Holdups, Quality Choice, and the Achilles' Heel in Government Contracting

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Abstract

This paper investigates a procurement relationship between a welfare-oriented government and a private supplier. The parties face several trading opportunities which differ in quality and production costs, and the differences between goods are undescribable ex ante. In presence of this 'quality-choice problem', no initial contract may induce efficient cost-reducing investments of the supplier. In contrast, a first-best result is always attainable in private procurement where the buyer maximizes profit rather than welfare. We identify the government's welfare goal as its Achilles' heel: equilibrium trade prices differ in public and private procurement, and private governance can lead to more efficient investment decisions even though renegotiation ensures the ex-post efficient trade decision in either regime.

Keywords: Procurement, Incomplete Contracts, Governance Structure.

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1 Introduction

Inefficiencies in government behavior are a real-world phenomenon. A large number of empirical studies report evidence that the private sector is more capable of providing efficient quality and cost control in the provision of goods and services. Despite the widespread agreement among politicians and economists on that account,[1] however, economic theory still has considerable difficulties in finding convincing explanations for the superiority of private economic performance: why should a civil servant or politician necessarily do worse than a private manager? The theoretical literature on this subject mostly argues that the observed inefficiencies arise from the self-interested goals of public officials.[2] While we do not doubt that a pessimistic view of government is often justified, one should note that a similar reasoning could be applied to the private sector: after all, corporate executives in private firms may - and often do - pursue their own agendas as well. Hence, it may be interesting to address the more fundamental question of why even a benevolent public agent may do worse than its private counterpart.

The present paper aims to identify such a reason in the context of a long-term procurement relationship between a government agency and a private contractor. We maintain the assumption that the government acts so as to maximize welfare, i.e. that the control mechanisms to which voters have access are sufficient to ensure that the interests of the general public and the government agency are aligned. The procurement process is modeled as a two-stage game where the private contractor engages in relationship-specific investments (research and development) in the first stage which increase the expected net benefits of a good to be purchased by a government in the second stage. At this production and trade stage, the government and the seller face several tradeable goods which differ in quality and production costs, only one of which is the efficient version. We find that the benevolent government may be unable to assign efficient investment incentives to the private contractor. Conversely, in private procurement where the buyer is a selfish profit maximizer, efficient investments and a first-best outcome are shown to be feasible in an otherwise identical environment. A private principal can thus outperform a public principal even if government is interpreted as a purely benevolent entity.

Following the incomplete-contracts approach, we assume that the initial contract must

[1] The recent privatization waves in most industrialized countries, for instance, have been pursued mainly as a reaction to the observed mismanagement in publicly owned firms. Among others, Galal et al. (1992) and Megginson et al. (1994) provide evidence that privatization increases a firm's operating performance.

[2] See, for example, Shapiro and Willig (1990) and Shleifer and Vishny (1994).

remain vague on certain important issues.[3] While both partners have complete information, neither costs and valuations of the trading goods nor the supplier's cost reducing investments are verifiable. In addition, the exact characteristics of the good to be traded ex post cannot be contracted upon ex ante.[4] This initial inability to precisely describe the attributes of the trading good gives rise to what we call a quality-choice problem: at any given trade price, the supplier prefers to produce a basic, low-cost (and low-quality) variant, whereas the buyer prefers delivery of a more costly high-quality version. We show that these antagonistic interests yield a reason for renegotiation and for a contract revision after investments have been expended and uncertainty has been resolved.[5] Besides, the non-contractibility of quality has an important impact on the contract that should be written at an ex-ante stage. While a fixed-price or specific-performance contract would yield efficiency in the absence of a quality-choice problem, a simple 'at-will' contract which forces neither party in subsequent trade is preferable in our setting.[6]

The paper thus asks whether there exists an initial at-will contract under which the seller exerts optimal investments. Doing so, we can build on previous work. In a simpler framework with only one good (so that no quality-choice problem arises), Hart and Moore (1988) have shown that in a private trade relationship a properly chosen at-will contract implements the first best if and only if just one party undertakes specific investments. Applying this model to public procurement, Bös and Lülfesmann (1996) find that this change in the buyer's objective may facilitate the first best even if both parties invest. Intuitively, a benevolent government has intrinsic preferences for a welfare-optimal outcome so that it will exert the first-best effort even if the entire marginal investment return flows

[3]See, among others, Hart and Moore (1988), Aghion, Dewatripont and Rey (1994), Nöldeke and Schmidt (1995), and Edlin and Reichelstein (1996). For an early paper which applies the incomplete-contracting methodology to public procurement, see Tirole (1986).

[4]See Aghion and Tirole (1994, 1997), Hart (1995), Hart and Moore (1999) and Segal (1999) for similar assumptions. Hart et al. (1997) investigate the privatization of public services when quality is undescribable.

[5]This feature is especially prominent in the weapons-acquisition process: the characteristics of a new combat aircraft can only roughly be specified prior to its development and the supplier may declare an old design to be a real innovation. Indeed, arguments about product quality are notorious in military procurement where governments often complain that the delivered good does not meet particular quality requirements. Judicial decisions are ambiguous in this respect, which indicates that initial contracts were not, and could not be, comprehensively written.

[6]See Lülfesmann (2001). In fact, we will assume that the court cannot find out which party is responsible if final trade fails, so that an at-will contract not only dominates fixed-price contracts but is indeed optimal (Hart and Moore, 1988).

to the seller. As should be expected, public procurement is thus (at least weakly) more efficient. In sharp contrast to this intuition, the present paper demonstrates that the presence of multiple goods and a quality choice problem can *reverse* the welfare implications of public and private procurement. Specifically, while efficient one-sided investments remain generically feasible in private procurement (Lülfesmann, 2001), underinvestment in public procurement may be unavoidable.

The following simple example illustrates some of the arguments which are made more thoroughly in our formal model. If a benevolent government is exclusively interested in allocative efficiency (that is, if shadow costs of public funds are almost negligible), it cannot credibly commit to accept the delivery of a low-quality 'basic' good if trading this item is welfare improving relative to no trade. If it is more efficient to procure a high-quality 'innovative' good because it has a higher net value, renegotiation prevails and an efficient trade decision is taken in equilibrium. However, since the supplier's default payoff is determined by the payoff which he can reap from trading the basic good and he has to share (at least) part of the bargaining gain with the government, he will underinvest in the innovative version. Conversely, a private buyer will not accept delivery of the basic good if the trade price exceeds her gross benefit, and renegotiation is not needed for efficient trade of the high-quality item. Her profit objective gives a private buyer an intrinsic commitment not to accept low quality, which raises the seller's investment incentives and can improve the overall outcome. Accordingly, the government's inability to refuse valuable low-quality goods under the initial terms of contract turns out to be its Achilles' heel.[7]

While our results are in line with some previous explanations of a relative inefficiency of public behavior even if government is benevolent, our arguments are not. In the context of privatization, it is often argued that a transition to private governance is beneficial because the harder budget constraint of a private owner imposes a shutdown threat on the firm's manager. Since this threat is sometimes incredible for a benevolent public owner, privatization may lead a manager to work more efficiently. While this argument is simple and has intuitive appeal, it is not fully convincing from a theoretical point of view. After all, a benevolent government has an incentive to bail out a bankrupt private firm if this is in the public interest, which is anticipated by a rational private manager and again weakens his work incentives. Privatization may then be beneficial if the government can - for some unexplained reason - commit to an ex-post inefficient behavior, but it remains

[7] If the government dislikes monetary expenses, it has a commitment power which is qualitatively similar (though not identical) to that of a private buyer. Nevertheless, we show that an efficient outcome may remain infeasible even in this case.

unclear why these commitment capabilities should be available. The present paper does not allow the government to make a non-credible commitment to accept ex-post inefficient outcomes. Accordingly, efficient trade prevails whether or not the buyer is a public or a profit-oriented private agent.[8] Still, commitment also plays an important role in our analysis because the buyer's type determines the set of situations in which renegotiation actually occurs, thereby affecting the equilibrium trade prices.

In the model, renegotiations between principal and supplier are modeled in extensive form. For definiteness, we employ the renegotiation game originating from Hart and Moore (1988) and extend it to the case of bargaining over multiple tradable goods.[9] New contract offers can always specify new pecuniary terms of trade, and in addition a description of the goods' physical attributes may be part of the renegotiation offer. In accordance with intuitive reasoning, we establish that the seller's investment incentives are an increasing function of the trade price that has been contracted in the initial stage.

Some recent contributions compare public and private governance under the assumption of benevolent government behavior. Schmidt (1996) shows that privatizing a public firm can be beneficial if an ownership transfer reduces the government's information on the firm's cost structure. In contrast to a public manager, a private manager/owner anticipates an informational rent which induces him to exert cost-reducing effort. As a tradeoff, the privatized firm suffers from an allocative inefficiency because the government optimally distorts its output decision.[10] Hart, Shleifer and Vishny (1997) investigate a privatization model where a firm's manager can expend cost-reducing and quality-enhancing activities. In their property-rights framework, privatization can be efficient because a private owner

[8] In a variant of the model, we show that renegotiation may yield an inefficient outcome under certain assumptions on the (extensive-form) bargaining process; see Section 4 below. Similarly, an allocative inefficiency arises in Schmidt (1996) because privatization erects an informational barrier between the firm and the government in its role as a regulator.

[9] See Lülfesmann (2001) for an analysis of this bargaining game in a private trade context. Our qualitative results extend to the cooperative Nash bargaining rule. In the present setting with at-will contracting, however, the analysis of Nash bargaining has the unconvenient property that equilibrium investments are not monotonically increasing in the precontracted trade price. In contrast, the Hart-Moore renegotiation process ensures this monotonicity because bargaining power is endogenously assigned to the party that agrees to efficient trade under the initial terms of contract.

