period competition under unbundling, while it has no effect under bundling because the increased number of designers are not able to find partners with which to form consortia; hence, they cannot participate in the bundling auction. Consequently, unbundling becomes appealing.

The effect of joint-task competition on the relative advantage of unbundling can be either positive or negative. The following proposition shows that the feature of externality is crucial in determining this effect.

Proposition 4.

(1) *Suppose $N_1 < N_2$, the joint-task competition tilts the principal's choice toward unbundling (resp. bundling) if the externality is positive (resp. negative).*
(2) *Suppose $N_2 < N_1$, then there exist $\hat{\delta}_1 > 0$ and $\hat{\delta}_2 < 0$, such that the joint-task competition tilts the principal's choice toward unbundling (resp. bundling) if $\delta > \hat{\delta}_1$ (resp. $\delta < \hat{\delta}_2$).*

Proof. See the Appendix. □

The logicality of Proposition 4(1) can be described in the following manner. Increasing N_1 benefits both bundling and unbundling in two ways. First, it increases allocation efficiency, that is, θ_{1min} decreases in the sense of first-order stochastic dominance. However, there is no difference between bundling and unbundling in terms of this benefit; therefore, it would not change the principal's bundling decision. Second, it decreases the winner's information rent, $(1-\alpha_1)E\frac{F_1}{f_1}(\theta_{1min})$, which increases if the share of the cost of designing borne by the winner, $(1-\alpha_1)$, increases. As we previously argued, this share is smaller in bundling if the externality is positive. Consequently, bundling benefits less from the decrease in information rent; hence, it becomes relatively less attractive.[26] According to the same logic, the result will be reversed if the externality is negative.

For $N_2 < N_1$, the number of joint-task bidders is N_2. On the one hand, increasing N_2 intensifies the second-period competition and hence mitigates the second-period agency problem under unbundling. On the other hand, it also intensifies the first-period competition, thereby mitigating the first-period agency problem under bundling. For sufficiently large positive externality, bundling itself already alleviates the agency problem and thus enjoys reduced benefit from an increase in N_2. Therefore, unbundling becomes appealing. For sufficiently negative externality, bundling aggravates the first-period agency problem, thereby enjoying increased benefit from an increase in N_2 and thus becomes relatively appealing.

In industries where positive externality prevails, our proposition predicts that competition in the market of both tasks biases the principal's choice toward unbundling. This result is consistent with the real-world evidence. On the one hand, it has been documented that a wave of mergers and acquisitions (M&A) swept over industrial business organizations in the late twentieth century, including the construction industry (see Choi and Russell, 2004). In the sample of M&A transactions in the construction industry in the US from 1980 to 2002 (Choi and Russell, 2004), only 5.3% occurred from 1980 to 1984, while 41.9% occurred from 1995 to 1999. On the other hand, the DBIA reported that the number of D–B projects accounted for more than 30% of the construction in the US in 2001, as compared to 5% in 1985 (Beard et al., 2001; Tulacz, 2002).

3.4. Discussions

3.4.1. Welfare

From the perspective of social welfare, an interesting problem is whether the principal bundles too much or too little. To answer this question, assume that the social welfare is equal to a weighted sum of the utility of the principal and the agents: $W^b = -\tau^b + \lambda E\pi_1^b(\theta_{1min})$ and $W^u = -\tau^u + \lambda[E\pi_1^u(\theta_{1min}) + E\pi_2^u(\theta_{2min})]$. Using this criteria, it is evident that

$$W^u - W^b = -\left(\tau^u - \tau^b\right) + \lambda\left[\left(\alpha_1^b - \alpha_1^u\right)E\frac{F_1}{f_1}(\theta_{1min}) + (1-\alpha_2^u)E\frac{F_2}{f_2}(\theta_{2min})\right]. \tag{18}$$

The principal bundles too much if $W^u - W^b > -(\tau^u - \tau^b)$. Once this condition is satisfied, whenever the principal chooses unbundling over bundling (i.e. $\tau^u - \tau^b < 0$), unbundling should also be desirable from the perspective of social welfare (because $W^u - W^b > -(\tau^u - \tau^b) > 0$). However, the reverse does not necessarily hold. In some cases, unbundling is socially desirable although the principal chooses bundling. According to the same logic, the principal bundles too little if $W^u - W^b < -(\tau^u - \tau^b)$.

