How (Not) to Foster Innovations in Public Infrastructure Projects

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Abstract

The government wants an infrastructure-based public service to be provided. First, the infrastructure has to be built; subsequently, it has to be operated. Should the government bundle the building and operating tasks in a public-private partnership? Or should it choose traditional procurement, i.e. delegate the tasks to different firms? Each task entails unobservable investments to come up with innovations. It turns out that depending on the nature of the innovations, bundling may either stimulate or discourage investments. Moreover, we find that if renegotiation cannot be prevented, public-private partnerships may lead the government to deliberately opt for technologically inferior projects.

Keywords: Contract theory; procurement; public-private partnerships; moral hazard; renegotiation

JEL classification: $D86$; $L33$; $H11$; $H54$; $H57$

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I. Introduction

Providing infrastructure-based public services is one of the main tasks of government. On average, public procurement accounts for around 12% of GDP in OECD countries (see OECD, 2017). Thus, the amounts at stake are certainly significant. While the public procurement system should strive to achieve the best possible performance in terms of cost and service, examples of inefficiencies are reported regularly in the daily news.[1] How to best organize the provision of public goods and services is therefore a highly relevant policy question that is of broad interest.

In particular, public infrastructure such as highways, bridges, airports, and hospitals first has to be built and subsequently it has to be operated. Traditionally, when the government wanted to procure an infrastructure-based service, the two tasks of first building and then operating the infrastructure were separated. Specifically, the construction of a project was contracted out to a private company. This firm built the project, received the agreed payment, and then the contract was completed. Afterwards, another party took charge of operating and maintaining the facility. Yet, around the early 1990s, public-private partnerships have emerged as a new organizational form and they have become increasingly popular since then. A key property of a public-private partnership is the fact that facility construction and service provision are bundled (see e.g. Hart, 2003); i.e., the tasks of first building and then operating the infrastructure are assigned to a single private company.[2]

In the present paper, our goal is to provide a new perspective on the pros and cons of public-private partnerships compared to traditional procurement. Specifically, we consider a contract-theoretic model with two stages, a building stage and an operating stage. We investigate whether the two tasks of building and operating the infrastructure should be delegated to two different firms or whether it is better to bundle these two

[1] Infrastructure projects plagued by delays, cost overruns, environmental issues, and quality shortfalls attract much attention in the media. Recent examples include the Berlin Brandenburg Airport in Germany (cf. Hammer, 2015), the Honolulu Rail Transit Project in Hawaii (cf. Nagourney, 2016), or the Alaskan Way Viaduct replacement tunnel in Seattle (cf. Anderson, 2017). See Flyvbjerg et al. (2003) for discussions of many other examples.

[2] Grimsey and Lewis (2004) and Yescombe (2007) also emphasize that in practice a defining characteristic of a public-private partnership is that design and construction as well as operation and maintenance of the public infrastructure are combined under one private contractor.

tasks and assign them to a single company, a consortium. Advocates of public-private partnerships often argue that bundling fosters innovation incentives (see e.g. HM Treasury, 2012). In this context, innovations can be defined in a very broad sense as "any positive efficiency gains achieved through productive investments" (cf. Roumboutsos and Saussier, 2014, p. 359). However, now that public-private partnerships have been in place for more than twenty years, the empirical evidence regarding the success of public-private partnerships in stimulating innovations is mixed.[3]

On the one hand, there are case studies which document that public-private partnerships have indeed spurred innovations. For example, in the transportation sector, public-private partnerships were successful in substantially reducing construction time and in developing innovative solutions for congestion management by introducing time-varying tolls.[4] On the other hand, there is evidence which suggests that bundling may stifle innovations. For example, in the health care sector it has been reported that consortia in charge of hospital projects faced strategic incentives *not* to come up with innovations facilitating the adaptability of the hospital design, because it would enable them to "achieve additional income through alterations needed in the future".[5] Hence, when the same party is in charge of building and operating, innovations in the building stage might actually be discouraged, since they may reduce rents that could be obtained in the operating stage.

Our formal model provides an explanation for the empirical finding that bundling the building and operating tasks in a public-private partnership can boost innovation incentives in some situations, while it may stifle incentives to innovate under different circumstances. Specifically, we consider an extension of Tirole's (1999) "R&D game" to two stages. We assume that firms in charge of building and/or operating the public

[3] See e.g. Leiringer (2006), Russell et al. (2006), Javed et al. (2013), Liu and Liu (2017), Himmel and Siemiatycki (2017), Saeed et al. (2018), Singh (2018), and the recent survey by Carbonara and Pellegrino (2018) for empirical studies investigating whether or not public-private partnerships are conducive to fostering innovations.

[4] For instance, it was a private consortium that took the initiative to introduce variable pricing for California's State Route 91 express lanes, which works well to eliminate traffic congestion during peak periods. In France, a private firm resolved a 30-year impasse over how to complete the missing link of the A86 Paris ring road, using a deep-bore tunnel under the Versailles palace. See Gilroy et al. (2007) and Small (2010) for further details.

[5] See Barlow and Köberle-Gaiser (2009, p. 135).

infrastructure are protected by limited liability. In the building stage as well as in the operating stage, unobservable effort can be exerted to come up with an innovation. In each stage, the outcome (i.e., whether or not there was a successful innovation) is verifiable.[6] Since effort is a hidden action, the government can incentivize effort only with the help of outcome-contingent contracts.

In particular, consider the operating stage. In the presence of uncertainty, the outcome is only a noisy signal of the chosen effort level. Hence, if the government wants to induce the firm in charge of operating to exert high effort, it must leave a rent to the firm (see e.g. Laffont and Martimort, 2002). In case of a public-private partnership, the expected rents in the operating stage are taken into account by the consortium when it decides on how much effort to spend in the building stage. Bundling can thus create positive or negative incentive spillover effects which are absent in case of traditional procurement.

Suppose first that a successful innovation in the building stage increases the government's value of an innovation in the operating stage. Hence, a success in the building stage and a success in the operating stage are complements. For example, an innovative design of an airport which makes it possible to deal with a significantly larger number of passengers would also make subsequent service improvements in the operating stage more valuable, since more passengers would benefit. The government will then implement a relatively large second-stage effort level after a first-stage success, while it implements a relatively small second-stage effort level after a first-stage failure. Thus, in case of a public-private partnership the consortium will be able to earn a larger rent in the operating stage if it was already successful in the building stage. As a consequence, it becomes cheaper for the government to provide incentives in the building stage, which gives a public-private partnership an advantage over traditional procurement.

Now suppose that a successful innovation in the building stage reduces the government's additional value that can be generated by an innovation in the operating stage. Thus, a success in the building stage and a success in the operating stage are substitutes. For instance, suppose there is an exogenously given upper limit on the benefits

[6] Note that these assumption are in line with Tirole's (1999, p. 745) one-shot model, which in turn is based on Aghion and Tirole's (1994) work on the management of innovation.

that can potentially be generated by a particular project such as a highway. An innovative solution in the building stage (say, a tunnel that avoids traffic congestion) may already bring us close to the maximum benefit, so in this case the additional value that can be generated by further innovations in the operating stage (say, implementing variable tolls to reduce traffic congestion) is rather small. A consortium may then prefer *not* to exert innovation effort in the building stage, in order to obtain a larger rent in the operating stage. As a result, it can become very expensive for the government to induce high effort in the building stage, such that traditional procurement may be preferred.

Therefore, in our model the pros and cons of bundling the building and operating tasks in a public-private partnership can be traced back to the same source, namely the effect of expected second-stage rents on first-stage incentives. An important take-home message of our analysis is that public-private partnerships are desirable in situations in which successful outcomes in the two stages can be expected to be of a complementary nature, while traditional procurement may be preferred when successful outcomes in the two stages are rather of a substitutive nature.

When the government has full commitment power, then the second-stage effort level that it implements after a first-stage success will be larger under a public-private partnership than under traditional procurement. In this way, the government further increases the consortium's incentives to exert effort in the building stage. In contrast, after a first-stage failure the government implements a smaller second-stage effort level under a public-private partnership than under traditional procurement, so the consortium is punished for not developing an innovation in the building stage.