[10] Relatedly, Segal (1998) analyzes the government's incentives to bail out a bankrupt private firm. He finds that the underinvestment resulting from this soft budget constraint can be much more detrimental than the welfare loss from monopoly pricing. Also, output competition among firms is shown to harden the government's budget constraint.

owns the productive asset which allows her to be residual claimant on her cost savings.[11] On the other hand, public ownership may improve the quality of service. In important contrast to the present approach, the above papers do not allow for monetary arrangements at an initial date.[12] Finally, Corneo and Rob (2001) consider a multi-task model where a firm's manager can produce an individual output and, in addition, engage in an unobservable team effort. Interestingly, the authors show that a private owner may offer a steeper linear incentive scheme than his public counterpart, which may (but not need not) translate in a larger accumulated effort and output.

The paper is organized as follows. Section 2 presents the model and calculates a first-best benchmark. In Section 3, we solve the model and provide a comparison of public and private procurement. Section 4 examines an alternative assumption on the bargaining process. A brief conclusion follows.

2 The Model

2.1 Setup and Stages

Consider a long-term procurement relationship between a government agency (G) and a private supplier (S).[13] At some future date, the parties face two mutually exclusive trading opportunities (goods) whose values and production costs are initially uncertain. More specifically, the government can purchase from the private supplier one unit of an indivisible good which takes two different forms: first, the private seller can develop a high-quality, innovative version I after the start of the relationship. The expected production costs of this innovation depend upon her level of relationship-specific investments. Second, the supplier also has a lower-quality, basic version of the good B at her disposal whose production costs are independent of the seller's investments.

Both agency and private supplier are risk neutral and have complete information throughout. The time structure is illustrated in Figure 1 and explained in detail below.

[11] In our procurement model, the investing party (the supplier) is always asset owner and can thus be made residual claimant for his cost saving activities.

[12] In Schmidt (1996) and Segal (1998), an initial long-term contract renders the first best feasible in either regime (see the discussion in Segal (1998), p.602).

[13] The assumption that there is only one supplier is justified if a prime contractor has been determined by means of some bidding process or, alternatively, if the firm is the only potential producer in the relevant market.

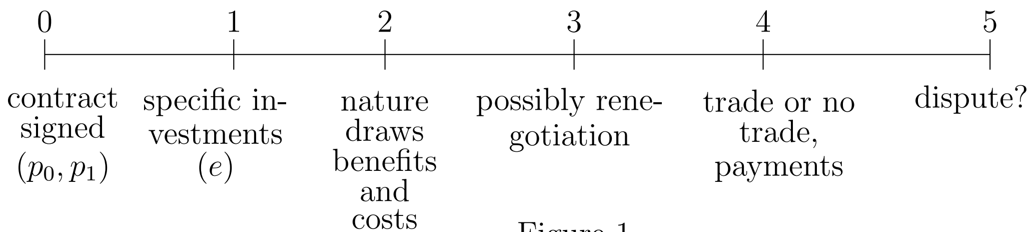

Figure 1

At *date 0* supplier and government agree on their future terms of trade and write a contract that governs their relationship. We assume that neither the relationship-specific investments of the private seller nor the realized costs and benefits of the two goods are verifiable. Furthermore, the goods' characteristics are sufficiently complex so that they cannot be described and contracted upon ex ante.[14] Hence, an initial contract can only be contingent on the event that trade occurs or not and whether the corresponding payments have been provided.[15] We follow Hart and Moore (1988) and consider simple 'at-will'-contracts. These contracts specify a trade price, p_t, and a transfer payment if there is no trade, p_0, and make final trade a voluntary decision of each agent.[16]

At *date 1*, after signing the contract, the supplier can invest in relationship-specific assets to decrease the expected production costs c_I of the innovation. These investments are denoted by e and subject to monotonically increasing, convex investment costs $\psi(e)$.[17]

At *date 2*, nature determines the state of the world $s = (v_I, c_I, v_B, c_B) \in \mathcal{S}$, where v_i and c_i, $i \in \{I, B\}$, indicate the gross values and production costs of the innovation and the basic good, respectively. We will assume that all components of s are drawn from independent distributions. A good $i \in \{I, B\}$ is *valuable* if the ex-post surplus from trade is positive, i.e. if $v_i - c_i(1 + \lambda) > 0$. The parameter $\lambda \geq 0$ is a measure for shadow costs of public funds (see, for example, Laffont and Tirole, 1993): production of good i causes

[14]See Aghion and Tirole (1994, 1997), Segal (1999) and Hart and Moore (1999) for similar assumptions. Note that even if the basic good is describable ex ante, the seller may have the opportunity to exercise (costless) cosmetic modifications to make it look like an innovative good. Hence, any contract prescribing different prices for 'trade of B' and 'trade of a good different from B' would be useless.

[15]If trade does not occur, the contract may also specify a breach penalty which can be imposed on the defecting party. However, one can show that simple contracts of this type, i.e., specific-performance or option contracts, are strictly dominated in our setting with non-verifiable goods (for details, see Lülfesmann, 2001).

[16]This contract type has also been analyzed in, e.g., MacLeod and Malcomson (1993) and Che and Chung (1998).

[17]In order to guarantee an interior optimum, we further impose the Inada-conditions on $\psi(e)$. In our context, the investment e can be interpreted as R&D expenditures of the supplier.

production costs c_i whose social value is therefore $c_i(1+\lambda)$. Throughout the paper, we impose the following assumption:

ASSUMPTION 1: $v_I > v_B$ and $c_I > c_B$ apply in any state of the world.

Since the innovative good is tailor-made for the government's specific demands, it is natural to assume that its gross value and production costs always exceed the corresponding values of the basic good. Assumption 1 is crucial for our subsequent results. In particular, it implies that the supplier prefers trade of B to trade of I at any given trade price. Hence, a quality-choice problem arises if trading the innovation is efficient. In order to simplify the subsequent exposition, we will in what follows refer to a parametric example that is compatible with Assumption 1 and described in table 1 below.[18]

Basic Good B	Innovative Good I
• benefits $v_B \in \{\underline{v}_B, \overline{v}_B\}$, with $q = \text{prob}\{v_B = \overline{v}_B\}$.	• benefits $v_I \in \{\underline{v}_I, \overline{v}_I\}$, with $\mu = \text{prob}\{v_I = \overline{v}_I\}$.
• costs c_B.	• costs $c_I \in \{\underline{c}_I, \overline{c}_I\}$, $\underline{c}_I = c_B + \underline{\delta}$, $\overline{c}_I = c_B + \overline{\delta}$, with $e = \text{prob}\{\delta = \underline{\delta}\}$,

$$\min\{\overline{v}_I - \overline{c}_I(1+\lambda), \underline{v}_I - \underline{c}_I(1+\lambda)\} > \overline{v}_B - c_B(1+\lambda) > 0 > \max\{\underline{v}_I - \overline{c}_I(1+\lambda), \underline{v}_B - c_B(1+\lambda)\}.$$

Table 1

The assumptions of Table 1 ensure that any of the following cases A to D can occur:
A: both basic and innovative good are valuable; trade of the innovative good is efficient;
B: only the innovative good is valuable and should be traded;
C: only the basic good is valuable and should be traded;
D: neither good is valuable; no trade is the efficient solution.

The relations in the last line of the table guarantee that the realization of the innovative good is efficient in every state of the world unless low benefits and high production costs of

[18]The focus on an example considerably simplifies the subsequent presentation. As will become clear below, results immediately generalize to more general settings that are based on Assumption 1.

this version appear simultaneously. In the latter case, the innovation is non-valuable and the basic good should be produced if it is valuable, i.e., if $v_B = \overline{v}_B$.

Facing one of the situations A to D, the parties can renegotiate the initial terms of contract at *date 3*. Finally, at *date 4*, at most one of the goods is produced and traded if both supplier and government voluntarily agree. The corresponding transfers - initially contracted or renegotiated - are made and the game ends unless the court has to settle a dispute on delivery or payments at *date 5*. We detail the exact specification of the renegotiation/trade stage of the game in subsection 2.3 below.

2.2 Objectives and First-Best Benchmark

The government is benevolent. It maximizes the sum of consumer surplus and the supplier's profit, and faces shadow costs of public funds $\lambda \geq 0$. Its objective function can be written as

$$\begin{aligned} U^G &= \sum_i x_i[v_i - p_i(1+\lambda) + (p_i - c_i)] - \psi(e) \\ &= \sum_i x_i(v_i - c_i - \lambda p_i) - \psi(e), \end{aligned} \tag{1}$$

where $x_i \in \{0, 1\}$ and p_i are the traded quantity and final price of good i, $i \in \{0, I, B\}$.[19] As will become clear shortly, equilibrium allocations depend only on the difference between trade and no-trade prices. The transfer p_0 can therefore be interpreted as a fixed up-front payment from the government to the private seller to compensate the firm for her investment outlays.

The profit-maximizing supplier bears the investment and production costs (if trade is realized) and receives payments from the government. Her objective function is

$$U^S = \sum_i x_i(p_i - c_i) - \psi(e). \tag{2}$$

Ex-post efficiency requires (a) that trade takes place if and only if this increases welfare (i.e., if at least one good is valuable) and (b) that the parties trade the innovation when both goods are valuable. Recall that the specific investments of the firm are sunk at the date of final trade and therefore do not influence the ex-post efficient trade decisions.

[19]Recall that trade is indivisible and mutually exclusive. Moreover, $x_0 = 1$ indicates no trade, and the corresponding benefits and production costs are $v_0 = c_0 = 0$.