We then obtain the following result: there exists $\tilde{\delta} < 0$, such that, from the perspective of social welfare, the principal bundles too much if $\delta > \tilde{\delta}$ and too little if $\delta < \tilde{\delta}$.[27]

3.4.2. Risk aversion

If we assume that agents are risk averse, then our result in Propositions 3 & 4 still hold. To obtain an analytic solution, we need to make the following specific assumptions: (1) Agents have CARA utility function $U(x) = \frac{1-e^{-rx}}{r}$; (2) the effort cost function is quadratic $\psi(e) = \frac{1}{2}e^2$; (3) both θ_2 and θ_1 are distributed exponentially on $[0, +\infty)$, $F_2(\theta_2) = 1-e^{-\theta_2}$ and $F_1(\theta_1) = 1-e^{-\theta_1}$. Since agents are risk averse, it is necessary to add a noise term on c_1 and c_2: $c_1 = \theta_1 - e_1 + \varepsilon_1$ and $c_2 = \theta_2 - e_2 - \delta e_1 + \varepsilon_2$. Assume that ε_1 and ε_2 are normally distributed with zero mean and variance σ_1^2 and σ_2^2.

Under these specific assumptions, it is easy to show that the results in Propositions 3 and 4 still hold with risk-averse agents. Moreover, we can discuss how the change in the uncertainties involved in the two periods affects the principal's bundling decision. Increasing uncertainty σ_1^2 in the first period worsens the principal's position under both bundling and unbundling since he or she has to pay a higher risk premium to the agent. If the externality is positive, the agent bears a larger share of the risk ε_1; therefore, the principal suffers more in unbundling. Consequently, bundling becomes relatively more attractive. The result is reversed if the externality is negative. Similarly, the principal's position worsens as the uncertainty increases in the second period. If the externality is sufficiently large, the agent bears a smaller share of the risk ε_2; therefore, the principal suffers less in unbundling. Consequently, bundling becomes relatively less attractive. The result is reversed if externality is small.[28]

3.4.3. Unbunding with advanced contracting

In the previous section, we followed the literature and assumed that contracting occurs only in the second period under the unbundling regime (Jeitschko and Wolfstetter, 2002; Grimm, 2007). However, there is another option for the principal, which is unbundling with advanced contracting, in which the principal can organize an auction for task 2 in the first period under unbundling. The only difference between bundling and unbundling with advanced contacting is externality internalization. Thus, the principal will choose bundling if the externality is positive, whereas he or she will choose unbundling if the externality is negative, which aligns with the findings of Bennett and Iossa (2006) and Martimort and Pouyet (2008). In positive externality, unbundling with advanced contracting is dominated by bundling; hence, the only relevant choices for the principal are unbundling without advanced contracting and bundling, as we considered in our paper. In negative externality, bundling is dominated by unbundling with advanced contracting. Hence, the principal has to choose between unbundling with advanced contacting and unbundling without advanced contracting. The advantage of advanced contracting is that the principal can save the information rent given to the bidders. The disadvantage is that he or she cannot choose the most efficient bidder, thereby creating inefficient allocation. As the number of second-stage bidders increases, the advantage of advanced contracting decreases as the competition erodes the information rent. The disadvantage of advanced contracting increases as allocation efficiency becomes more important. Consequently, the principal will not choose to contract in advance if there is sufficient second-stage competition.