Yet, practitioners emphasize that in reality the government often cannot commit not to renege on its contract with the consortium.[7] When mutually beneficial renegotiation cannot be prevented, the government loses the possibility to punish the consortium for a first-stage failure by implementing a smaller second-stage effort level than under traditional procurement.[8] As a consequence, the possibility of renegotiations reduces

[7] The fact that in practice renegotiations cannot be prevented has often been emphasized in the empirical literature on public-private partnerships, see e.g. Guasch (2004), Engel et al. (2014, ch. 7), and Beuve et al. (2014).

[8] However, we will show that optimal contracts remain to be history-dependent even when renegotiation cannot be ruled out.

the advantages of a public-private partnership compared to traditional procurement and may have important implications for the initial choice of a public infrastructure project. In particular, we find that if under a public-private partnership renegotiation cannot be ruled out, then the government may prefer to choose a technologically *inferior* project. Intuitively, the reason is that the choice of such a project may reduce the scope for renegotiations. In contrast, under a public-private partnership with full commitment as well as under traditional procurement the government would never choose a technologically inferior project.

Related literature. The theoretical literature analyzing the pros and cons of bundling tasks in public-private partnerships was initiated by Hart (2003), who applies the incomplete contracting approach.[9] Hart (2003) considers two different kinds of investments which both can be made in the building stage in order to reduce costs in the operating stage. One kind of investment is desirable, while the other kind of investment is undesirable, since it leads to a strong reduction in service quality. A public-private partnership results in too much undesirable investment, while under traditional procurement there are weaker incentives to make the desirable investment. In line with Hart (2003), we focus on the bundling decision and do not study the choice between public and private ownership.[10] In contrast, Bennett and Iossa (2006) explore the interaction of the bundling decision with the choice between different ownership structures.[11] However, in models combining agency problems and property rights, Iossa and Martimort (2015, p. 23) conclude that "the important issue is not who owns the asset but instead whether tasks are bundled or not." Following Hart (2003), these authors assume that effort invested in the building stage has a *direct* external effect on the costs incurred in the operating stage. In contrast, in our model an innovation in the building

[9]See also Bös and De Fraja's (2002) earlier incomplete contracting model on bundling in the health care sector. The incomplete contracting paradigm was developed by Grossman and Hart (1986), Hart and Moore (1990), and Hart (1995). See Maskin and Tirole (1999) and Tirole (1999) for critical discussions of the foundations of the incomplete contracting methodology.

[10]Hart (2003, p. C71) points out that he ignores ownership issues and that he takes bundling to be the key property of a public-private partnership. On the decision between public and private ownership, see Hart et al. (1997) and the subsequent literature, e.g. Besley and Ghatak (2001), King and Pitchford (2008), Hoppe and Schmitz (2010), De Brux and Desrieux (2014), and Hamada (2017).

[11]See also Chen and Chiu (2010) for a variant of Bennett and Iossa's (2006) model.

stage can make an innovation in the operating stage either more or less valuable for the government, so from the consortium's perspective an external effect is created *only if* the government conditions payments in the operating stage on the outcome of the building stage.[12]

Our contribution is based on agency problems due to moral hazard.[13] Early contributions to the literature on moral hazard models were based on the trade-off between incentives and insurance when agents are risk-averse.[14] In particular, Rogerson (1985) considers a repeated moral hazard problem and shows that the optimal second-period incentives depend on the first-period outcome (i.e., the contract exhibits memory), even though the periods are technologically independent. His result is driven by the consumption-smoothing motive of the risk-averse agent. More recently, several authors such as Ohlendorf and Schmitz (2012), Kräkel and Schöttner (2016), and Schöttner (2017) have studied repeated moral hazard problems where agents are risk-neutral but protected by limited liability.[15] Yet, these papers do not study the differences between bundling and unbundling, which is the focus of the present paper.[16]

Recently, Martimort and Straub (2016) have also studied public-private partnerships in a two-stage moral hazard model with risk-neutral firms that are protected by

[12] In particular, the effort costs and the success probability for a given effort level in the second stage do *not* depend on what happened in the first stage. Thus, for a fixed second-stage incentive scheme the agent's second-stage behavior depends neither on the first-stage effort nor on the first-stage outcome. Our model thus differs from the sequential agency problems studied by Baliga and Sjöström (1998), Schmitz (2005), and Pi (2018).

[13] In contrast, Hoppe and Schmitz (2013) discuss the costs and benefits of public-private partnerships in an adverse selection model, where the consortium may strategically gather information about future costs to adapt the service provision to changing circumstances. The role of adverse selection in the context of public-private partnerships has recently also been studied by Buso (2018).

[14] See Holmström and Milgrom (1991) and Itoh (1991) for studies in the multi-task agency literature focused on the effort-substitution problem when tasks are simultaneously performed.

[15] For static moral hazard models with risk-neutral agents and limited liability, see the earlier work by Innes (1990) and Pitchford (1998).

[16] For instance, Ohlendorf and Schmitz (2012) study a single-agent financial contracting problem in which the principal must make an investment to continue a project. Potential second-stage returns are independent of the outcome of the first stage. In line with Rogerson (1985), they find that the optimal contract exhibits memory. They do not study the two-agents case, since in their setup unbundling could not outperform bundling.

limited liability. However, there are important differences. In particular, Martimort and Straub (2016) assume that the effort level exerted in the second stage must always be larger than first-stage effort, and they exogenously rule out second-stage payments that depend on the outcome of the first stage. Their focus is on the effects of an uncertain productivity shock after the first stage. Our model is complementary to Martimort and Straub's (2016) setup, since we do not impose any intertemporal restrictions on the effort levels and since history-dependent payments play a central role in our analysis. To the best of our knowledge, the different implications of public-private partnerships and traditional procurement for the initial choice of a public project have not yet been explored in the literature so far.

Finally, it should be noted that in practice policy makers may be tempted to favor public-private partnerships for the wrong reasons, since they are often not included in the fiscal balance sheets.[17] From an economic perspective, public-private partnerships should be given the same treatment in budgetary accounting as traditional procurement, so the choice between the organizational forms should be based on efficiency considerations (see Hart, 2003, p. C75). Hence, in the present contribution we abstract from financing issues and instead focus on the different incentive structures that prevail in public-private partnerships and traditional procurement.

Organization of the paper. The remainder of the paper is organized as follows. In Section II, we introduce the model. The case of traditional procurement is analyzed in Section III, while the organizational form of a public-private partnership is investigated in Section IV. In Section V, we compare the two modes of provision. In Section VI, we analyze a scenario where renegotiations cannot be ruled out and we explore the implications for project choice. Concluding remarks follow in Section VII. All formal proofs have been relegated to the Appendix.

II. The Model

Suppose the government (the principal) wants two sequential tasks to be performed in order to provide a public good or service. First, an infrastructure has to be designed

[17] See e.g. Vining and Boardman (2008, p. 153), Engel et al. (2013, 2014), Iossa and Martimort (2015, p. 29), and Buso et al. (2017).

and built (stage 1); subsequently, it has to be maintained and operated (stage 2). Before the first stage begins, the government has the choice between two different governance structures, traditional procurement (TP) and a public-private partnership (PPP). In the case of traditional procurement, the government contracts with one agent (the builder) in charge of stage 1 and with another agent (the operator) in charge of stage 2. In the case of a public-private partnership, the two tasks are bundled; i.e., the government contracts with only one agent (a consortium) that is in charge of both stages. We assume that all parties are risk-neutral, the agents are protected by limited liability, and their reservation utilities are zero.[18]

In the first stage, the agent in charge of designing and building the infrastructure can choose an unobservable effort level $E \in \{0, 1\}$ in order to come up with innovative ideas to improve the social value of the infrastructure. The verifiable outcome of the building stage is a success ($x = 1$) with probability pE and a failure ($x = 0$) otherwise, where $0 < p < 1$. Let the agent's disutility of effort be given by ψE, where $\psi > 0$.[19]

In the second stage, the agent in charge of operating and maintaining the infrastructure exerts unobservable effort $e \in [0, 1]$, incurring a disutility of effort given by $(1/2)e^2$. The second-stage effort aims at innovations to further increase the social value of providing the public good or service. The verifiable outcome of the operating stage is a success ($y = 1$) with probability e and a failure ($y = 0$) otherwise. Note that the effort level $e(x)$ chosen in the second stage can depend on the outcome x of the first stage.