Ex-ante efficiency requires optimal specific investments e^*. Under the assumptions of Table 1, the efficient investment level maximizes the following concave program:[20]

$$\begin{aligned} max_e\, \mathcal{W} &= e\mu[\overline{v}_I - \underline{c}_I(1+\lambda)] + e(1-\mu)[\underline{v}_I - \underline{c}_I(1+\lambda)] + (1-e)\mu[\overline{v}_I - \overline{c}_I(1+\lambda)] \\ &+ (1-e)(1-\mu)q[\overline{v}_B - c_B(1+\lambda)] - \psi(e)(1+\lambda) - \lambda\bar{U}^S. \end{aligned} \tag{3}$$

The unique efficient investment level is implicitly determined by the first-order condition

$$\mathcal{W}_e(e^*) = 0 \quad \Leftrightarrow \quad (1-\mu)\left[(\frac{\underline{v}_I}{1+\lambda} - \underline{c}_I) - q(\frac{\overline{v}_B}{1+\lambda} - c_B)\right] + \mu[\overline{c}_I - \underline{c}_I] = \psi_e(e^*). \tag{4}$$

To attain efficiency, investments should be set at a level where the (adjusted) social return equals their marginal costs. In our example, the social marginal value of investment consists of two terms: first, the cost reduction in states where the innovation is efficient independent of its production costs (which occurs with a probability μ). Second, the social value of trade in states where trading I is efficient only if this good has low production costs (with probability $(1-\mu)$). In these latter states, the social value of investments is reduced by the expected social value of the basic good, i.e., first-best investments are strictly decreasing in q. We will use the efficiency condition in (**??**) as a benchmark to be compared with the actual choice of the supplier's investments in the equilibrium of the game. A *first-best result* is established if both ex-ante and ex-post efficiency are attained in subgame-perfect equilibrium.

2.3 Renegotiation and Trade

After both parties have observed the state of the world, they can renegotiate the initial terms of contract at date 3. Since the original contract cannot account for all possible contingencies, it is evident that renegotiation will often be necessary to ensure an ex-post efficient allocation. We suppose that renegotiations follow a version of the non-cooperative renegotiation game developed by Hart and Moore (1988). As is well known, this bargaining process yields the convenient (and realistic) property that the equilibrium trade price is increasing in p_t, the trade price on which the parties initially agreed.[21] The main text

[20]Since transfers are not welfare neutral for any $\lambda > 0$, an efficient investment level maximizes the government's objective subject to the constraint that the supplier obtains at least a given utility $\bar{U}^S$. Hence, the government has to compensate the supplier for his investment and production costs, and must provide an additional payment of size $\bar{U}^S$.

[21]The literature often employs the Nash bargaining rule which does not have this property. In the present model where at-will contracting dominates contracts which enforce a positive level of trade, though, this rule only complicates the analysis while preserving our qualitative results.

only provides a brief overview on the timing of the Hart-Moore renegotiation game while a detailed description is relegated to Appendix A.

We will distinguish between two scenarios. In Section 3 below, it is assumed that the physical attributes of either good become verifiable after the state of the world has been realized; revised contracts can then be contingent on the different versions. We will refer to this case as a framework with *ex-post verification*. Subsequently, Section 4 analyzes a second scenario where the court lacks the technical knowledge to distinguish between different versions even if the parties provide a detailed description of goods, or where writing costs prevent the parties from specifying the vector of characteristics (see Tirole, 1999). In this latter case, ex-post verification is ruled out and contingent contracts remain infeasible.

In either case, the renegotiation process starts at *date 3* after investments have been made and both parties have observed the state of the world. At that date, each agent may (simultaneously) submit a written message to his trade partner which is interpreted as a new contract offer.[22] In a setting where no ex-post renegotiation is admitted, a message is basically the proposal of a revised trade price. Conversely, if ex-post verification is feasible, a description of one or more goods can be part of the message, and price proposals can be made contingent on the specific version of the good. These new contract offers are submitted to the other party before date 4. At *date 4*, the seller can produce and deliver one good. If the government rejects delivery at this stage, trade does not take place.

Finally, at *date 5* after trade has occurred (or not), both agents can simultaneously reveal the message they may have received from their trading partner to the court, respectively. If only one agent presents a message, the corresponding new contract is enforced if it is 'relevant' in the sense that it prescribes a new price for the allocative outcome at date 4.[23] Otherwise, the initial terms of contract remain in force and the court enforces the corresponding payments. If both parties present revised contracts, the court enforces these new contracts if and only if they are 'relevant', and are not in contradiction to each other with respect to payments.[24]

[22]In contrast to the original formulation in Hart and Moore (1988) where messages are submitted sequentially over a certain time interval, we assume that revision offers are sent simultaneously at a single date [see also Nöldeke and Schmidt (1995)]. This modification simplifies the analysis considerably without changing equilibrium outcomes.

[23]The allocative outcome is either no trade, or trade of one of the goods I or B. Notice that the court can enforce a version-contingent trade price only if ex-post verification is feasible, and if the revealed message refers to a certain type of good.

[24]Irrelevant offers are ignored by the court. As indicated above, Appendix A provides a detailed de-

3 Equilibrium Analysis

3.1 Renegotiation and Trade

Using backwards induction, we start with the equilibria of the renegotiation and trade stage (dates 3 – 5). Recall that at date 3 the parties face a state of the world which falls in one of the four categories (A) to (D). For shortness of exposition, we have relegated the analysis of the renegotiation and trade stages to the Appendix and summarize the equilibrium outcomes in

Proposition 1: *Suppose that ex-post verification is feasible. If $\lambda < \overline{\lambda} \equiv (\bar{v}_B - c_B)/\bar{c}_I$, the renegotiation and trade game has a unique undominated and pareto-efficient subgame-perfect equilibrium.*

(1) If no trade is the ex-post efficient decision (Case D), neither good is traded and p_0 is paid by the government to the private supplier without renegotiations.

(2) If only one good $i \in \{I, B\}$ is valuable (Cases B and C), i is traded at price $p_i^* = p_t$ if both parties prefer trade at p_t to no trade, i.e., if $(v_i - c_i)/\lambda \geq p_t - p_0 \geq c_i$. Conversely, if only one party $k \in \{G, S\}$ agrees to trading good i at p_t, renegotiation arises and the equilibrium trade price makes the other party $l \neq k$ indifferent between trade and no-trade. Accordingly, $p_i^* = p_0 + c_i$ if $l = S$, and $p_i^* = p_0 + (v_i - c_i)/\lambda$ if $l = G$.

(3) If both goods are valuable but trade of I is ex-post efficient (Case A), the innovation is traded and equilibrium prices are as follows:

(a) If $(p_t - p_0) < c_B$ so that S prefers no trade to trade of both I and B, the realized trade price makes S indifferent between trade of I and no trade, i.e. $p_I^* = p_0 + c_I$;

(b) If $(\bar{v}_B - c_B)/\lambda \geq (p_t - p_0) \geq c_B$, both parties prefer trade of B to no trade and the renegotiated trade price makes the supplier indifferent between trade of B and I, i.e., $p_I^* = p_t + \delta$;

(c) If $(v_I - c_I)/\lambda p_t - p_0 > (\bar{v}_B - c_B)/\lambda$,[25] both parties prefer trade of good I over no trade, whereas G credibly refuses acceptance of good B. Then, no renegotiation arises and good I is traded at p_t.

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scription of the court's decision rule.

[25]This implies $p_t - p_0 > \bar{c}_I$ for $\lambda < \bar{\lambda}$.

(d) *If* $(p_t - p_0) > (v_I - c_I)/\lambda$ *so that* G *prefers no trade to trade of both* I *and* B*, the realized trade price makes* G *indifferent between trade of* I *and no trade , i.e.,* $p_I^* = p_0 + (v_I - c_I)/\lambda$.

Proof: See Appendix B.

Proposition 1 asserts that any initial contract facilitates an ex-post efficient outcome when ex-post verification is feasible. Renegotiation arises only if trade is efficient, and if one party would not voluntarily trade the efficient good at the precontracted price. In renegotiations, the bargaining power endogenously rests with the party that agreed to efficient trade at the initial prices. To see this, consider first those states of the world in which at most one of the goods is valuable: if no good is valuable (case D), it is impossible that both parties agree on trade at any price and there is no reason to modify the initial agreement. Accordingly, p_0 is paid without renegotiation. Similarly, if only one good is valuable (cases B and C) and both parties prefer trade under the initial terms of the contract to no trade, p_t is paid without renegotiations. Otherwise, if one agent can credibly refuse trade at p_t, renegotiation occurs and the revised trade price makes this party indifferent between trade and no trade. Taken together, the above outcomes coincide with those in Hart and Moore (1988): if renegotiation arises, the entire bargaining power is endogenously assigned to the party which is willing to trade under the initial terms of contract.[26] Also observe that a non-valuable good has no impact on the parties' default points in renegotiations, and thus leaves the equilibrium payoffs unaffected.

If both goods are valuable and trade of the innovation is efficient (case A), these properties still apply with an important modification. Consider an initial contract and a state where *both* parties prefer trading the basic good to no trade. If renegotiations fail, the supplier can then successfully deliver the inefficient good B, and she has an interest to do so since production costs are lower than those of good I. Accordingly, the seller's default point is now shifted upward, and determined by the net payoff she obtains from trading B at p_t. In equilibrium, the government will then tender a revised contract offer to facilitate efficient trade of good I. This revised offer will explicitly refer to trade of the innovation (i.e., it will include a description of I), and the proposed price will make the supplier indifferent between trade of I at the new price and trade of B at p_t. Accordingly, this

[26]This feature of the Hart-Moore renegotiation game is in contrast to the outcome of Nash bargaining. There, the outcome of renegotiations would be unaffected by the identity of the party which refused trade at the prespecified trade price. Versions of the Hart-Moore bargaining process have also been utilized in, e.g., MacLeod and Malcomson (1993) and Nöldeke and Schmidt (1995).

new equilibrium price is $p_I^* = p_t + \delta$. Clearly, the supplier delivers I under this offer and appropriates a net payoff of $p_t - c_B$.[27]

3.2 Investment Choice

Having established the prevalence of an ex-post efficient outcome, we can now ask whether ex-ante efficiency can be achieved, that is, whether there is an initial contract (p_0, p_t) that induces efficient specific investments of the private seller.