[26] The key for this result is that compared to unbundling, the power of incentive in the first period is lower under bundling. The result also holds using Laffont and Tirole's (1988) method of modeling positive externality. Under unbundling, the agent chooses $i = 0$ and the power of incentive in the first period is chosen to balance the standard tradeoff between providing incentive in the cost reducing activity and information rent reduction. However, under bundling, a higher power of incentive in the first period has an additional cost: it reduces the agent's incentive to invest in i. Therefore, the principal will provide a lower power of incentive under bundling.

[27] The proof and the explanation are given in the Appendix.

[28] Detailed proofs of these results are available upon request.

4. Concluding remarks

In this paper, we combined the literature on bundling tasks with the literature on auctioning incentive contracts. Externality between two tasks plays the important role of determining how other factors, such as competition in the market of joint tasks, uncertainties involved in the two tasks, and agents' risk aversion attitude, affect the principal's bundling decision. In positive externality, bundling alleviates the agency problem in the first period by providing incentives in the second period. Hence, any factors that mitigate the first-period agency problem, such as strong competition or small uncertainty in the first period, weaken the advantage of bundling and therefore biased the principal's choice toward unbundling. In contrast, any factors that mitigate the second-period agency problem, such as strong competition or small uncertainty in the second period, strengthen the advantage of bundling and hence tilt the principal's choice toward it.

Many areas remains to be explored in future work. First, we have implicitly assumed that, once bundling is chosen, the winner will build by himself or herself under any circumstance, even when the realized cost is very high. It would be interesting to relax this assumption and explore whether the principal can do better by allowing the winner to subcontract with other bidders in the second period. Subcontracting is a common phenomenon in many procurement situations (see Kamien et al., 1989; Gale et al., 2000; Grimm, 2007). In the construction industry, the D–B method leads to a situation in which the designer is responsible for both the design and construction but often subcontracts with on-site personnel.

Second, we treated all agents in a symmetric manner in this paper. Even so, it is well documented in the secondary literature that the effort in the first task increases the incumbent's cost advantage over outsiders (Anton and Yao, 1987; Riordan and Sappington, 1989). Consequently, the problem becomes one of auctions with endogenously asymmetric bidders. Under this asymmetric treatment, unbundling provides incentives for the incumbent in the first period: he or she can work hard to increase the chance of getting the contract in second period auction.

Finally, although we assume that the first-period activity reduces cost, the model also applies to the case in which the agent exerts a quality-improving effort, as shown in the literature on PPP. Therefore, future research could investigate the optimal combination of ownership and the bundling decision.

Appendix A. Proofs

A1. Deriving $B_1(\theta_1)$ under unbundling

In period 1, the utility of an agent with cost parameter θ_1 who has been selected for task 1 can be written as

$$\begin{aligned}\pi_1(\theta_1, b_1) &= b_1 + \alpha_1 c_1 - c_1 - \psi(e_1) \\ &= b_1 - (1-\alpha_1)\theta_1 + (1-\alpha_1)e_1 - \psi(e_1)\end{aligned} \tag{19}$$

Maximizing over e_1 yields $\psi'(e_1) = 1 - \alpha_1$ and hence $e_1 = \psi'^{-1}(1 - \alpha_1)$. In equilibrium, we obtain $b_1 = B_1(\theta_1)$. Denote $\pi_1(\theta_1) = \pi_1(\theta_1, B_1(\theta_1))$. Substituting these into the first-order condition of Eq. (19) yields

$$\frac{B_1'(\theta_1)}{\pi_1(\theta_1)} = \frac{(N_1-1)f_1(\theta_1)}{1-F_1(\theta_1)} \quad \text{for all} \quad \theta_1 \in [\underline{\theta}_1, \overline{\theta}_1] \tag{20}$$

Combining Eqs. (19) and (20), we obtain

$$\frac{d\pi_1(\theta_1)}{d\theta_1} = \frac{(N_1-1)f_1(\theta_1)}{1-F_1(\theta_1)}\pi_1(\theta_1) - (1-\alpha_1)$$