The social benefits generated by the public good or service are given by $B_x + yb_x$. The benefits are net of the monetary and verifiable costs of building and operating

[18] The assumption that the reservation utilities are zero is made for expositional simplicity only. The results still hold if the reservation utilities are strictly positive but sufficiently small. Similar assumptions are often made in the related literature, see e.g. the recent work by Martimort and Straub (2016).

[19] It should be noted that the assumption $E \in \{0, 1\}$ is made only to simplify the exposition. The results still hold when $E \in [0, 1]$, since a corner solution is always optimal due to linearity. One could alternatively consider strictly convex effort costs, so that the government would have to leave a rent to the agent in charge of the building stage in order to motivate him to exert effort. However, we do not want to obfuscate the analysis by introducing first-stage rents. Instead, our focus will be on the implications of second-stage rents. The reason is that first-stage rents are simply sunk in the second stage, whereas anticipated second-stage rents can have economically interesting effects on the behavior in the first stage, which we want to isolate in the analysis.

the infrastructure, which are always reimbursed by the government. We assume that a successful innovation always increases the social value. Specifically, $B_1 > B_0 > 0$, so the benefits are larger when an innovative infrastructure was built in the first stage. Similarly, $b_0 > 0$ and $b_1 > 0$, so a second-stage innovation always increases the benefits from service provision. Note that the magnitude of the increase may depend on whether or not there was an innovation in the building stage. Moreover, we make the technical assumptions that $b_0 \leq 1$ and $b_1 \leq 1$. This normalization allows us to follow the usual convention that effort e can be directly interpreted as a success probability.[20] Furthermore, in order to focus the analysis on the economically most interesting case, we assume throughout that $\psi > (1/2)pb_1^2$, i.e. the first-stage effort costs are sufficiently large.[21] For simplicity, we assume throughout that there is no discounting.[22]

The sequence of events is illustrated in Figure 1. At the outset, the government chooses the organizational mode (traditional procurement or a public-private partnership). In the building stage, the agent who is in charge can exert unobservable effort E. Since the outcome is verifiable, it is feasible to contractually specify a payment T that the government must make to the agent whenever there was a success ($x = 1$). In the operating stage, the agent who is in charge can exert unobservable effort e. The outcome is again verifiable, so it is possible to contractually specify a payment t_x that has to be made from the government to the agent whenever there was a success ($y = 1$). Note that the amount to be paid for a second-stage innovation can depend on whether or not there was a first-stage innovation. Under traditional procurement, the government offers a contract (specifying T) to the builder at the outset, while it offers a contract (specifying t_x) to the operator at the beginning of the second stage. Under a public-private partnership, the government offers a contract (T, t_0, t_1) to the

[20] At the expense of a more involved notation, we could drop the normalization and instead assume that the success probability in the second stage is given by a strictly increasing and concave function $q(e)$ that lies between zero and one.

[21] In particular, the assumption ensures that the first-stage effort costs are not so trivially small that in case of a public-private partnership the consortium could be willing to exert high first-stage effort even in the absence of a direct reward for a first-stage innovation, just in order to increase the second-stage rent. Dragging this case along would complicate the exposition without yielding additional insights.

[22] This assumption is made in most papers on public-private partnerships, cf. the literature surveyed by Iossa and Martimort (2015).

consortium at the outset.[23] We will study the case in which the government has full commitment power as well as the case in which it cannot commit not to renege on the contract at the beginning of the operating stage.

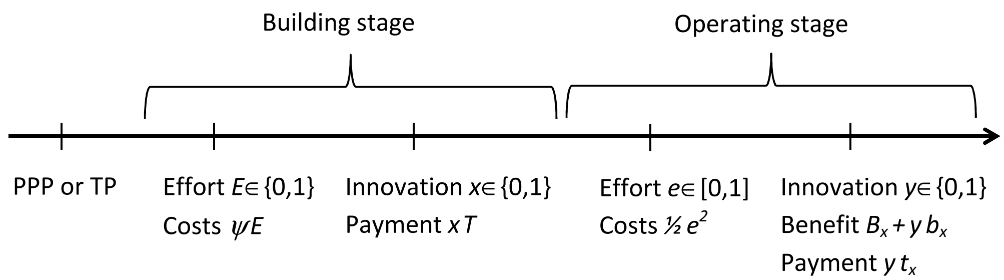

Figure 1. The sequence of events.

The first-best benchmark. Consider for a moment a first-best world in which the effort decisions are verifiable. The first-best effort level in the operating stage maximizes $eb_x - (1/2)e^2$. Hence, the marginal effort costs must be equal to the marginal benefit, $e^{FB}(x) = b_x$. In the building stage, it is first-best to choose high effort ($E = 1$) whenever

$$p[B_1 + \frac{1}{2}b_1^2] + (1-p)[B_0 + \frac{1}{2}b_0^2] - \psi \geq B_0 + \frac{1}{2}b_0^2. \tag{1}$$

The left-hand side is the expected total benefit net of effort costs given high effort in the building stage, while the right-hand side is the corresponding expression given low effort in the building stage. Hence, there is a cutoff value

$$\psi^{FB} := p[B_1 - B_0 + \frac{1}{2}b_1^2 - \frac{1}{2}b_0^2] \tag{2}$$

such that $E^{FB} = 1$ if $\psi \leq \psi^{FB}$ and $E^{FB} = 0$ otherwise.

[23] Note that we can confine our attention to contracts specifying non-negative payments T, t_0, t_1. Under traditional procurement, it is straightforward to see that it would never be optimal to make a strictly positive payment to an agent who was not successful. Moreover, nothing could be gained by making the builder's payment dependent on whether or not the operator is successful. Under a public-private partnership, in general we could allow for payments $\tau(x,y) \geq 0$ made to the consortium at the end of the operating stage. It is easy to see that $\tau(0,0) = 0$ is optimal. Moreover, we can denote $\tau(1,0)$ by T and $\tau(0,1)$ by t_0. Hence, by assuming that $\tau(1,1) = T + t_1$ and $t_1 \geq 0$, our only additional restriction on $\tau(x,y)$ is that $\tau(1,1) \geq \tau(1,0)$. It is straightforward to show that this constraint is never binding; i.e., given a first-period success the government never wants to specify a strictly larger payment for a second-stage failure than for a second-stage success.

If the effort levels were verifiable, the government would implement the first-best effort choices with a simple forcing contract that would in each stage reimburse the agent in charge for his effort costs. Thus, the government would be indifferent with regard to the bundling decision. Yet, in the remainder of the paper we assume that the effort choices are hidden actions. As a consequence, when we find that one of the two organizational forms is strictly preferred by the government, then this result must be due to incentive considerations only.

III. Traditional Procurement

We now investigate the incentive structure under traditional procurement. Consider first the operating stage, so the outcome of the building stage $x \in \{0, 1\}$ has already been realized. In the operating stage, given the contractually specified reward $t_x \leq 1$ for a second-stage innovation,[24] the operator maximizes his expected payoff $et_x - (1/2)e^2$. Thus, the operator chooses $e(x) = t_x$.

Anticipating the operator's effort choice, at the beginning of the second stage the government sets the reward t_x in order to maximize its expected payoff $e(x)[b_x - t_x] = t_x[b_x - t_x]$. Thus, the government will specify the payment $t_x^{TP} = (1/2)b_x$. Observe that the operator's expected rent $(1/2)t_x^2 = (1/8)b_x^2$ is increasing in the additional benefit generated by a second-stage innovation. Moreover, note that the government's second-stage payoff is $(1/4)b_x^2$.

Next, consider the building stage. Given that the reward T was contractually specified for a first-stage innovation, the builder will choose high effort ($E = 1$) whenever the incentive compatibility constraint $pT - \psi \geq 0$ is satisfied. Hence, the government sets $T^{TP} = \psi/p$ if it wants to induce high effort in the first stage, while it sets $T = 0$ otherwise.