For subsequent comparison, let us first briefly sketch the solution for the case of private procurement where the buyer is a self-interested agent.[28] Importantly, the set of situations where renegotiation actually arises depends on the buyer's objective function. We can state the following result which will serve as a benchmark for comparison with the equilibrium investments in public procurement:

Proposition 2 (Lülfesmann 2001): *Consider a profit-maximizing buyer (private procurement). Then, there exists an initial at-will contract $(p_0, p_t)^*$ which implements the efficient investment and trade decisions. Accordingly, a first-best result is attained in private procurement.*

To understand this result, notice that the qualitative outcome of Proposition 1 carries over to private procurement: if one agent does not agree to trade the *efficient* good under the initial prices, the other party endogenously holds the entire bargaining power in renegotiations. In private procurement, the buyer's ex-post utility is $U^B = v_i - p_t$ if good i is traded, and p_0 if no trade arises. Consider an initial contract from the interval $p_t - p_0 > \bar{v}_I$. Since any such price difference exceeds the buyer's maximal gross benefit from trade, he is never willing to accept any good under the initial terms of contract. Accordingly, the seller will submit a renegotiation offer to facilitate trade, and the best she can do is to make the buyer indifferent between trade and no trade. If good $i \in \{I, B\}$ is the ex-post efficient

[27]This outcome is the key to our result in Proposition 4 below. The uniqueness result of Proposition 1 rests upon the restriction to sufficiently small shadow costs of public funds ($\lambda < \bar{\lambda}$). This restriction ensures that $(\bar{v}_B - c_B)/\lambda > \bar{c}_I$ such that - at the price difference $(p_t - p_0)$ where the government ceases to accept the basic version of the good - the supplier is always willing to deliver the innovation. For $\lambda \geq \bar{\lambda}$ where the seller does not deliver I under this contract when production costs c_I are high, there exists an additional (inefficient) equilibrium where the basic good is traded. One can show, however, that all subsequent results of this paper continue to apply for $\lambda \geq \bar{\lambda}$.

[28]See Lülfesmann (2001) for an extensive analysis of a profit-maximizing buyer and both-sided investments in an otherwise identical framework.

trading alternative, she will thus propose a new trade price $p_i^* = p_0 + v_i$ which ensures ex-post efficiency.[29] It is now easy to see that the supplier's investment incentives are also optimal: up to the constant p_0 she appropriates the entire surplus from trade in each state of the world and, hence, she reaps the full marginal return on her specific investments.[30]

We will now show that these arguments do not extend to public procurement. Table 2 below depicts the possible states of the world $s_n, n = i, ...viii$ which nature determines under the assumptions of table 1.

x_I \ x_B	valuable	not valuable
valuable	A $x_I^* = 1$ $s_i = (\overline{v}_I, \underline{c}_I, \overline{v}_B)$ $s_{iii} = (\underline{v}_I, \underline{c}_I, \overline{v}_B)$ $s_v = (\overline{v}_I, \overline{c}_I, \overline{v}_B)$	B $x_I^* = 1$ $s_{ii} = (\overline{v}_I, \underline{c}_I, \underline{v}_B)$ $s_{iv} = (\underline{v}_I, \underline{c}_I, \underline{v}_B)$ $s_{vi} = (\overline{v}_I, \overline{c}_I, \underline{v}_B)$
not valuable	C $x_B^* = 1$ $s_{vii} = (\underline{v}_I, \overline{c}_I, \overline{v}_B)$	D $x_0^* = 1$ $s_{viii} = (\underline{v}_I, \overline{c}_I, \underline{v}_B)$

Table 2

Consider an arbitrary ex-ante contract (p_0, p_t) and let $p_i^{(s)}$ be the equilibrium trade price in state s given that good i is traded. Inserting the subgame-perfect continuation of

[29] Notice that the seller cannot defect and deliver the low-cost basic good if I is efficient: since p_I^* is larger than $p_0 + \bar{v}_B$, the buyer would decline acceptance of the low-quality good.

[30] A government commitment not to intervene in the private relationship is needed because the government's presence and possible intervention after out-of-equilibrium moves may affect the equilibrium behavior of the private parties. However, if the government commits not to monitor the progress of the private relationship, the parties behave efficiently and the government's commitment is indeed sequentially rational.

the game (Proposition 1), the supplier's optimization problem at date 1 is

$$\begin{aligned}\max_{e} \quad U^S &= e\mu \left[q(p_I^{(i)} - \underline{c}_I) + (1-q)(p_I^{(ii)} - \underline{c}_I)\right] \\ &+ e(1-\mu)\left[q(p_I^{(iii)} - \underline{c}_I) + (1-q)(p_I^{(iv)} - \underline{c}_I)\right] \\ &+ (1-e)\mu\left[q(p_I^{(v)} - \overline{c}_I) + (1-q)(p_I^{(vi)} - \overline{c}_I)\right] \\ &+ (1-e)(1-\mu)\left[q(p_B^{(vii)} - c_B) + (1-q)p_0\right] - \psi(e).\end{aligned} \tag{5}$$

This concave program yields a unique solution e^S, which is implicitly determined by the necessary and sufficient first-order condition

$$\begin{aligned}U_e^S = 0 \iff \quad & \mu\left[q(p_I^{(i)} - p_I^{(v)}) + (1-q)\,(p_I^{(ii)} - p_I^{(vi)})\right] \\ + \quad & (1-\mu)\left[q(p_I^{(iii)} - p_B^{(vii)}) + (1-q)\,(p_I^{(iv)} - p_0)\right] \\ + \quad & \mu\overline{\delta} - \underline{\delta} - (1-\mu)(1-q)c_B = \psi_e(e^S).\end{aligned} \tag{6}$$

Obviously, e^S is a function of the final prices which in turn depend on the initial contract (p_0, p_t), as shown in Proposition 1. Comparing (**??**) with equation (**??**) which determines the welfare-optimal investments, one immediately finds that $e^S = e^*$ if and only if

$$\begin{aligned}A \;\equiv\;& \mu\left[q(p_I^{(i)} - p_I^{(v)}) + (1-q)\,(p_I^{(ii)} - p_I^{(vi)})\right] \\ +\;& (1-\mu)\left[q(p_I^{(iii)} - p_B^{(vii)}) + (1-q)\,(p_I^{(iv)} - p_0)\right] \\ \overset{!}{=}\;& (1-\mu)\,\frac{\underline{v}_I - q\overline{v}_B}{1+\lambda} \equiv A^*.\end{aligned} \tag{7}$$

No Shadow Costs

Let us first investigate the special case $\lambda = 0$.[31] Analyzing (**??**) under this assumption, we can state:

Proposition 3: *Suppose $\lambda = 0$ and ex-post verification is feasible. Then,*

(a) if the basic good is non-valuable with positive probability ($q < 1$), efficient investment and trade decisions can be achieved. Renegotiation arises in some but not all states of the world and the optimal contracted price difference $(p_t - p_0)^*$ is monotonically increasing in q;

[31] We assume that in this case the government has a lexicographic preference ordering with respect to allocative efficiency and monetary payments to the firm. This is equivalent to the government's objective function (**??**) as $\lambda \to 0$.

(b) if the basic good is valuable in every state of the world ($q = 1$), there is no ex-ante contract which induces the firm to invest at all into relationship-specific assets.

Proof: See Appendix C.

To assess Proposition 4, the crucial point to recognize is that whenever the basic good is valuable, the government prefers trading this good to no trade *at any price* because the shadow costs of public funds are negligible. If $q = 1$, the seller always has the option to deliver B at p_t, and strictly prefers to do so even if trade of the innovation is efficient. Renegotiation is thus required to ensure efficient trade of I. In these renegotiations, the government holds all the renegotiation power and the supplier's net payoff is $max\{p_0, p_t - c_B\}$ independent of nature's draw. Hence, the private seller's payoff is invariant with regard to the level of specific investments, and her investment incentives disappear. Note that $q = 1$ is not unlikely to occur in practice: one can think of B as a good which is produced by a reliable standard technology, whence $v_B > c_B$ has been established for a long time. Then, the government strictly prefers ongoing trade of this basic version to the termination of trade. For any $q < 1$, in contrast, there is a positive probability that the basic good is non-valuable and delivery of this commodity will not be accepted by the government. In this case, the equilibrium investment level of the supplier is a continuous and unboundedly increasing function of the initially contracted price difference $(p_t - p_0)$. Intuitively, the supplier now faces a positive probability of a failure to trade (if I has large production costs) which she can reduce by investing. An increase in the precontracted price difference then raises investment incentives because there is some chance that she can appropriate the trade rent $p_t - p_0 - c_I$ only if production costs c_I are low.[32] By an appropriate choice of the initial contract efficient incentives can thus be guaranteed.

While the above arguments already establish a reason why government procurement may be inefficient, they rely on the assumption of negligible shadow costs of public funds. In this setting, there exist no (whatever large) price difference which can lead the government to reject a valuable good. In reality, governments are often concerned with the level of expenditures which they spend for procurement purposes. If shadow costs are positive, however, there exist ex-ante contracts under which the government can - similar to a private buyer - commit *not* to accept a good even if it is valuable. This scenario is the focus of our subsequent analysis.

[32] An increase in q diminishes the equilibrium probability of no trade, so that the optimal 'incentive difference' $(p_t - p_0)^*$ must be an increasing function of q.

Positive Shadow Costs

Does the inefficiency in the procurement process disappear if the government faces non-negligible costs of public funds? For a strictly positive λ, the government's value of each dollar paid to the supplier is $-\lambda$. As a consequence, the government agrees on trade of a good i only if $v_i - c_i \geq \lambda(p_t - p_0)$.[33] This implies that it now can commit to reject valuable trade if the price of the good initially agreed upon is too high.

Since payments to the seller enter the government's objective function, the objectives of private and public buyer are more closely aligned. Hence, one might believe that - as in the case of a private buyer - the initial contract can always be chosen in a way as to ensure optimal investments of the supplier. In particular, one would think this to be true for any ex-ante probability q with which the basic good is valuable. However, the next result shows that this intuition is misleading.

Proposition 4: *Suppose that ex-post verification is feasible and $\lambda > 0$. If $\mu > \underline{\delta}/\overline{\delta}$, there exists a nonempty interval of strictly positive parameters $q \in (\hat{q}, \tilde{q})$, $\tilde{q} > \hat{q}$, for which no ex-ante arrangement (p_0, p_t) implements efficient investments in public procurement. In this range, the second-best optimal contract induces either under- or overinvestment.*

Proof: See Appendix C.