Solving the differential equation, we obtain

$$\pi_1(\theta_1) = (1-F_1(\theta_1))^{-(N_1-1)}\left(K + (1-\alpha_1)\int_{\theta_1}^{\overline{\theta}}(1-F_1(s))^{N_1-1}ds\right) \tag{21}$$

where K is some constant. Since $\pi_1|_{\theta_1=\overline{\theta}_1} = 0$, we obtain $K = 0$. The term π_1 is also known as information rent, which represents the benefit the winner enjoys from his information advantage. Note that $\pi_1(\theta_1)$ increases with the power of incentive $1 - \alpha_1$. From the viewpoint of an agent, the principal bearing a share of the realized cost is equivalent to all the agents (including the principal) having cost type $(1 - \alpha_1)\theta_1$. A lower power of incentive indicates that everyone's cost type has a more concentrated distribution; hence, the information rent is smaller. In the extreme case, where $1 - \alpha_1$ is close to 0, everyone has almost the same cost type and hence earns a rent close to zero. Combining Eqs. (21) with (19), we obtain the following bidding strategy:

$$\begin{aligned}B_1(\theta_1) = (1-\alpha_1)&\left((1-F_1(\theta_1))^{-(N_1-1)}\int_{\theta_1}^{\overline{\theta}_1}(1-F_1(s))^{N_1-1}ds + \theta_1\right) \\ &+(\psi(e_1) - (1-\alpha_1)e_1)\end{aligned} \tag{22}$$

where $e_1 = \psi'^{-1}(1 - \alpha_1)$.

A2. Deriving $\pi_2(\theta_2)$ and $B_2(\theta_2)$

Similar to the first period, the utility of an agent with cost parameter θ_2, who has been selected for task 2 is

$$\begin{aligned}\pi_2(\theta_2, b_2) &= b_2 + \alpha_2 c_2 - c_2 - \psi(e_2) \\ &= b_2 - (1-\alpha_2)\theta_2 + (1-\alpha_2)e_2 + \delta(1-\alpha_2)e_1 - \psi(e_2)\end{aligned}$$

where we have used Eq. (2). Maximizing $\pi_2(\theta_2, b_2)$ over e_2 yields $\psi'(e_2) = 1 - \alpha_2$ and hence $e_2 = \psi'^{-1}(1 - \alpha_2)$.The contract in the second period is also awarded by means of a first-price, sealed-bid auction. Again, we consider the symmetric Nash equilibrium, in which each agent's bid function is given by the strictly monotonic function, $B_2(\cdot)$. Given that all other agents follow the bid function $B_2(\cdot)$, an agent with cost type θ_2, by bidding b_2, will have an ex-ante expected utility

$$E\pi_2(\theta_2, b_2) = \left[1 - F_2\left(b_2^{-1}(b_2)\right)\right]^{N_2-1}\pi_2(\theta_2, b_2)$$

The optimal b_2 that maximizes the above expression should be $b_2 = B_2(\theta_2)$. Substituting this into the first-order condition from the above equation and denoting $\pi_2(\theta_2) = \pi_2(\theta_2, B_2(\theta_2))$, we obtain

$$\frac{B_2'(\theta_2)}{\pi_2(\theta_2)} = \frac{(N_2-1)f_2(\theta_2)}{1-F_2(\theta_2)} \quad \text{for all} \quad \theta_2 \in [\underline{\theta}_2, \overline{\theta}_2]$$