It is optimal for the government to implement high effort in the first stage whenever

$$p[B_1 + \frac{1}{4}b_1^2 - \psi/p] + (1 - p)[B_0 + \frac{1}{4}b_0^2] \geq B_0 + \frac{1}{4}b_0^2, \tag{3}$$

i.e., whenever the expected social benefits net of the payments to the agents are larger in the case of high first-stage effort than in the case of low first-stage effort. Rewriting

[24] It is straightforward to verify that the government will never offer a reward larger than one, since the additional benefit generated by a second-stage innovation b_x is smaller than one.

the condition we find that the government implements $E = 1$ whenever $\psi \leq \psi^{TP}$, where

$$\psi^{TP} := p[B_1 - B_0 + \frac{1}{4}b_1^2 - \frac{1}{4}b_0^2]. \tag{4}$$

The preceding discussion can thus be summarized as follows.

Proposition 1 *Consider traditional procurement.*
(i) If $\psi \leq \psi^{TP}$, it is optimal for the government to set $t_0^{TP} = (1/2)b_0$, $t_1^{TP} = (1/2)b_1$, and $T^{TP} = \psi/p$. Then the builder will choose $E^{TP} = 1$ and the operator will choose $e^{TP}(1) = (1/2)b_1$, $e^{TP}(0) = (1/2)b_0$.
(ii) If $\psi > \psi^{TP}$, it is optimal for the government to set $t_0^{TP} = (1/2)b_0$, $t_1^{TP} = (1/2)b_1$, and $T^{TP} = 0$. Then the builder will choose $E^{TP} = 0$ and the operator will choose $e^{TP}(0) = (1/2)b_0$.

Note that when the government implements low effort in the building stage, there will be no first-stage success, so on the equilibrium path the payment t_1 is irrelevant if $\psi > \psi^{TP}$. Furthermore, observe that ψ^{TP} is smaller than ψ^{FB} whenever $b_0 < b_1$. Hence, the following result holds.

Corollary 1 *Consider traditional procurement.*
(i) In the building stage, $E^{TP} \leq E^{FB}$ if $b_0 < b_1$, while $E^{TP} \geq E^{FB}$ if $b_0 > b_1$.
(ii) In the operating stage, $e^{TP}(x) < e^{FB}(x)$ for $x \in \{0, 1\}$.

Compared to the benchmark case in which efforts are verifiable, unobservability of efforts leads to a smaller effort level in the second stage, since in this way the expected rent that must be left to the operator is reduced. In the building stage, there may be effort cost parameters ψ such that high effort would be chosen when efforts were verifiable, while only low effort is induced when efforts are hidden actions. This happens when $b_0 < b_1$, because in this case the second-stage rent is larger following a first-stage success, so from the government's perspective the value of a first-stage innovation is reduced. In contrast, if $b_0 > b_1$, there are cost parameters ψ such that low effort would be preferred when effort was verifiable, while high effort is induced when effort is unobservable. The reason is that in this case a larger second-stage rent must be paid following a first-stage failure, which from the government's perspective further increases the attractiveness of a first-stage success.

IV. Public-Private Partnership

Let us now analyze the incentive structure in case of a public-private partnership, assuming that the government can commit not to renege on the contractually specified payments. Suppose that the payments $t_0 \leq 1$ and $t_1 \leq 1$ have been contractually agreed upon.[25] In the second stage, following the first-stage outcome $x \in \{0, 1\}$, the consortium chooses the effort level e that maximizes its expected payoff $et_x - (1/2)e^2$. Thus, the consortium will exert effort $e(x) = t_x$. Observe that the consortium's expected second-stage rent is $(1/2)t_x^2$. Applying backward induction, we can now study the consortium's effort decision in the first stage. Given that the payment T was specified in the contract, the consortium prefers to exert high effort ($E = 1$) whenever

$$p[T + \frac{1}{2}t_1^2] + (1-p)\frac{1}{2}t_0^2 - \psi \geq \frac{1}{2}t_0^2, \tag{5}$$

i.e., whenever the consortium's expected payoff over the whole life of the project is larger if it exerts high instead of low effort in the building stage. This incentive compatibility constraint can be rewritten as

$$T \geq \psi/p - \frac{1}{2}t_1^2 + \frac{1}{2}t_0^2. \tag{6}$$

Anticipating the consortium's behavior, at the outset the government offers a contract (T, t_0, t_1) that maximizes the expected social benefits net of the payments made to the consortium,

$$pE[B_1 + t_1(b_1 - t_1) - T] + (1 - pE)[B_0 + t_0(b_0 - t_0)]. \tag{7}$$

In order to characterize the solution to the government's problem, let us define a threshold level of the first-stage effort costs,

$$\psi^{PPP} := p[B_1 - B_0 + \frac{1}{2}b_1^2 - \frac{1}{4}\frac{3-2p}{2-p}b_0^2]. \tag{8}$$

Then the solution under a public-private partnership can be summarized as follows.

Proposition 2 *Consider a public-private partnership and suppose the government has full commitment power.*

[25] It is again straightforward to verify that the government will never offer payments larger than one.

(i) If $\psi \leq \psi^{PPP}$, it is optimal for the government to set $t_0^{PPP} = (1-p)b_0/(2-p)$, $t_1^{PPP} = b_1$, and $T^{PPP} = \psi/p - (1/2)b_1^2 + \frac{1}{2}((1-p)b_0/(2-p))^2$. Then the consortium will choose $E^{PPP} = 1$ in the building stage and $e^{PPP}(1) = b_1$, $e^{PPP}(0) = (1-p)b_0/(2-p)$ in the operating stage.

(ii) If $\psi > \psi^{PPP}$, it is optimal for the government to set $t_0^{PPP} = (1/2)b_0$, $t_1^{PPP} = (1/2)b_1$, and $T^{PPP} = 0$. Then the consortium will choose $E^{PPP} = 0$ in the building stage and $e^{PPP}(0) = (1/2)b_0$ in the operating stage.

Proof. See the Appendix.

When the same agent is in charge of both stages, the government can make use of incentive spillovers from the second to the first stage. In the building stage, the consortium's effort decision will not only depend on the payment T for a first-stage success, but also on the expected rents that it may get in the second stage. Suppose the government wants to implement high first-stage effort. The government can indirectly reward the consortium for a first-stage success by implementing a relatively large second-stage effort (and thus a large rent) following $x = 1$, while it can punish the consortium for a first-stage failure by implementing a relatively small second-stage effort (and thus a small rent) following $x = 0$. Observe that according to Proposition 2(i), following a first-stage success the government implements the first-best effort level in the operating stage. While the expected rent could be further increased by specifying an even larger second-stage effort level, this would be an inefficient way to reward the consortium; i.e., it would be cheaper for the government to increase the direct reward T for a first-stage success.

Furthermore, note that $\psi^{PPP} > \psi^{FB}$, so there are first-stage effort cost parameters ψ such that in the building stage low effort would be chosen when efforts were verifiable, while high effort is chosen when they are unobservable. Intuitively, since the government must leave a rent to the consortium in order to induce second-stage effort, it would like to extract this rent from the consortium by an up-front payment. Yet, since negative payments are ruled out due to limited liability, utility may instead be transferred from the consortium to the government in an inefficient way only, namely by implementing an inefficiently large first-stage effort level.

These findings are summarized in the following result.

Corollary 2 *Consider a public-private partnership and suppose the government has full commitment power.*
(i) In the building stage, $E^{PPP} \geq E^{FB}$.
(ii) In the operating stage, $e^{PPP}(1) = e^{FB}(1)$ *and* $e^{PPP}(0) < e^{FB}(0)$ *if* $\psi \leq \psi^{PPP}$, *while* $e^{PPP}(0) < e^{FB}(0)$ *if* $\psi > \psi^{PPP}$.

V. Public-Private Partnership Versus Traditional Procurement

We can now analyze the government's choice between the two organizational modes. Propositions 1 and 2 immediately reveal that if the government implements low effort in the building stage, the second-stage effort level does not depend on the organizational form; i.e., in this case the government is indifferent between traditional procurement and a public-private partnership. However, when the government wants to implement high effort in the building stage, the two modes of provision lead to different agency costs.

Specifically, suppose that b_1 is larger than b_0, so under traditional procurement higher second-stage rents are earned by the operator after a first-stage success than after a first-stage failure. In this case it is clearly better to bundle the two tasks, because then the payment that is necessary to directly reward a first-stage success can be reduced. The reason is that in the building stage, the consortium already has an indirect incentive to exert effort, since a first-stage success leads to a larger rent in the second-stage.