Under some technical conditions, there exists a nonempty interval of probabilities q for which efficient investments cannot be implemented in public procurement. To understand this result, consider first an ex-ante contract for which the government is never willing to trade, and recall that such a contract ensures a first-best outcome in private procurement. Since the government maximizes welfare, this contract is characterized by a price difference $p_t - p_0 > (\bar{v}_I - \underline{c}_I)/\lambda$. Since the seller holds the entire bargaining power in states where renegotiation arises, she accrues a net payoff $U^S = p_0 + (v_i - c_i)/\lambda - c_i = p_0 + (v_i - c_i(1+\lambda))/\lambda$ if trade of a good i turns out to be ex-post efficient. By (3), the social value of trade (adjusting for the shadow costs of investments) is only $(v_i - c_i(1+\lambda))/(1+\lambda)$. Accordingly,

[33] For any $\lambda > 0$, public and private procurement are not directly comparable because both ex-ante efficient investment levels and ex-post efficient decisions differ. This dichotomy, however, can easily be eliminated: suppose that v_i represents the intrinsic rather than the monetary gross valuation $\hat{v}_i$ from trade of good i. Then, these two measures coincide for a private buyer, while the government's intrinsic valuation v_i is equivalent to $\hat{v}_i(1+\lambda)$ when good i has a market value $\hat{v}_i$. It is easy to see that this redefinition synchronizes the conditions for ex-ante and ex-post efficiency under either regime. Observe also that the government is then willing to 'privatize' procurement to the private buyer in exchange for a fixed sales price whenever a more efficient investment level can be attained in private procurement.

under the proposed contract, the seller's trade rent is *larger* than the social surplus for any λ which leads her to *overinvest* relative to the first best. Since investment incentives are monotonically increasing in $(p_t - p_0)$, this result implies that the optimal contracted price difference must be strictly lower, and a situation as displayed in Figure 2 may arise. The figure illustrates the seller's equilibrium investments depending on the initially contracted prices for some $q \in [\tilde{q}, \hat{q}]$.

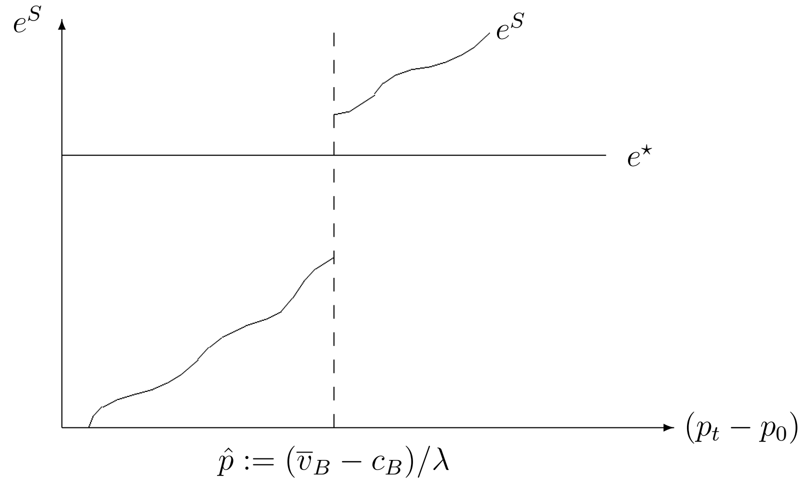

Figure 2

There exists a critical price difference $\hat{p} := (\overline{v}_B - c_B)/\lambda$ where the government ceases to accept delivery of the basic good under the initial prices. At this price difference, a discontinuity in marginal and absolute investment incentives arises for the following reason:

(i) at low price differences $(p_t - p_0) \leq \hat{p}$, the government is willing to accept trade of the (valuable) basic good at the initial prices. Hence, if trade of the innovation is efficient, the government proposes a revised trade price $p_t + \delta$ for good I which makes the private contractor indifferent between trade of both goods.[34] Note that this contract is of a 'cost plus' form: it includes the innovation's (additional) production costs. Therefore, the seller has no investment incentives if the basic good is valuable. As long as $q \leq \hat{q}$, efficient investments can nevertheless be generated by an ex-ante contract with $(p_t - p_0)^* \leq \hat{p}$. For $q > \hat{q}$, however, the supplier underinvests.

[34] We consider $p_t - p_0 \geq c$. For very small price differences $p_t - p_0 < c$, the supplier is unwilling to deliver any good under the initial terms. By Proposition 1, ex-post efficiency is then attained but the seller's trade rent is always zero so that she will not invest.

(ii) at high price differences $(p_t - p_0) > \hat{p}$, the government is unwilling to trade the basic good at the initial prices even if it is valuable. In this case, the innovative good is traded at the initial price p_t (instead of $p_t + \delta$ for $p_t - p_0 \leq \hat{p}$). Since the seller can now no longer recover the higher production costs of the innovation via renegotiation, her incentives to invest rise discontinuously at the point $\hat{p}$. For $q \geq \tilde{q}$ efficient investments can again be attained by an ex-ante contract specifying $(p_t - p_0)^* > \hat{p}$. For $q < \tilde{q}$, the supplier overinvests.

Summarizing, when $q \in [\hat{q}, \tilde{q}]$, the government is caught between Scylla and Charybdis: regardless of how the initial contract is chosen, the supplier will either under- or overinvestment in specific assets.[35] The occurence of a discontinuity in the supplier's investment response function is a necessary condition for those suboptimal investments. Since discontinuities always arise in a discrete setup, our results therefore apply more generally to models with a finite number of benefits and costs. In addition, we can also expand the number of valuable basic goods without affecting our qualitative conclusions.[36]

To conclude this section, it is now instructive to briefly contrast our findings with the economic implications of a situation where either no basic good exists, or where it is never valuable. For this standard scenario, we obtain:

Corollary: *Both $\tilde{q}$ and $\hat{q}$ are strictly larger than zero. If $q = 0$, or, alternatively, if the basic good does not exist, efficient investments are always feasible and public procurement yields a first-best outcome.*

Proof: see Appendix C.

This result is in line with the previous literature on the holdup problem, especially Hart and Moore (1988) and Bös and Lülfesmann (1996): as long as no (valuable) alternative trade opportunity exists, one-sided first-best investments can always be induced by a proper choice of ex-ante prices.

[35] Appendix C shows that $lim_{\lambda \to 0}\ \hat{q} = lim_{\lambda \to 0}\ \tilde{q} = 1$. For $\lambda \to 0$, the interval $(\hat{q}, \tilde{q})$ converges to the point $q = 1$, and the result of Proposition 4 applies.

[36] Note that an increase in the number of valuable basic goods has similar consequences as an increase in the number of possible cost and benefit realizations. Consider, however, the limit case where distributions are continuous and c_i, v_i are realizations from compact intervals $[\underline{c}_i, \bar{c}_i]$ and $[\underline{v}_i, \bar{v}_i]$, respectively. Then, at a price slightly smaller than $\hat{p} = (\bar{v}_B - \underline{c}_B)/\lambda$, the seller can successfully deliver the basic good only with very small probability, which triggers a continuous investment response over the whole interval of initial price differences and admits an efficient outcome.

4 Verification infeasible

In this section, we briefly extend our previous results and consider a situation where ex-post verification is not feasible. We will first show that the ex-post efficiency result of Proposition 1 does not generically apply in this case.

Proposition 5: *Suppose that ex-post verification is infeasible. Then,*

(a) for any initial contract characterized by $p_t - p_0 \leq (\bar{v}_B - c_B)/\lambda \equiv \hat{p}$, the innovation will not be traded in equilibrium if (and only if) the basic good is valuable. Instead, the basic good is traded at a price max$\{p_0 + c_B, p_t\}$. Accordingly, an initial contract with price difference weakly smaller than $\hat{p}$ does not facilitate an ex-post efficient outcome whenever $q > 0$;

(b) conversely, for any $p_t - p_0 > \hat{p}$, ex-post efficiency is attained and the equilibrium prices coincide with those in Proposition 1.

Proof: See Appendix B.

An inefficient outcome may arise in Case A where both goods are valuable and trading I is ex-post optimal. Specifically, the parties cannot prevent inefficient trade of good B for contracts where the government accepts a valuable basic good, i.e., if $p_t - p_0 \leq \hat{p}$. An intuitive argument for this finding is as follows. When $p_t - p_0 \leq \hat{p}$, trade of I requires the government to submit a renegotiation offer at date 3. Provided the supplier tenders no counteroffer, the government will propose a revised price which is only slightly larger than $\hat{p}$, i.e., it will commit not to accept delivery of B. Anticipating this proposal, however, the seller can gain by a counteroffer which induces an equilibrium trade price *identical* to $\hat{p}$ in the court dispute game at date 5. This counteroffer allows her to successfuly deliver the less costly basic version, and therefore increases her profit.[37] Accordingly, equilibrium strategies are incompatible with efficient trade in case A for any $p_t - p_0 \leq \hat{p}$, and the parties cannot do better than trading the basic good. In contrast, for initial contracts with a higher price difference, an upward price renegotiation is never needed and the outcome of Proposition 1 is replicated.

[37] Hence, efficient trade would require a government offer which triggers an equilibrium trade price (weakly) larger than $\hat{p} + \delta$. Unfortunately, though, such an offer is not rational: when the government expects no counteroffer, it will never propose a revised trade price (slightly) larger than $\hat{p}$. Conversely, if S submits an offer which is compatible with efficient trade, there always exists a government counteroffer inducing a trade price of (slightly more than) $\hat{p}$ in continuation equilibrium.

If ex-post verification is infeasible, a first-best result in public procurement can thus be attained only if some initial contract from the range $p_t - p_0 > \hat{p}$ implements efficient investments. Recalling that $\hat{q}$ is the threshold probability below which the seller overinvests for any initial price difference $p_t - p_0 > \hat{p}$, the following result is now immediate.