Similar to the case in the first period, by solving the above differential equation, we can obtain each bidder's expected utility function $\pi_2(\cdot)$ and the equilibrium bid function $B_2(\cdot)$

$$\pi_2(\theta_2) = (1-\alpha_2)(1-F_2(\theta_2))^{-(N_2-1)}\int_{\theta_2}^{\overline{\theta}_2}(1-F_2(s))^{N_2-1}ds$$

$$\begin{aligned}B_2(\theta_2) = (1-\alpha_2)&\left((1-F_2(\theta_2))^{-(N_2-1)}\int_{\theta_2}^{\overline{\theta}_2}(1-F_2(s))^{N_2-1}ds + \theta_2\right) \\ &+(\psi(e_2) - (1-\alpha_2)e_2) - \delta(1-\alpha_2)e_1\end{aligned}$$

where $e_1 = \psi'^{-1}(1 - \alpha_1)$ and $e_2 = \psi'^{-1}(1 - \alpha_2)$.

Proof of Lemma 1. Substituting the expressions of $B_1(\theta_1)$, $B_2(\theta_2)$, c_1 and c_2 into Eq. (9) yields

$$\begin{aligned}\tau^u &\equiv \tau_1+\tau_2\\ &=\sum_{t=1}^{2}N_t\int_{\underline{\theta}_t}^{\bar{\theta}_t}(b_t(\theta_t)+\alpha_t c_t)(1-F_t(\theta_t))^{(N_t-1)}f_t(\theta_t)d\theta_t\\ &=\sum_{t=1}^{2}(1-\alpha_t)N_t\int_{\underline{\theta}_t}^{\bar{\theta}_t}\int_{\theta_t}^{\bar{\theta}_t}(1-F_t(s))^{N_t-1}ds f_t(\theta_t)d\theta_t\\ &\quad+\sum_{t=1}^{2}N_t\int_{\underline{\theta}_t}^{\bar{\theta}_t}\theta_t(1-F_t(\theta_t))^{(N_t-1)}f_t(\theta_t)d\theta_t\\ &\quad+\psi(e_1)-(1+\delta)e_1+\psi(e_2)-e_2\end{aligned}$$

Note that the p.d.f. of θ_{tmin} is $N_t(1-F_t(\theta_t))^{(N_t-1)}f_t(\theta_t)$, and we have

$$N_t\int_{\underline{\theta}_t}^{\bar{\theta}_t}\theta_t(1-F_t(\theta_t))^{(N_t-1)}f_t(\theta_t)d\theta_t=E\theta_{tmin}.$$

Moreover, integrating by parts yields

$$\begin{aligned}&N_t\int_{\underline{\theta}_t}^{\bar{\theta}_t}\int_{\theta_t}^{\bar{\theta}_1}(1-F_t(s))^{N_t-1}ds f_t(\theta_t)d\theta_t\\ &=N_t\int_{\underline{\theta}_t}^{\bar{\theta}_t}F_t(\theta_t)(1-F_t(\theta_t))^{N_t-1}d\theta_t\\ &=E\frac{F_t}{f_t}(\theta_{tmin})\end{aligned}$$

Hence, the total payment can be rewritten as

$$\begin{aligned}\tau^u &=\sum_{t=1}^{2}E\theta_{tmin}+\sum_{t=1}^{2}(1-\alpha_t)E\frac{F_t}{f_t}(\theta_{tmin})\\ &\quad+\psi(e_1)-(1+\delta)e_1+\psi(e_2)-e_2\end{aligned}$$

which completes the proof.

A3. Deriving $B(\theta_1)$ under bundling

Let $B(\cdot)$ be the optimal bidding strategy in the symmetric Nash equilibrium. Again, we first assume $B(\cdot)$ as strictly monotonic in θ_1 (we check subsequently and confirm that this is indeed the case). Given that all the other consortiums follow this bidding strategy, a consortium with cost parameter θ_1, by bidding b, will have the following ex-ante expected utility

$$E\pi^b(\theta_1,b)=\left[1-F_1\left(B^{-1}(b)\right)\right]^{N_1-1}\pi^b(\theta_1,b)$$