In contrast, if b_1 is smaller than b_0, then under traditional procurement a larger second-stage rent is earned after a first-stage failure. At first glance, one might guess that in this case bundling would be undesirable, since the consortium would have an indirect incentive not to exert effort in the building stage, in order to avoid a first-stage success. However, this intuition is correct only if b_1 is much smaller than b_0. Otherwise, a public-private partnership can still outperform traditional procurement. To see this, observe that if the government implements high effort in the building stage, then compared to traditional procurement, under a public-private partnership the second-stage effort is larger in case of a first-stage success, $e^{PPP}(1) > e^{TP}(1)$, while it is smaller in case of a first-stage failure, $e^{PPP}(0) < e^{TP}(0)$. Hence, when the same agent is in charge of both stages, the government can commit to second-stage effort levels that are different from the ones implemented under traditional procurement in order to indirectly reward a first-stage success and punish a first-stage failure.

Let us now take a closer look at the government's expected payoffs under the two organizational modes. Under traditional procurement, Proposition 1 implies that high effort ($E = 1$) is implemented in the building stage whenever $\psi \leq \psi^{TP}$. In this case, the government's expected payoff is

$$G_H^{TP} = p[B_1 + \frac{1}{4}b_1^2] + (1-p)[B_0 + \frac{1}{4}b_0^2] - \psi. \tag{9}$$

Under a public-private partnership, Proposition 2 implies that high effort is implemented in the building stage whenever $\psi \leq \psi^{PPP}$. In this case, the government's expected payoff reads

$$G_H^{PPP} = p[B_1 + \frac{1}{2}b_1^2] + (1-p)[B_0 + \frac{1}{2}\frac{1-p}{2-p}b_0^2] - \psi. \tag{10}$$

Furthermore, under both modes of provision the government's expected payoff is given by

$$G_L = B_0 + \frac{1}{4}b_0^2 \tag{11}$$

when low effort is implemented in the building stage.

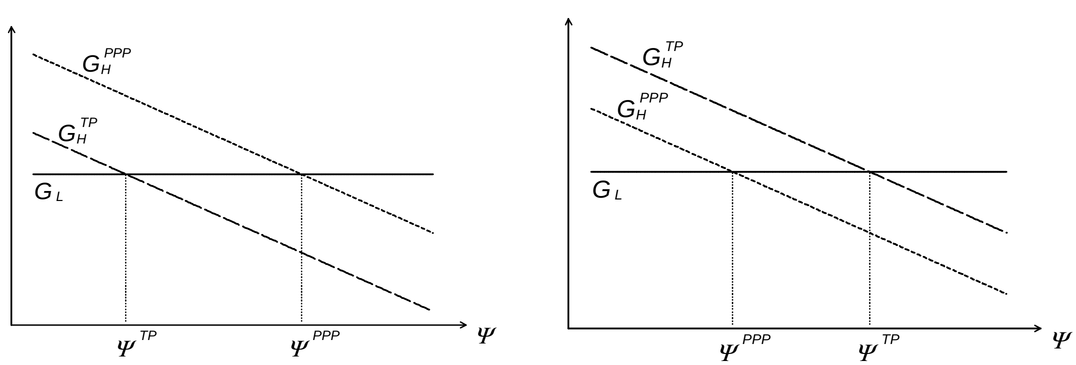

Figure 2. The government's expected payoff depending on the first-stage effort costs. In the left panel, $b_1^2 > (1-p)b_0^2/(2-p)$. In the right panel, $b_1^2 < (1-p)b_0^2/(2-p)$.

Figure 2 depicts the government's expected payoff depending on the first-stage effort costs ψ. In the left panel, the condition $b_1^2 > (1-p)b_0^2/(2-p)$ is satisfied.[26] This condition implies that $\psi^{PPP} > \psi^{TP}$ and $G_H^{PPP} > G_H^{TP}$ must hold. The government will implement high effort in the building stage whenever the effort costs ψ are smaller than ψ^{PPP} and in this case the government strictly prefers a public-private partnership.

In the right panel, the condition $b_1^2 < (1-p)b_0^2/(2-p)$ holds (i.e., a second-stage success is sufficiently more valuable when there was a first-stage failure). This condition implies $\psi^{PPP} < \psi^{TP}$ and $G_H^{PPP} < G_H^{TP}$, so whenever ψ is smaller than ψ^{TP} the government implements high effort in the building stage and strictly prefers traditional procurement.

Taken together, the following result holds.

Proposition 3 *Suppose the government has full commitment power.*
(i) If $b_1^2 > (1-p)b_0^2/(2-p)$ and $\psi < \psi^{PPP}$, the government strictly prefers a public-private partnership.
(ii) If $b_1^2 < (1-p)b_0^2/(2-p)$ and $\psi < \psi^{TP}$, the government strictly prefers traditional procurement.
(iii) Otherwise, the government is indifferent between the two modes of provision.

VI. Renegotiation

Public-Private Partnership Versus Traditional Procurement Reconsidered

So far, we have assumed that the government can commit not to renege on the contractually specified payments.[27] We now relax this assumption and explore what will

[26] Note that this condition always holds when $b_1 > b_0$; i.e., when a second-stage success is more valuable in case of a first-stage success.

[27] It should be noted that renegotiation has often been studied in traditional moral hazard models with a risk-averse agent. In such a framework, renegotiation is an important issue even in a one-shot problem, because after the agent has chosen the effort level, there is no need to expose the agent to further risk. Fudenberg and Tirole (1990), Ma (1994), and Matthews (1995) demonstrate that it depends on the details of the renegotiation game whether or not effort incentives are reduced when renegotiation cannot be ruled out. In contrast, in a framework with risk-neutral agents, there is scope for renegotiation only in the case of a dynamic moral hazard problem with sequential effort choices.

happen if mutually beneficial renegotiation at the beginning of the operating stage cannot be prevented.[28] In the case of traditional procurement the analysis remains unchanged, since two different parties are in charge of the two stages and hence the government has no reason to ex ante commit to a second-stage contract that it would want to renege on after the building stage is finished. However, in case of a public-private partnership, ex ante the government wants to commit to second-stage payments that affect the consortium's second-stage incentives as well as its first-stage incentives. Once it is known whether or not there was a success in the building stage, the government is interested only in the consortium's incentives in the operating stage and thus the government might want to renege on the original contract.

Specifically, consider a public-private partnership and suppose that $\psi \leq \psi^{PPP}$, so that the government would implement high first-stage effort ($E = 1$) if renegotiation could be ruled out. According to Proposition 2, under full commitment the contract specifies $t_1^{PPP} = b_1$, so that following a first-stage innovation the second-stage effort level is $e^{PPP}(1) = b_1$. Yet, when there was a first-stage success, then at the beginning of the second stage the government would prefer to implement only $e(1) = \frac{1}{2}b_1$ in order to reduce the expected second-stage rent, as we have seen in the analysis of the operating stage under traditional procurement. However, if the government tried to renege on the agreed-upon contract by reducing the payment for a second-stage innovation, the consortium would not give in. The consortium would insist on the original contract, since otherwise its expected rent would be reduced. Hence, there is no scope for mutually beneficial renegotiation when there was a first-stage success.

Now suppose that there was no innovation in the building stage. According to Proposition 2, for this case the contract under full commitment specifies $t_0^{PPP} = (1 - p)b_0/(2 - p)$. As a consequence, the consortium would choose the second-stage effort level $e^{PPP}(0) = (1 - p)b_0/(2 - p)$, while at the beginning of the operating stage the government would prefer to implement the effort level $e(0) = (1/2)b_0$, as we know from the analysis of traditional procurement. Clearly, when the government offers to increase the payment for a second stage innovation to $t_0 = (1/2)b_0$, the consortium will accept

[28]Several authors have pointed out that renegotiation is an important problem in the context of public-private partnerships, see e.g. the recent contributions by Henckel and McKibbin (2017) and Ahmad et al. (2018).

the offer, since then its expected rent will be larger. Therefore, the outcome described in Proposition 2 is no longer sustainable when mutually beneficial renegotiation cannot be prevented.

To characterize the solution to the government's problem when renegotiation cannot be ruled out, let us define a new threshold level of the first-stage effort costs,

$$\hat{\psi}^{PPP} := p[B_1 - B_0 + \frac{1}{2}b_1^2 - \frac{3}{8}b_0^2]. \tag{12}$$

Applying the renegotiation-proofness principle, we can without loss of generality focus on contracts that are not renegotiated in equilibrium.[29] We thus obtain the following result.