Proposition 6: *Suppose that ex-post verification is infeasible. Then, a first-best outcome cannot be attained under public procurement whenever $q \in (0, \hat{q}]$.*

The result of Proposition 6 is easily understood when one recalls our previous findings: first, ex-post efficiency (for any $q > 0$) can only be ensured by an initial contract from the interval $p_t - p_0 > \hat{p}$ (Proposition 5). Second, any of those candidate contracts leads the contractor to overinvest whenever $q < \hat{q}$ (Proposition 4). In contrast to the scenario with ex-post verification, the inefficiency result of Proposition 6 thus does not rely upon a discontinuity of the investment response function at the critical price difference $\hat{p}$. The parties may rather fail to implement an efficient outcome even if investments smoothly increase over the whole price interval, and the second-best contract now balances overinvestments (for contracts $p_t - p_0 > \hat{p}$) and an ex-post inefficient outcome in case A (for contracts $p_t - p_0 \leq \hat{p}$).[38]

Conversely, one can easily show that the efficiency result in private procurement (Proposition 2) still applies if contingent renegotiation offers are not allowed.[39] Again, the private trade relationship is thus more efficient than public procurement.

5 Conclusion

This paper has focused on a long-term procurement relationship where a buyer wants to purchase a good from a private seller. Our incomplete-contracting model incorporated the following crucial elements: first, the supplier has several goods at her disposal whose gross values increase in their costs of production. Second, at a pre-production stage the supplier can expend investments which decrease the expected production costs of a high-quality 'innovative' good, but leave the value of low-quality 'basic' goods unaffected. Finally, we supposed that an initial contract cannot describe the good which should be traded ex post.

[38]This implies that the first-best can never be attained if $q > 0$ and shadow costs are absent, $\lambda = 0$: since *any* feasible price difference is smaller than $\hat{p}$ when $\lambda = 0$, the parties must fail to reach an ex-post efficient outcome in case A.

[39]This is because under the optimal contract the trade price is so large that there is a downward renegotiation in every state of the world under the optimal contract. Intuitively, since the seller proposes a revised trade price which makes the buyer just indifferent between trading the efficient good i and no trade, the latter would not accept the basic good if $i = I$. See also Lülfesmann (2001).

Within this framework, we compared the relative performance of public procurement (benevolent buyer) and private procurement (profit-maximizing buyer). Our main result is that, despite the buyer's welfare objective, public procurement can induce lower welfare than private contracting. Two reasons for this inefficiency were identified. In a first scenario where the differences between goods can be made verifiable after the investment stage, the outcome is ex-post efficient under either governance structure. However, the different objectives of a public and private buyer, respectively, affect the occurence of renegotiation. While a private buyer's objectives render an optimal adjustment of the seller's investments feasible, the government's welfare goal gives rise to a discontinuous relation between prices and investment levels. These discontinuities, in turn, can prevent the optimal adjustment of incentives in public procurement, and efficient investments may become infeasible. We also analyzed an alternative scenario where the characteristics of goods cannot be verified ex post. For this case, we find that only a subset of initial at-will contracts guarantees ex-post efficiency. While this constraint does not impede the efficiency in the private trade relationship, it further hampers the performance of public procurement, and may even lead the government to sacrifice efficient trade.

Fundamentally, the paper has offered a new reason of why public activities can yield inefficient results even if the government is purely benevolent. We did not assume that distinct contracting possibilities or different informational assumptions put a wedge across different regimes. Rather, it is the welfare objective of a government which restricts its commitment capability not to accept low quality under the initial contracting terms. In comparison to trade between two private parties, this can adversely affect the incentives of a seller to undertake specific investments in the bilateral relationship.

Appendix

Appendix A: Description of the Renegotiation game

Renegotiations proceed according to a version of the extensive game form developed in Hart and Moore (1988). Specifically, we adopt the renegotiation game in Lülfesmann (2001) which allows to incorporate trade over multiple objects. Renegotiation and trade are modelled in three stages.

(a) Revision game (date 3)

Both agents can simultaneously submit messages to each other. The content of a message depends on whether ex-post verification is feasible or not. If verification is infeasible, a revision offer of party k is an *unconditional message* (p_0^k, p_t^k), i.e., the proposal of a revised trade and/or no-trade price. Conversely, if ex-post verification is feasible, agent k can alternatively submit a *conditional message*. A *conditional offer* contains a description of attributes V_i of at least one good, and a corresponding price proposal p_i^k.[40] Hence, a conditional offer of party k is a message $(V_i, p_i^k, V_j, p_j^k, P_0^k)$ for $i, j \in \{I, B\}$. Blanks are allowed which means that components can be left out, or that at the extreme no message is submitted. Taken together, a message can include

(1) (if ex-post verification is feasible) a physical description of the goods, which is represented by the vector of physical attributes V_i if only one good is specified, or (V_i, V_j) if two goods are described.

(2) any vector of revised prices. If the contract offer includes a description of goods, this vector can be (p_0, p_I, p_B). Otherwise, the only (enforceable) new price vector is (p_0, p_t).

A message is interpreted as a revised contract offer. It is delivered to the other party before date 4, and we assume that the submission is non-observable for the court.[41]

(b) Trade stage (date 4)

We consider the following sequential structure: the seller S first commits to the delivery of a good i or to no trade. Having observed the seller's decision, the government agrees to or refuses trade of good i. In the former case, the seller produces (and delivers) good i. If the government rejects, trade does not take place.[42] In either case, monetary payments may be exchanged.

[40] While in principle any arbitrary description is feasible, it is straightforward to check that there is no strategic use in specifying any non-existing good, and it suffices to concentrate on V_I, V_B.

[41] As a technical point, this assumption implies that the court cannot force parties to submit offers and, hence, rules out revelation games.

[42] Alternatively, one could imagine a sequential structure where the supplier immediately produces and delivers a good $i \in \{I, B\}$. Next, the government can decide whether to accept or reject delivery. If it accepts, physical trade is realized. This alternative sequencing leaves the qualitative conclusions of the paper unaffected.

(c) Dispute game (date 5)
Each party can sue its trade partner if it does not agree to the payments as realized at date 4. Specifically, both parties decide simultaneously whether to present a revised contract offer (which an agent received from its trading partner) to the court. The court rules as follows: the initial contract (p_0, p_t) remains in force unless

(1) one agent presents a new contract referring to the trade outcome at date 4 as observed by the court (which is 'trade' or 'no trade' if the message is non-contingent, or 'no trade' and 'trade of a good i' if ex-post verification is feasible and the revealed contract includes V_i);

(2) both parties present new contracts which refer to the physical outcome of date 4 as observed by the court, and which do not contradict each other with respect to payment provisions.

According to these rules, the court considers a new contract as irrelevant if it does not refer to the information partition of the court, which depends on whether ex-post verification is feasible or not.[43] Hence, if the court observes just one relevant offer, (1) applies and the new trade price contained in this offer is enforced. If both parties submit relevant new contracts, these new contracts are enforced if and only if both relevant trade prices coincide.[44]

Appendix B: Proofs of Propositions 1 and 5

We start by summarizing the equliibrium allocations and equilibrium prices in the unique undominated subgame-perfect equilibria of the renegotiation/trade stage:

Let $\lambda < (\overline{v}_B - c_B)/\overline{c}_I$. Under at-will contracting, the unique undominated subgame-perfect equilibrium of the renegotiation/trade game is ex-post efficient when ex-post verification is feasible. The corresponding equilibrium prices and allocations are as follows:

(A) $v_I - c_I(1+\lambda) > v_B - c_B(1+\lambda) > 0 \Leftrightarrow x_I = 1 = x_I^*$,

$$p_I^* = \begin{cases} max\{p_t + \delta, p_0 + c_I\} & if \quad p_t - p_0 \leq (v_B - c_B)/\lambda \\ min\{p_t, p_0 + (v_I - c_I)/\lambda\} & if \quad p_t - p_0 > (v_B - c_B)/\lambda, \end{cases}$$

[43] If ex-post verification is feasible, a conditional messages shifts the court's information partition from $\mathcal{I} = \{(x_0), (x_I, x_B)\}$ to $\mathcal{I}^* = \{(x_0), (x_I), (x_B)\}$.

[44] If one party k presents an offer consisting of a new trade price p_t^l, while $l \neq k$ presents an offer (p_i^k, V_i^k), these offers are not in contradiction after good i has been traded, and the court enforces the new contract if $p_t^l = p_t^k$. Otherwise, it is confronted with contradicting evidence with respect to prices, and the old contract remains valid. If $j \neq i$ has been traded in the same situation, however, the message presented by l is considered as irrelevant since it refers to a physical allocation not in line with the actual object of trade. Hence, only the message presented by k matters, and p_t^l is enforced by the court.

(B) $v_I - c_I(1+\lambda) > 0 > v_B - c_B(1+\lambda) \;\Leftrightarrow\; x_I = 1 = x_I^*$

$$p_I^* = \begin{cases} max\{p_t, p_0 + c_I\} & if \quad p_t - p_0 \leq (v_I - c_I)/\lambda \\ p_0 + (v_I - c_I)/\lambda & if \quad p_t - p_0 > (v_I - c_I)/\lambda \end{cases}$$

(C) $v_B - c_B(1+\lambda) > 0 > v_I - c_I(1+\lambda) \;\Leftrightarrow\; x_B = 1 = x_B^*,$

$$p_B^* = \begin{cases} max\{p_t, p_0 + c_B\} & if \quad p_t - p_0 \leq (v_B - c_B)/\lambda \\ p_0 + (v_B - c_B)/\lambda & if \quad p_t - p_0 > (v_B - c_B)/\lambda. \end{cases}$$

(D) $max\{v_I - c_I(1+\lambda), v_B - c_B(1+\lambda)\} < 0 \;\Leftrightarrow\; x_0 = 1 = x_0^*,\; p_0^* = p_0,$

where p_i^* *indicates the equilibrium trade price of good* i*. If ex-post verification is infeasible, the same outcome applies unless* $p_t - p_0 \leq (\bar{v}_B - c_B)/\lambda$ *in case (A). In this latter case, the basic good is traded at an equilibrium price* $p_B = max\{p_t, p_0 + c_B\}$*.*

The following proof computes equilibrium allocations and transfers in each possible state of the world for given initial terms of contract (p_0, p_t).