Again, maximizing the above expected utility over b yields the following first-order condition

$$(N_1-1)f_1\left(B^{-1}(b)\right)\frac{\pi^b(\theta_1,b)}{B'(B^{-1}(b))}=\left[1-F_1\left(B^{-1}(b)\right)\right]$$

Denoting $\pi^b(\theta_1)=\pi^b(\theta_1,B(\theta_1))$ and substituting it with $b=B(\theta_1)$ into the first-order condition, we obtain

$$\frac{B'(\theta_1)}{\pi^b(\theta_1)}=\frac{(N_1-1)f_1(\theta_1)}{1-F_1(\theta_1)}\quad\text{for all}\quad\theta_1\in[\underline{\theta}_1,\bar{\theta}_1]$$

Solving the above differential equation, we can obtain each consortium's expected utility function $\pi^b(\cdot)$ and the following equilibrium bid function $B(\cdot)$

$$\pi^b(\theta_1)=(1-F_1(\theta_1))^{-(N_1-1)}(1-\alpha_1)\int_{\theta_1}^{\bar{\theta}_1}(1-F_1(s))^{N_1-1}ds$$

$$\begin{aligned}B(\theta_1)&=(1-\alpha_1)\left((1-F_1(\theta_1))^{-(N_1-1)}\int_{\theta_1}^{\bar{\theta}_1}(1-F_1(s))^{N_1-1}ds+\theta_1\right)\\ &\quad+\psi(e_1)-[1-\alpha_1+\delta(1-\alpha_2)]e_1+\psi(e_2)-(1-\alpha_2)e_2\\ &\quad+(1-\alpha_2)E\theta_2\end{aligned}$$

where $e_1=\psi'^{-1}(1-\alpha_1+\delta(1-\alpha_2))$ and $e_2=\psi'^{-1}(1-a_2)$.

Proof of Lemma 2. Substituting the expressions $B(\theta_1)$, c_1 and c_2 into Eq. (13) yields

$$\begin{aligned}\tau^b&=N_1\int_{\underline{\theta}}^{\bar{\theta}_1}(B(\theta_1)+\alpha_1c_1+\alpha_2c_2)(1-F_1(\theta_1))^{(N_1-1)}f_1(\theta_1)d\theta_1\\ &=(1-\alpha_1)N_1\int_{\underline{\theta}_1}^{\bar{\theta}_1}\int_{\theta_1}^{\bar{\theta}}(1-F_1(s))^{N_1-1}ds\ f_1(\theta_1)d\theta_1\\ &\quad+N_1\int_{\underline{\theta}_1}^{\bar{\theta}_1}\theta_1(1-F_1(\theta_1))^{(N_1-1)}f_1(\theta_1)d\theta_1\\ &\quad+E\theta_2+\psi(e_1)-(1+\delta)e_1+\psi(e_2)-e_2\end{aligned}$$

From Lemma 1 we know that

$$N_1\int_{\underline{\theta}_1}^{\bar{\theta}_1}\theta_1(1-F_1(\theta_1))^{(N_1-1)}f_1(\theta_1)d\theta_1=E\theta_{1min}$$

and

$$N_1\int_{\underline{\theta}_1}^{\bar{\theta}_1}\int_{\theta_1}^{\bar{\theta}_1}(1-F_1(s))^{N_1-1}ds f_1(\theta_1)d\theta_t=E\frac{F_1}{f_1}(\theta_{1min})$$

Thus, the total payment can be rewritten as

$$\begin{aligned}\tau^b&=E\theta_{1min}+E\theta_2+(1-\alpha_1)E\frac{F_1}{f_1}(\theta_{1min})\\ &\quad+\psi(e_1)-(1+\delta)e_1+\psi(e_2)-e_2\end{aligned}$$

which completes the proof.