Proposition 4 *Consider a public-private partnership and suppose that mutually beneficial renegotiation cannot be prevented.*
(i) If $\psi \leq \hat{\psi}^{PPP}$*, it is optimal for the government to set* $t_0^{PPP} = (1/2)b_0$*,* $t_1^{PPP} = b_1$*, and* $T^{PPP} = \psi/p - (1/2)b_1^2 + (1/8)b_0^2$*. Then the consortium will choose* $E^{PPP} = 1$ *in the building stage and* $e^{PPP}(1) = b_1$*,* $e^{PPP}(0) = (1/2)b_0$ *in the operating stage.*
(ii) If $\psi > \hat{\psi}^{PPP}$*, it is optimal for the government to set* $t_0^{PPP} = (1/2)b_0$*,* $t_1^{PPP} = (1/2)b_1$*, and* $T^{PPP} = 0$*. Then the consortium will choose* $E^{PPP} = 0$ *in the building stage and* $e^{PPP}(0) = (1/2)b_0$ *in the operating stage.*

Proof. See the Appendix.

Observe that the government still rewards the consortium for a first-stage success by implementing a larger second-stage effort level in this case than it would do under traditional procurement. However, when renegotiation cannot be ruled out the government loses its possibility to punish the consortium for a first-stage failure by implementing a smaller second-stage effort level than under traditional procurement. As a consequence, given that high first-stage effort is implemented, the government's expected payoff is smaller when renegotiation cannot be prevented than in the case of full commitment.[30]

[29] See Hart and Tirole (1988) for more on the renegotiation-proofness principle. Intuitively, the allocation that would result from renegotiation can already be specified in the original contract, so there is no need to consider contracts that are renegotiated on the equilibrium path.

[30] It should be noted that even when renegotiation cannot be ruled out, the government still makes

The new threshold value $\hat{\psi}^{PPP}$ satisfies $\psi^{FB} < \hat{\psi}^{PPP} < \psi^{PPP}$. High effort in the building stage is now implemented for a smaller range of first-stage effort costs compared to the case of a public-private partnership where the government has full commitment power. Yet, the impossibility to prevent renegotiation does not qualitatively change the comparison with the first-best benchmark where efforts are verifiable.

Corollary 3 *Consider a public-private partnership and suppose that mutually beneficial renegotiation cannot be prevented.*
(i) In the building stage, $E^{PPP} \geq E^{FB}$.
(ii) In the operating stage, $e^{PPP}(1) = e^{FB}(1)$ *and* $e^{PPP}(0) < e^{FB}(0)$ *if* $\psi \leq \hat{\psi}^{PPP}$, *while* $e^{PPP}(0) < e^{FB}(0)$ *if* $\psi > \hat{\psi}^{PPP}$.

Let us now turn to the comparison between the two organizational modes. When renegotiation cannot be ruled out, Proposition 4 implies that under a public-private partnership high effort is implemented in the building stage whenever $\psi \leq \hat{\psi}^{PPP}$. In this case, the government's expected payoff reads

$$\hat{G}_H^{PPP} = p[B_1 + \frac{1}{2}b_1^2] + (1-p)[B_0 + \frac{1}{8}\frac{2-3p}{1-p}b_0^2] - \psi, \tag{13}$$

which is smaller than G_H^{PPP}. Otherwise, the government's expected payoffs remain unchanged.

Suppose now that the condition $b_1^2 > (1/2)b_0^2$ holds, which is always the case if a second-stage innovation is more valuable when there also was a first-stage innovation. Then $\hat{\psi}^{PPP} > \psi^{TP}$ and $\hat{G}_H^{PPP} > G_H^{TP}$ hold. Hence, the government implements high first-stage effort whenever the effort costs ψ are smaller than $\hat{\psi}^{PPP}$ and in this case the government strictly prefers a public-private partnership. Next, suppose that the condition $b_1^2 < (1/2)b_0^2$ is satisfied, so a second-stage innovation is sufficiently more valuable when there was no first-stage innovation. Then $\hat{\psi}^{PPP} < \psi^{TP}$ and $\hat{G}_H^{PPP} < G_H^{TP}$ hold. Thus, whenever ψ is smaller than ψ^{TP}, the government implements high first-stage effort and strictly prefers traditional procurement.

Taken together, the parameter range where a public-private partnership is optimal is now smaller than in the case of full commitment.

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use of history-dependent contracts. Hence, our model illustrates that limited commitment power does not invalidate the insight of the repeated moral hazard literature that optimal contracts exhibit memory.

Proposition 5 *Suppose that mutually beneficial renegotiation cannot be prevented.*
(i) If $b_1^2 > (1/2)b_0^2$ and $\psi < \hat{\psi}^{PPP}$, the government strictly prefers a public-private partnership.
(ii) If $b_1^2 < (1/2)b_0^2$ and $\psi < \psi^{TP}$, the government strictly prefers traditional procurement.
(iii) Otherwise, the government is indifferent between the two modes of provision.

Project Choice

We now investigate implications that the impossibility to rule out renegotiation in case of a public-private partnership may have with regard to the initial choice of a public project. Suppose that at the outset, the government has the choice between two different projects I and II. In what follows, we assume that $b_0^I > b_0^{II}$, while the projects are identical otherwise. Hence, the two projects differ only in the value of a second-stage innovation when there was no first-stage success. This value is larger in case of project I, which means that project I is the technologically superior project.[31]

If the government implements low first-stage effort (so that the organizational mode does not matter) or if the government opts for traditional procurement, it is obvious that it will never choose the technologically inferior project II. To see this formally, observe that G_L and G_H^{TP} are increasing in b_0. Moreover, in case of a public-private partnership the government always prefers project I when it has full commitment power, since also G_H^{PPP} is increasing in b_0.

Now consider a public-private partnership and suppose that renegotiation cannot be prevented. Recall that when high first-stage effort is implemented, the government's expected payoff as a function of b_0 is given by

$$\hat{G}_H^{PPP}(b_0) = p[B_1 + \frac{1}{2}b_1^2] + (1-p)[B_0 + \frac{1}{8}\frac{2-3p}{1-p}b_0^2] - \psi. \tag{14}$$

Observe that when the probability of a first-stage success given high first-stage effort is relatively large, then the government's expected payoff is decreasing in b_0. Specifically, $\hat{G}_H^{PPP}(b_0^{II}) > \hat{G}_H^{PPP}(b_0^I)$ whenever $p > 2/3$.

[31] We focus on two projects that differ only with regard to b_0 in order to clearly isolate the reason why an inferior project may be chosen by the government. Yet, by continuity it is straightforward to verify that the inferior project II may be chosen even if in addition to $b_0^I > b_0^{II}$ also $B_1^I > B_1^{II}$, $B_0^I > B_0^{II}$, and $b_1^I > b_1^{II}$ hold.

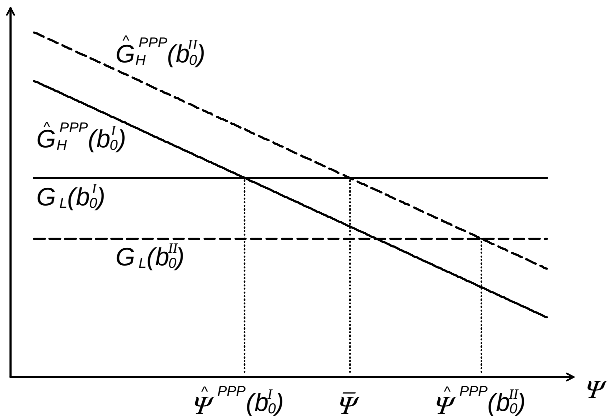

Figure 3. Choice between projects I and II with $b_0^I > b_0^{II}$, when $p > 2/3$.