Case D: $x_i^* = 0,\; i \in \{I, B\}$
Trade of a good i under at-will contracting requires an equilibrium trade price p_i^* characterized by $(v_i - c_i)/\lambda \geq p_i^* - p_0 \geq c_i$. Since $v_i < c_i(1+\lambda), i \in \{I, B\}$, such a price does not exist. Hence, the parties face a zero-sum game at date 3: $x_0 = x_0^* = 1$ is the unique equilibrium allocation, and p_0 is paid by the government to the supplier.

Cases B, C: $x_i^* = 1$ *and* $v_j < c_j(1+\lambda), j \neq i$
First, note that the possibility of ex-post verification is irrelevant here: since the non-valuable good j can never be traded under at-will contracting, verification does not substantially enlarge the parties' strategy spaces. We begin by considering the case $(v_i - c_i)/\lambda \geq p_t - p_0 \geq c_i$, where both parties prefer trading i to no-trade under the initial terms of contract. Since each party can refrain from submitting any offer, and does not have to reveal received offers to the court, there is no room for renegotiation. Hence, the unique equilibrium allocation is $x_i = x_i^* = 1$, and x_i is traded at a price p_t. Now, assume initial terms of trade violating the above condition. Then, exactly one of the parties is not willing to trade i, such that trade requires renegotiation. Assume that the party k which is unwilling to trade submits an offer proposing a revised trade price p_t^k, where $(v_i - c_i)/\lambda \geq p_t^k - p_0 \geq c_i$. Imagine trade of i at date 4. Then, the receiver of the new contract offer will never reveal p_t^k to the court, since $p_t > p_t^k$ for $k = S$, and $p_t < p_t^k$ for $k = G$. Since the proposer was not willing to trade i at price p_t, equilibrium trade cannot occur at date 4. Therefore, a necessary condition for trade is a revision offer of the party which prefers trade to no trade under the initial prices. Consider an offer p_t^l of this party $l \neq k$ where

$(v_i - c_i)/\lambda \geq p_t^l - p_0 \geq c_i$. Suppose trade prevails at date 4. Then, the receiver k can (and will) reveal l's offer to the court in case of dispute, and p_t^l is enforced. Since k (at least weakly) prefers trade of i to no-trade, trade is realized at date 4. Moreover, l will submit the most favorable offer, which makes k just indifferent between trade and no trade, i.e. $p_t^{*l} = p_0 + c_i$ if $l = G$, and $p_t^{*l} = p_0 + (v_i - c_i)/\lambda$ if $l = S$. Notice that, given offer p_t^{*l}, agent k cannot submit a counteroffer which increases his equilibrium payoff. To check this, one must recognize that l always has the option not to reveal p_t^k to the court, so that his minimum continuation payoff is determined by p_t^{*l}. Moreover, both parties prefer trade of i to no trade at the price p_t^{*l}. This proves the existence of a unique trade equilibrium where $x_i = x_i^* = 1$ at a price $p_i^* = p_t^{*l}$.

Case A: $x_I^* = 1, v_B - c_B(1 + \lambda) > 0$

In these states of the world, both goods are valuable. First, consider initial contracts characterized by $p_t - p_0 > (\bar{v}_B - c_B)/\lambda$, where the seller cannot successfully deliver B under the initial contract. We will show that equilibrium outcomes are unaffected by the possibility to verify projects ex post, and that a unique undominated outcome prevails. In our analysis, we must distinguish between two subcases: (a) $(v_I - c_I)/\lambda \geq p_t - p_0 > (\bar{v}_B - c_B)/\lambda\,[> \bar{c}_I]$, i.e. both parties prefer trading I (but not B) to no trade under the initial terms of contract. In this case, no renegotiation is needed to attain an efficient outcome. Since either party can choose not to tender an offer, and will reveal only offers that lead to a higher own surplus to the court, the initial contract is not renegotiated and I is traded at $p_I^* = p_t$. (b) $p_t - p_0 > (v_I - c_I)/\lambda$. Now, efficient trade requires S to submit an offer. Therefore, consider the non-contingent message $p_t^S = p_0 + (v_I + c_I)/\lambda$. Given this offer, there exists no counteroffer which guarantees G a payoff larger than p_0: S will reveal any (contingent or non-contingent) counteroffer after trade only if this increases her surplus, which is impossible because trading I at p_t^S yields the largest possible U^S in any trade equilibrium. Along the same lines as in the states where only one good is valuable, one can also show that no additional undominated equilibrium outcome exists. Taken together, any initial contract comprising $p_t - p_0 > (\bar{v}_B - c_B)/\lambda$ will trigger efficient trade; moreover, ex-post verification is neither required nor does it affect the equilibrium outcome.

Finally, we analyze initial contracts $p_t - p_0 \leq (\bar{v}_B - c_B)/\lambda \equiv \hat{p}$. To start with, suppose that ex-post verification is feasible. First, consider $p_t - p_0 < c_B$. Then, the government submits an offer $(p_0 + c_B, V_I)$ which makes S indifferent between trade of I and no trade. This equilibrium outcome is unique if pareto-dominated (no-trade or B-trade) equilibria are ruled out. Second, consider an initial contract $(\bar{v}_B - c_B)/\lambda \geq p_t - p_0 \geq c_B$. Then, G will submit an offer $(p_I^G = p_t + \delta, V_I)$ while S tenders a counteroffer $(p_B^S = p_t, V_B)$.[45]

[45] G may have an interest to prevent trade of B by submitting a contingent offer $(p_B^G > (\bar{v}_B - c_B)/\lambda, V_B)$ in order to obtain I at a price smaller than $p_t + \delta$. The seller's counteroffer neutralizes this incentive since it protects her option to successfully deliver B at price p_t (note that, for given messages comprising

Suppose now that ex-post verification is infeasible. As a necessary condition for efficient trade of I, the government must submit a renegotiation offer which increases the equilibrium trade price above $\hat{p}$. Provided that S submits no counteroffer, G's unique best response is therefore an offer (slightly higher than) $p_t^G = \hat{p}$. We will show that this one-sided offer cannot represent an equilibrium profile of strategies at the revision stage. To continue our analysis, it is useful to state the following lemma:

Lemma 1: *Suppose that both parties submit a renegotiation offer. (a) For any initial contract (p_0, p_t), the equilibrium trade price is characterized as $p_t^e \leq max\{p_t^S, p_t^G\}$. (b) Suppose $p_t - p_0 \leq \hat{p}$. For any offer $p_t^k > \hat{p}$ submitted by party k, there exists a counteroffer $p_t^l \geq p_t$ which implements any arbitrary equilibrium trade price p_t^e from the interval $[p_t, p_t^k]$.*

Proof: (a) Note that any strategy combination (p_t^S, p_t^G) cannot lead to an equilibrium trade price $p_t^e > p_t$ unless $\min\{p_t^G, p_t^S\} >> p_t$. Notice further that, whenever $\bar{p} \equiv \min\{p_t^S, p_t^G\} >> p_t$, there does not exist a pure-strategy equilibrium at the dispute stage of the game unless $p_t^S = p_t^G$. Suppose that $p_t^S >$ (respectively $<$) p_t^G. In either case, the government can itself ensure its minmax payoff $-\bar{p}$ by revealing p_t^S with probability $g = 0$ (or $g = 1$, respectively). Accordingly, $p^e \leq \bar{p}$ prevails. (b) Suppose $p_t^k > \hat{p}$, $p_t^l > p_t$ and $p_t^l \neq p_t^k$. The unique mixed equilibrium is characterized by the equilibrium revelation strategies $g^* = (p_t^G - p_t)/(p_t^G + p_t^S - 2p_t)$ and $s^* = (p_t^S - p_t)/(p_t^G + p_t^S - 2p_t)$ at the dispute stage. Accordingly, the expected trade price is computed as $p_t^e = p_t + (p_t^G - p_t)(p_t^S - p_t)/(p_t^G + p_t^S - 2p_t)$. For any p_t^k, this equilibrium trade price is monotonically increasing in p_t^l, takes the value $p_t^e = p_t$ for $p_t^l = p_t$, and converges to $p_t^e = \min\{p_t^G, p_t^S\}$ as $p_t^l \to \infty$. $\square$

The second part of Lemma 1 asserts that, for any offer $p_t^G > \hat{p}$ that is necessary to trigger efficient trade, the seller can tender a counteroffer p_t^S which induces an equilibrium trade price of $p_t^e = \hat{p}$, and accordingly leads to trade of B in any continuation equilibrium. In combination with the first part of the lemma, this implies that efficient trade requires the government to tender a renegotiation offer weakly larger than $\hat{p} + \delta$. By our earlier arguments, G will not submit such an offer provided S tenders no counteroffer. Hence, consider a tuple of offers (p_t^S, p_t^G) with $p_t^G \geq \hat{p} + \delta$. Clearly, S's best response on p_t^G is then either no counteroffer (which cannot constitute an equilibrium by our earlier arguments), or an offer characterized by $p_t^S >> p_t^G$. By Lemma 1, however, the government's best response on p_t^S is again an offer $p_t^G > p_t$ that triggers an equilibrium trade price slightly above $\hat{p}$.[46] Accordingly, I cannot be traded in equilibrium and it is easy to compute the parties' equilibrium strategies for any $p_t - p_0 \leq \hat{p}$: first, if $p_t - p_0 < c_B$, G submits an offer $p_t^G = p_0 + c_B$ which leads to trade of B at a price $p_t^e = p_t^G$. Second, if

$(p_B^S = p_t, V_B)$ and $(p_B^G > \bar{p}, V_B)$, both parties have a dominant strategy to reveal messages in the dispute game after B has been traded, and $p^e = p_t$ prevails).

[46]Similarly, the parties will not submit identical messages with $p_t^G = p_t^S \geq \hat{p} + \delta$ in equilibrium.