Proof of Proposition 2. By Eqs. (11) and (15), we obtain

$$\frac{\alpha_1^u+\delta}{\psi''(\psi'^{-1}(1-\alpha_1^u))}=\frac{\alpha_1^b+\delta\alpha_2^b}{\psi''(\psi'^{-1}(1-\alpha_1^b+\delta(1-\alpha_2^b)))}\tag{23}$$

Denote $h(x)=\frac{x}{\psi''\left(\psi'^{-1}(1+\delta-x)\right)}$. The above equation then can be rewritten as

$$h(\alpha_1^u+\delta)=h\left(\alpha_1^b+\delta\alpha_2^b\right).$$

Because ψ'' and ψ'^{-1} are increasing functions, $h(x)$ is monotonously increasing. Thus, we obtain

$$\alpha_1^u+\delta=\alpha_1^b+\delta\alpha_2^b.\tag{24}$$

Eq. (24) yields $\alpha_1^b=\alpha_1^u+\delta(1-\alpha_2^b)$. Since $(1-\alpha_2^b)>0$, we obtain Eq. (1). Moreover, Eq. (2) is immediate by comparing Eq. (12) and Eq. (16). Note that $e_1^u=\psi'^{-1}(1-\alpha_1^u)$ and $e_1^b=\psi'^{-1}(1-\alpha_1^b+\delta(1-\alpha_2^b))$. Hence Eqs. (23) and (24) implies Eq. (3) i).

Proof of Proposition 3. We only need to prove $\frac{\partial(\tau^u-\tau^b)}{\partial\delta}>0$; $\frac{\partial(\tau^u-\tau^b)}{\partial N_2}<0$; and $\frac{\partial(\tau^u-\tau^b)}{\partial N_1}\le 0\Leftrightarrow\delta\ge 0$. Using the envelope theorem, we obtain

$$\begin{aligned}\frac{\partial\left(\tau^u-\tau^b\right)}{\partial\delta}&=-e_1^u+e_1^b-\left(\psi'\left(e_1^b\right)-(1+\delta)\right)\frac{\partial e_1^b}{\partial\delta}\\ &=\left(\alpha_1^b+\delta\alpha_2^b\right)\frac{\partial e_1^b}{\partial\delta}\\ &=\left(1-\alpha_2^b\right)E\frac{F_1}{f_1}(\theta_{1min})>0\end{aligned}$$

The second equality is because $e_1^u = e_1^b$ and $\psi'(e_1^b) = 1 - \alpha_1^b + \delta(1 - \alpha_2^b)$. The last equality is due to Eq. (15). Now, we show that $\frac{\partial(\tau^u - \tau^b)}{\partial N_2} < 0$. Using the envelope theorem again, we obtain

$$\frac{\partial\left(\tau^u - \tau^b\right)}{\partial N_2} = \frac{\partial E\theta_{2min}}{\partial N_2} + (1-\alpha_2^u)\frac{\partial}{\partial N_2}E\frac{F_2}{f_2}(\theta_{2min})$$

Note that $E\theta_{2min}$ is decreasing in N_2 because $\theta_{2min}^{N_2+1} \underset{\leq}{FOS}\, \theta_{2min}^{N_2}$. Moreover, since $\frac{F_2}{f_2}$ is an increasing function, $E\frac{F_2}{f_2}(\theta_{2min})$ is also decreasing in N_2. Hence, $\frac{\partial(\tau^u - \tau^b)}{\partial N_2} < 0$.

Proof of Proposition 4.