As an illustration consider Figure 3, which depicts the government's expected payoff from a given project depending on the first-stage effort costs. The solid curves refer to the technologically superior project I, while the dashed curves refer to the technologically inferior project II. Recall that when low first-stage effort is implemented, the government's expected payoff as a function of b_0 is given by $G_L(b_0) = B_0 + (1/4)b_0^2$. In each project, high first-stage effort is implemented when the first-stage effort costs are sufficiently small, $\psi \leq \hat{\psi}^{PPP}(b_0) = p[B_1 - B_0 + (1/2)b_1^2 - (3/8)b_0^2]$. Note that $\hat{\psi}^{PPP}(b_0^I) < \hat{\psi}^{PPP}(b_0^{II})$ must hold. When low first-stage effort is implemented, the government prefers project I, since $G_L(b_0^I)$ is larger than $G_L(b_0^{II})$. Yet, when high first-stage effort is implemented, the government prefers project II, given that $p > 2/3$. Hence, there exits a threshold value $\bar{\psi}$ such that the government chooses the technologically *inferior* project whenever the first-stage effort costs are smaller than $\bar{\psi}$.

Proposition 6 *Consider a public-private partnership and suppose that mutually beneficial renegotiation cannot be prevented.*
(i) If $p < 2/3$, the government chooses the technologically superior project I.
(ii) If $p > 2/3$, there exists a cutoff-value $\bar{\psi} \in (\hat{\psi}^{PPP}(b_0^I), \hat{\psi}^{PPP}(b_0^{II}))$ such that the government chooses project I if $\psi > \bar{\psi}$, while it chooses the technologically inferior project II if $\psi < \bar{\psi}$.

Proof. See the Appendix.

Intuitively, the government may prefer the technologically inferior project II because a smaller b_0 means that there is less scope for renegotiation. Recall that when renegotiation cannot be prevented the government loses its ability to punish the consortium for a first-stage failure by implementing a very small second-stage effort. This is less of a problem when b_0 is small, since then the second-stage effort (and hence the consortium's expected second-stage rent) following a first-stage failure will be small anyway; i.e., renegotiation has less bite. However, choosing the technologically inferior project can be optimal only if the probability p is relatively large, so the probability that b_0 will actually become relevant on the equilibrium path is relatively small.

Finally, regarding the choice between a public-private partnership and traditional procurement, it should be noted that the preceding findings imply that the availability of a technologically inferior project can increase the parameter range for which the government prefers a public-private partnership. In particular, the following result holds.

Corollary 4 *Suppose that mutually beneficial renegotiation cannot be prevented, $p > 2/3$, and $\psi < \bar{\psi}$.*
(i) If only project I is available, the government strictly prefers a public-private partnership over traditional procurement whenever $b_1^2 > (1/2)(b_0^I)^2$.
(ii) If in addition the technologically inferior project II becomes available, the government chooses project II and strictly prefers a public-private partnership over traditional procurement whenever $b_1^2 > ((1-p)/p)(b_0^I)^2 + ((3p-2)/(2p))(b_0^{II})^2$.

Proof. See the Appendix.

VII. Concluding Remarks

The relatively new organizational form of public-private partnerships was promoted to foster incentives to innovate, such that increased quality would be achieved at lower costs. However, after more than 20 years of experience we observe mixed evidence regarding innovation incentives within public-private partnerships. Our model explains in a unified framework that compared to traditional procurement, a public-private partnership may indeed either foster or stifle innovation incentives, depending on whether successes in the two stages are of a complementary or of a substitutive nature.

In contrast to earlier contributions to the literature on public-private partnerships that was initiated by Hart (2003), in our model the operating costs (as well as the success probability in the operating stage) are technologically independent of the effort invested in the building stage.[32] Instead, in our moral hazard setting future expected rents in the operating stage can increase or decrease incentives to innovate in the building stage. Thus, from the consortium's perspective an externality between the stages is endogenously created only if the government conditions payments in the operating stage on the outcome of the building stage.[33] Therefore, in our model there is a single force working in two ways. The costs and benefits of bundling the building and operating tasks in a public-private partnership are two sides of the same coin, since in each case they stem from the intricate effects that expected rents have on the prevailing incentive structure.

Specifically, it turns out that if a first-stage innovation increases the social value of a second-stage innovation (i.e., successful outcomes of the two stages are complements), then bundling the tasks in a public-private partnership reduces the agency costs. In contrast, if a first-stage innovation reduces the social value of a second-stage innovation (i.e., successful outcomes of the two stages are substitutes), then in a public-private partnership the consortium may face strategic reasons *not* to exert effort in the building stage, in order to extract a larger rent in the provision stage. Moreover, we find that the impossibility to rule out mutually beneficial renegotiations reduces the advantages of bundling and that in this case a public-private partnership may even lead the government to opt for a technologically *inferior* project.[34]

We hope that the insights gained by our analysis will help to spur further empirical research on the important topic of innovations in public infrastructure projects.[35] In

[32] We have not introduced such externalities into our model since their effects have already been studied in the literature and in order to make clear that we identify a separate force that may also be relevant when comparing public-private partnerships to traditional procurement.

[33] Note that our setup is thus different from and complementary to Martimort and Straub's (2016) recent work on moral hazard in public-private partnerships, since they rule out second-stage payments that depend on the first-stage outcome.

[34] Note that this result identifies a potential selection bias that should be taken care of in the empirical literature, since it could affect the assessment of the performance of public-private partnerships compared to traditional procurement.

[35] As has been pointed out by Iossa and Martimort (2015, p. 40), in spite of the policy relevance, still relatively little research has been carried out on public-private partnerships. In particular, the empirical literature on innovations in public-private partnerships (cf. footnote 3 above) is still scarce,

particular, a testable implication of our analysis is that the complementary or substitutive nature of successful outcomes of the building and operating stages should have an impact on the choice of the organizational form. Moreover, from a contract-theoretic perspective, our model could be extended in several directions. For example, following most of the theoretical literature on public-private partnerships, we have abstracted from agency problems within the consortium and we have focused our analysis on the relationship between the government and a given consortium. Exploring the interactions of internal agency problems and of the award procedure with the incentive effects identified in the present paper might be interesting avenues for future research.[36]

so much more work needs to be done on that front.

[36] Regarding agency problems within consortia, see Greco (2015) for an analysis of imperfect bundling in an incomplete contracting model based on Hart (2003) and Bennett and Iossa (2006). With regard to award procedures, see Li et al. (2015) who study the bundling of tasks in procurement auctions where the firms have private information about their costs.

Appendix

Proof of Proposition 2. The government offers a contract (T, t_0, t_1) to the consortium in order to maximize its expected payoff

$$pE[B_1 + t_1(b_1 - t_1) - T] + (1 - pE)[B_0 + t_0(b_0 - t_0)] \tag{A1}$$

subject to the constraint that in the building stage the consortium will choose high effort ($E = 1$) if $T \geq \psi/p - (1/2)t_1^2 + (1/2)t_0^2$, while it will choose low effort otherwise.

If the government wants to implement high effort in the building stage, it sets $T = \psi/p - (1/2)t_1^2 + (1/2)t_0^2$ and chooses the payments t_0 and t_1 that maximize

$$p[B_1 + t_1 b_1 - \frac{1}{2}t_1^2 - \frac{1}{2}t_0^2] + (1 - p)[B_0 + t_0(b_0 - t_0)] - \psi. \tag{A2}$$

Hence, in this case the optimal contract is given by $t_1^{PPP} = b_1$, $t_0^{PPP} = (1-p)b_0/(2-p)$, and $T^{PPP} = \psi/p - (1/2)b_1^2 + \frac{1}{2}((1-p)b_0/(2-p))^2$. Observe that under our assumption $\psi > (1/2)pb_1^2$ the limited liability constraint $T^{PPP} \geq 0$ is satisfied.

If the government wants to implement low effort in the building stage, it sets $T = 0$ and chooses the payment t_0 that maximizes $B_0 + t_0(b_0 - t_0)$. Thus, in this case the optimal contract must satisfy $t_0^{PPP} = (1/2)b_0$ and $T^{PPP} = 0$. Note that in order to satisfy the constraint $T < \psi/p - (1/2)t_1^2 + (1/2)t_0^2$, the government can specify any t_1 such that $(1/2)t_1^2 < \psi/p + (1/8)b_0^2$. Under the assumption that $\psi > (1/2)pb_1^2$, the government can thus set $t_1^{PPP} = (1/2)b_1$, which would be the optimal payment off the equilibrium path.