$\hat{p} \geq p_t - p_0 \geq c_B$, S submits an offer $p_t^S = p_t$ which induces trade of B at p_t (recall that S needs to tender this offer), and renders any counteroffer by G useless. Accordingly, the equilibrium coincides with a situation where I does not exist.□

Appendix C: Proofs of Propositions 3 and 4

Table 1 in combination with our restriction on λ implies that

$$(\overline{v}_I - \underline{c}_I)/\lambda > \min\{(\overline{v}_I - \overline{c}_I)/\lambda, (\underline{v}_I - \underline{c}_I)/\lambda\} > (\overline{v}_B - c_B)/\lambda > \overline{c}_I > c_B$$

where $\lambda < \bar{\lambda}$ implies the third inequality. The following proof constructs and examines all feasible ex-ante contracts.

(1) $p_t - p_0 < c_B$.
If trade of good $i \in \{I, B\}$ is ex-post efficient, the equilibrium trade price is $p_i^* = p_0 + c_i$. Inserting these prices into (**??**) yields zero investment incentives, since the supplier's net payoff is p_0 in all states of the world.

(2) $\underline{c}_I > p_t - p_0 \geq c_B$.
Here, we have $p_I^{(i)} = p_I^{(iii)} = p_t + \underline{\delta}$, $p_I^{(ii)} = p_I^{(iv)} = p_0 + \underline{c}_I$, $p_I^{(v)} = p_t + \overline{\delta}$, $p_I^{(vi)} = p_0 + \overline{c}_I$ and $p_B^{(vii)} = p_t$. Substituting into (**??**), we once again obtain zero equilibrium investments: the supplier realizes a production rent $p_t - p_0 - c_B$ with probability q, which is independent of the firm's investment decision.

(3) $\overline{c}_I > p_t - p_0 \geq \underline{c}_I$.
At these prices, the firm's production rent depends on the innovation's production costs. Corollary 1 yields $p_I^{(i)} = p_I^{(iii)} = p_t + \underline{\delta}$, $p_I^{(ii)} = p_I^{(iv)} = p_t$, $p_I^{(v)} = p_t + \overline{\delta}$, $p_I^{(vi)} = p_0 + \overline{c}_I$ and $p_B^{(vii)} = p_t$. Inserting these prices into (**??**), we obtain the following condition for efficient investments:

$$A^* = \frac{\underline{v}_I - q\overline{v}_B}{1+\lambda}(1-\mu) = (p_t - p_0)(1-q) + q\underline{\delta} - \mu\overline{\delta} - (1-q)\mu c_B = A. \tag{8}$$

Defining $S = A - A^*$ as the excess investment function of the firm, we have $\partial S/\partial(p_t - p_0) = (1-q) \geq 0$ and

$$\frac{\partial S}{\partial q} = \frac{\overline{v}_B}{1+\lambda}(1-\mu) + c_B\mu + \underline{\delta} - (p_t - p_0) < 0 \quad \text{iff} \quad p_t - p_0 > \frac{\overline{v}_B}{1+\lambda}(1-\mu) + c_B\mu + \underline{\delta} \tag{9}$$

If $q = 0$, the optimal $(p_t - p_0)^* = (1-\mu)\underline{v}_I/(1+\lambda) + \mu\overline{c}_I$ meets the condition on the right-hand side of (12). Hence, since $\partial S/\partial q < 0$ and $\partial S/\partial(p_t - p_0) > 0$, $(p_t - p_0)^*$ must increase in q in the neighborhood of $q = 0$. At the upper bound of interval (3), i.e. $p_t - p_0 = \overline{c}_I$, efficient investments are feasible for all q smaller than

$$q^*(S = 0, p_t - p_0 = \overline{c}_I) = \frac{(\overline{c}_I - \underline{v}_I/(1+\lambda))(1-\mu)}{\overline{\delta} - \underline{\delta} + [c_B - \overline{v}_B/(1+\lambda)](1-\mu)} \tag{10}$$

where $0 < q^* < 1$ by the assumptions made in table 1. We can conclude that the first-best investment level is feasible as long as $0 \leq q \leq q^* < 1$.

(4) $(\overline{v}_B - c_B)/\lambda \geq p_t - p_0 \geq \overline{c}_I$.
Corollary 1 implies $p_I^{(i)} = p_I^{(iii)} = p_t + \underline{\delta}$, $p_I^{(ii)} = p_I^{(iv)} = p_I^{(vi)} = p_t$, $p_I^{(v)} = p_t + \overline{\delta}$ and $p_B^{(vii)} = p_t$. Inserting these equilibrium prices, the efficiency condition (**??**) becomes

$$A^* = \frac{\underline{v}_I - q\overline{v}_B}{1+\lambda}(1-\mu) = (p_t - p_0)(1-q)(1-\mu) + q\underline{\delta} - q\mu\overline{\delta} = A. \tag{11}$$

Again, defining $S = A - A^*$ as the excess investment function of the firm, one obtains $\partial S/\partial(p_t - p_0) = (1-q)(1-\mu) \geq 0$ and

$$\frac{\partial S}{\partial q} = -(p_t - p_0 - \frac{\overline{v}_B}{1+\lambda})(1-\mu) + \underline{\delta} - \mu\overline{\delta} < 0 \tag{12}$$

by the assumptions made in table 1 (note that $\overline{v}_B/(1+\lambda) < \underline{v}_I/(1+\lambda) - \underline{\delta} < \overline{\delta} + c_B - \underline{\delta}$). At the lower bound of interval (4), i.e. $p_t - p_0 = \overline{c}_I$, the excess investment function S becomes zero for $q = q^*$. Since S is decreasing in q for any initial contract, and increasing in the price difference, we can now calculate the threshold level $\hat{q}$ generating $S(\hat{q}, p_t - p_0 = (\overline{v}_B - c_B)/\lambda) = 0$ at the upper bound of the interval. We obtain

$$\hat{q} = \frac{[(\overline{v}_B - c_B)(1+\lambda) - \lambda\underline{v}_I](1-\mu)}{[(\overline{v}_B - c_B)(1+\lambda) - \lambda\overline{v}_B](1-\mu) + [\mu\overline{\delta} - \underline{\delta}](1+\lambda)\lambda}\,. \tag{13}$$

Under the assumptions of table 1 and on λ, numerator (note that $\overline{v}_B - c_B > \overline{c}_I\lambda$ for any $\lambda < \bar{\lambda}$) and denominator (recall the sign of (**??**)) are positive, and in addition $\hat{q} << 1$ (note that $\underline{v}_I/(1+\lambda) > \overline{v}_B/(1+\lambda) + \underline{\delta}$). Therefore, efficient investments can be induced in interval (4) for all $q \in [0, \hat{q} << 1]$, while underinvestments prevail in the complementary non-empty interval $q > \hat{q}$.

(5) $(\overline{v}_B - c_B)/\lambda < p_t - p_0 \leq \min\{(\overline{v}_I - \overline{c}_I)/\lambda, (\underline{v}_I - \underline{c}_I)/\lambda\}$.
Under these initial contracts, equilibrium prices are $p_I^i = p_I^{ii} = p_I^{iii} = p_I^{iv} = p_I^v = p_I^{vi} = p_t$ and $p_B^{vii} = p_0 + (\overline{v}_B - c_B)/\lambda$. Substituting these prices into (**??**) gives

$$A^* = \frac{\underline{v}_I - q\overline{v}_B}{1+\lambda}(1-\mu) = (1-\mu)[(p_t - p_0) - q\frac{\overline{v}_B - c_B}{\lambda}] = A. \tag{14}$$

Examining this condition, we again observe that the excess investment function is increasing in the price difference. Moreover,

$$\frac{\partial S}{\partial q} = (1-\mu)[-\frac{\overline{v}_B - c_B}{\lambda} + \frac{\overline{v}_B}{1+\lambda}] < 0. \tag{15}$$

Hence, excess investment decreases in q for any ex-ante prices in interval (5). We investigate the lower bound of the interval, and calculate $S(\tilde{q}, p_t - p_0 = (\overline{v}_B - c_B)/\lambda) = 0$. Solving for the threshold level $\tilde{q}$, we arrive at

$$\tilde{q} = \frac{(\overline{v}_B - c_B)(1+\lambda) - \lambda \underline{v}_I}{(\overline{v}_B - c_B)(1+\lambda) - \lambda \overline{v}_B}, \tag{16}$$

where $1 > \tilde{q} > 0$ under the assumptions of table 1 and on λ. Accordingly, overinvestments in the considered interval prevail for any $q \in [0, \tilde{q})$. Notice that $\tilde{q} > \hat{q}$ if and only if

$$\mu > \underline{\delta}/\overline{\delta}, \tag{17}$$

and equilibrium investments discontinuously increase at $p_t - p_0 = (\overline{v}_B - c_B)/\overline{c}_I \equiv \hat{p}$. Hence, no contract from the price intervals (1) to (5) induces efficient investments whenever $q \in (\tilde{q}, \hat{q})$ and (**??**) applies.

(6) Finally, for intervals characterized by a price difference $p_t - p_0 > \min\{(\underline{v}_I - \underline{c}_I)/\lambda, (\overline{v}_I - \overline{c}_I)/\lambda\}$, equilibrium investments are increasing in the ex-ante contracted price difference. Moreover, since incentives are continuous at the lower bounds of each of these intervals, we have proved that efficient investments are feasible only if $q \notin [\hat{q}, \tilde{q}]$, or if (**??**) does not apply.

To conclude, in the scenario with ex-post verification efficient investments can be implemented unless $q \in (\hat{q}, \tilde{q})$ and (**??**) jointly hold, which proves Proposition 4. To prove Proposition 3, note that efficient investments can be implemented for all $q \leq \hat{q}$. Since $\hat{q}$ converges to unity as $\lambda \to 0$, efficient investments can be implemented unless $q = 1$. In particular, inserting equilibrium prices in intervals (1) to (4) into the first-order condition (**??**) in the main text, we obtain $e^S(q = 1) = 0$, which completes the proof of Proposition 3. □

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