1) We need to prove that $\frac{\partial(\tau^u - \tau^b)}{\partial N_1} \leq 0 \Leftrightarrow \delta \geq 0$. We obtain

$$\frac{\partial\left(\tau^u - \tau^b\right)}{\partial N_1} = \left(\alpha_1^b - \alpha_1^u\right)\frac{\partial}{\partial N_1}E\frac{F_1}{f_1}(\theta_{1min}).$$

Since $\theta_{1min}^{N_1+1} \underset{\leq}{FOS}\, \theta_{1min}^{N_1}$ and $\frac{F_1}{f_1}$ is increasing, we obtain $\frac{\partial}{\partial N_1}E\frac{F_1}{f_1}(\theta_{1min}) < 0$. Thus, $\frac{\partial(\tau^u - \tau^b)}{\partial N_1} \leq 0 \Leftrightarrow \alpha_1^b \geq \alpha_1^u \Leftrightarrow \delta \geq 0$, by Proposition 2. 2) $N_2 < N_1$, it is easy to obtain $\frac{\partial \tau^u - \tau^b}{\partial N_2} = \frac{\partial}{\partial N_2}\left\{\left(E\theta_{2min}^{N_2} - E\theta_{1min}^{N_2}\right) + (1-\alpha_2^u)E\frac{F_2}{f_2}\left(\theta_{2min}^{N_2}\right) - \left(1-\alpha_1^b\right)E\frac{F_1}{f_1}\left(\theta_{1min}^{N_2}\right)\right\}$ where $\theta_{1min}^{N_2} = min\left(\theta_1^1, \ldots, \theta_1^{N_2}\right)$ and $\theta_{2min}^{N_2} = min\left(\theta_2^1, \ldots, \theta_2^{N_2}\right)$. Then calculation yields $\frac{\partial^2 \tau^u - \tau^b}{\partial N_2 \partial \delta} = \frac{\partial}{\partial N_2}E\frac{F_1}{f_1}\left(\theta_{1min}^{N_2}\right)\frac{\partial \alpha_1^b}{\partial \delta} < 0$. Assuming θ_2s and θ_1s are i.i.d, we obtain $\frac{\partial \tau^u - \tau^b}{\partial N_2} < 0$ for small δ and $\frac{\partial \tau^u - \tau^b}{\partial N_2} > 0$ for large δ. Large positive (negative) externality determines that the principal is more likely to choose unbundling if N_2 is larger (smaller).

Proof of the result on "welfare" and its explanation. We show that the principal bundles too much if $\delta > \widetilde{\delta} = -\frac{E\frac{F_2}{f_2}(\theta_{2min})}{E\frac{F_1}{f_1}(\theta_{1min})}$, and bundles too little if $\delta < \widetilde{\delta}$. Let $\Delta \equiv W^u - W^b + (\tau^u - \tau^b)$. According to Eq. (18), we obtain

$$\Delta = \left(\alpha_1^b - \alpha_1^u\right)E\frac{F_1}{f_1}(\theta_{1min}) + (1-\alpha_2^u)E\frac{F_2}{f_2}(\theta_{2min}) \tag{25}$$

From the proof of part 3) of Proposition 2, we know that

$$\alpha_1^b - \alpha_1^u = \delta\left(1-\alpha_2^b\right) \tag{26}$$

Substituting Eq. (26) into Eq. (25) yields

$$\Delta = \delta\left(1-\alpha_2^b\right)E\frac{F_1}{f_1}(\theta_{1min}) + (1-\alpha_2^u)E\frac{F_2}{f_2}(\theta_{2min})$$

Since α_2^u is independent of δ, and α_2^b is decreasing in δ according to Eq. (16), Δ is increasing in δ. It remains is to show that $\Delta\left(\widetilde{\delta}\right) = 0$, which is obvious according to part (2) of Proposition 2. The following is the explanation of the "welfare" result: the intuition is that of a social planner, in which the principal cares less about the utility of the agents; hence, information rent is more costly for him or her. Thus, he is less likely to choose the method that provides the agents with larger information rent. Compared to bundling, for positive externality, under unbundling, agents obtain a larger information rent in the first period and an extra information rent in the second period. Therefore, the principal rarely will choose unbundling. For sufficiently negative externality, under unbundling, agents obtain much less information rent in the first period. Even though they still obtain some extra information rent in the second period, the total information rent might be smaller. Consequently, the principal often chooses unbundling.

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