Comparing the two cases, we see that the government prefers to induce high effort in the building stage whenever

$$p[B_1 + \frac{1}{2}b_1^2] + (1 - p)[B_0 + \frac{1}{2}\frac{1-p}{2-p}b_0^2] - \psi \geq B_0 + \frac{1}{4}b_0^2 \tag{A3}$$

holds. This condition can be rewritten as

$$\psi \leq p[B_1 - B_0 + \frac{1}{2}b_1^2 - \frac{1}{4}\frac{3-2p}{2-p}b_0^2], \tag{A4}$$

which completes the proof of the proposition. □

Proof of Proposition 4. Given that the payments $t_0 \leq 1$ and $t_1 \leq 1$ have been contractually agreed upon, in the operating stage the consortium will maximize its expected stage-2 payoff $et_x - (1/2)e^2$ and thus exert effort $e(x) = t_x$. Recall from our analysis of traditional procurement that at the beginning of the operating stage, the government would like to set $t_x = (1/2)b_x$. Due to concavity of the government's payoff, at the beginning of the operating stage the government would like to reduce t_x when in the original contract it was larger than $(1/2)b_x$, while the government would like to increase t_x when in the original contract it was smaller than $(1/2)b_x$. Since the consortium's expected second-stage rent $(1/2)t_x^2$ is increasing in t_x, the consortium will accept a renegotiation offer at the beginning of the operating stage whenever the payment is larger than in the original contract. Hence, the original contract must satisfy $t_x \geq (1/2)b_x$ to be renegotiation-proof. In the building stage, given that the payment T was specified in the contract, the consortium exerts high effort ($E = 1$) whenever $p[T + (1/2)t_1^2] + (1-p)(1/2)t_0^2 - \psi \geq (1/2)t_0^2$.

Thus, if the government wants to implement $E = 1$, it proposes a contract (T, t_0, t_1) to the consortium in order to maximize its expected payoff

$$p[B_1 + t_1(b_1 - t_1) - T] + (1-p)[B_0 + t_0(b_0 - t_0)] \tag{A5}$$

subject to the incentive-compatibility constraint $T \geq \psi/p - (1/2)t_1^2 + (1/2)t_0^2$ and the renegotiation-proofness constraints $t_0 \geq (1/2)b_0$ and $t_1 \geq (1/2)b_1$. Applying the Kuhn-Tucker Theorem (see e.g. Dixit, 1990), the solution to the government's problem maximizes the Lagrangian

$$\begin{aligned} &p[B_1 + t_1(b_1 - t_1) - T] + (1-p)[B_0 + t_0(b_0 - t_0)] \\ &+\lambda_0(t_0 - \frac{1}{2}b_0) + \lambda_1(t_1 - \frac{1}{2}b_1) + \lambda_2(T - \psi/p + \frac{1}{2}t_1^2 - \frac{1}{2}t_0^2), \end{aligned} \tag{A6}$$

where $\lambda_0 \geq 0$, $\lambda_1 \geq 0$, and $\lambda_2 \geq 0$. Hence, $p(b_1 - 2t_1) + \lambda_1 + \lambda_2 t_1 = 0$, $(1-p)[b_0 - 2t_0] + \lambda_0 - \lambda_2 t_0 = 0$, and $-p + \lambda_2 = 0$ must hold. Moreover, the complementary slackness conditions $\lambda_0(t_0 - (1/2)b_0) = 0$, $\lambda_1(t_1 - (1/2)b_1) = 0$, and $\lambda_2(T - \psi/p + (1/2)t_1^2 - (1/2)t_0^2) = 0$ must be satisfied. Observe that $\lambda_2 = p > 0$ implies that $T = \psi/p - (1/2)t_1^2 + (1/2)t_0^2$. Next, suppose that $\lambda_0 = 0$ would hold. Then $(1-p)[b_0 - 2t_0] + \lambda_0 - \lambda_2 t_0 = 0$ and $\lambda_2 = p$ would imply $t_0 = (1-p)b_0/(2-p)$, which would violate the constraint $t_0 \geq (1/2)b_0$. Therefore the constraint is binding; i.e., $\lambda_0 > 0$ and $t_0^{PPP} = (1/2)b_0$ must hold. Moreover, observe that $\lambda_1 > 0$ would imply $t_1 = (1/2)b_1$, but then $p(b_1 - 2t_1) + \lambda_1 + \lambda_2 t_1 = 0$ and $\lambda_2 = p$ would imply $\lambda_1 < 0$. Hence, $\lambda_1 = 0$

and $t_1^{PPP} = b_1$ must hold. Finally, observe that under our assumption $\psi > (1/2)pb_1^2$ it is ensured that $T^{PPP} = \psi/p - (1/2)b_1^2 + (1/8)b_0^2$ is positive.

If the government wants to implement $E = 0$, it sets $T^{PPP} = 0$ and $t_0^{PPP} = (1/2)b_0$, which maximizes $B_0 + t_0(b_0 - t_0)$. To satisfy the constraint $T < \psi/p - (1/2)t_1^2 + (1/2)t_0^2$, under our assumption $\psi > (1/2)pb_1^2$ the government can specify $t_1^{PPP} = (1/2)b_1$. Note that the contract is renegotiation-proof.

A comparison of the government's expected payoffs implies that the government implements $E = 1$ whenever

$$p[B_1 + \frac{1}{2}b_1^2] + (1-p)[B_0 + \frac{1}{8}\frac{2-3p}{1-p}b_0^2] - \psi \geq B_0 + \frac{1}{4}b_0^2 \tag{A7}$$

is satisfied. Thus, the government implements high effort in the building stage whenever

$$\psi \leq p[B_1 - B_0 + \frac{1}{2}b_1^2 - \frac{3}{8}b_0^2], \tag{A8}$$

so the proposition must hold. $\square$

Proof of Proposition 6. Recall that $b_0^I > b_0^{II}$ implies $G_L(b_0^I) > G_L(b_0^{II})$. Hence, part (i) of the proposition immediately follows from the fact that $\hat{G}_H^{PPP}(b_0^I) > \hat{G}_H^{PPP}(b_0^{II})$ when $p < 2/3$. Now consider part (ii) of the proposition. Recall that $p > 2/3$ implies $\hat{G}_H^{PPP}(b_0^{II}) > \hat{G}_H^{PPP}(b_0^I)$. Hence, while the government prefers project I when it implements low first-stage effort, it prefers project II when it implements high first-stage effort. The government thus implements high first-stage effort whenever $\hat{G}_H^{PPP}(b_0^{II}) \geq G_L(b_0^I)$. This condition can be rewritten as $\psi \leq \bar{\psi}$, where

$$\bar{\psi} := p[B_1 - B_0 + \frac{1}{2}b_1^2 - \frac{3p-2}{8p}(b_0^{II})^2 - \frac{1}{4p}(b_0^I)^2]. \tag{A9}$$

It is straightforward to verify that the cutoff-value $\bar{\psi}$ satisfies the condition $\hat{\psi}^{PPP}(b_0^I) < \bar{\psi} < \hat{\psi}^{PPP}(b_0^{II})$. $\square$

Proof of Corollary 4. Part (i) of the corollary follows immediately from Propositions 5 and 6. Now consider part (ii) of the corollary. We already know that the government prefers project I in case of traditional procurement. Given a public-private partnership, the government prefers project II if it wants to implement high first-stage effort, while it prefers project I otherwise. Hence, the government chooses the technologically inferior project II and a public-private partnership if

$$\hat{G}_H^{PPP}(b_0^{II}) > G_H^{TP}(b_0^I) = p[B_1 + \frac{1}{4}b_1^2] + (1-p)[B_0 + \frac{1}{4}(b_0^I)^2] - \psi \tag{A10}$$

and $\hat{G}_H^{PPP}(b_0^{II}) > G_L(b_0^I)$. The latter condition is satisfied since by assumption $\psi < \bar{\psi}$. The former condition can be rewritten as

$$b_1^2 > \frac{1-p}{p}(b_0^I)^2 + \frac{3p-2}{2p}(b_0^{II})^2. \tag{A11}$$

Observe that $p > 2/3$ implies

$$\frac{1-p}{p}(b_0^I)^2 + \frac{3p-2}{2p}(b_0^{II})^2 < \frac{1}{2}(b_0^I)^2, \tag{A12}$$

so a public-private partnership is preferred for a larger parameter range when project II is available. □

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