Incomplete Procurement Contracting with a Risk-Averse Agent

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Abstract

In a two-stage procurement model, we compare long-term fixed-price contracting with sequential contracting such that after the risk-averse seller invests in cost reduction and the uncertainty regarding production costs is resolved, the product price is determined through competitive bidding between the seller and the entrant. We show that sequential contracting generates higher surplus than long-term contracting when both the seller and the entrant confront an aggregate risk not an and the investment externality on the entrant's production cost is low.

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1. Introduction

There are two concerns in procurement contracting: providing incentives for cost-reducing investment and risk sharing between contracting parties. In plant or building construction, a large company contracts with a contractor. The contractor's investment in design specifications at an early stage can reduce costs in the subsequent construction stages. The exact amount of construction costs is determined only at a later stage, depending on various exogenous factors, such as the availability of subcontractors and price fluctuations for raw materials, and thus is uncertain at the early stage. The performance of a contract can be assessed by its effect on these two issues.

While the result in the moral-hazard literature demonstrates the effectiveness of cost-sharing contracts, simple fixed-price contracts are also commonly used in many industries.[1] In the plant engineering industry, the scheme called "lump-sum turnkey" has historically been prevalent. Under this contracting scheme, a fixed price for entire works is agreed at the outset of a long-term project. The scheme provides the contractor with strong incentives for cost-reducing investment, but it imposes most of the risk on the contractor. The bankruptcy of a major US engineering firm, Stone & Webster, in 2000 was attributed to the lump-sum turnkey projects (Engineering News-Record, 2000). Alternatively, the scope for execution can be split into several contracts to be awarded sequentially as the project information and design develop (Navarrete, 1995). A purchaser, for instance, initially awards the FEED (Front End Engineering Design) contract to a contractor at a fixed price, and then awards the EPC (Engineering, Procurement, and Construction) contract to the contractor selected via competitive bidding at a fixed price. This alternative scheme may decrease the amount of risk allocated to the contractor, but may lessen the contractor's *ex ante* investment incentives since the scheme allows the purchaser to extract the benefit from cost reduction in the *ex post* awarding process.

The aim of this study is to compare two fixed-price contracting schemes, *long-term contracting* and *sequential contracting*, and to derive conditions under which each scheme is more efficient than the other. We develop a model based on the *incomplete contract* setting. A risk-neutral buyer (purchaser) procures a product such as a plant from a risk-averse seller (contractor).[2] Under long-term contracting, the fixed prices of design specifications and product are prespecified, and then the seller invests in cost reduction and produces the product. Under sequential contracting, after the seller invests and the uncertainty about production costs is resolved, the buyer procures the product via competitive bidding between the seller and a potential entrant, with the design specifications delivered by the seller. As one would expect, long-term contracting dominates sequential contracting when the seller is risk-neutral.

The main results are as follows. Once the seller is risk-averse, sequential contracting generates higher surplus than long-term contracting when both the seller and the entrant confront *aggregate risk* in production costs and the investment externality on the entrant's production cost is low. On the other hand, long-term contracting generates higher surplus than sequential contracting when each of them confronts his *idiosyncratic risk* in production costs.

[1] Bajari and Tadelis (2001) argue that fixed-price contracts, which have no need to measure actual construction costs, will dominate a larger set of cost-sharing contracts as it becomes more expensive to measure costs.

[2] In the petroleum industry, large oil companies (e.g., Exxon Mobil) procure new plants from specialized contractors. Olsen and Osmundsen (2005), who also assume that the seller is risk-averse, argue that contractors are less able to carry risk since, for example, their portfolios of projects are less diversified.

One of the insights of transactions cost economics is that long-term contracts can enhance efficiency by fostering relation-specific investment (Miceli, 2008). Assuming that both the buyer and the seller are risk-neutral, Edlin and Reichelstein (1996) formally show that a long-term contract (with either a breach remedy for specific performance or expectation damages) can induce a party to choose an efficient level of "selfish" investment (in the sense of Che and Hausch, 1999), such as cost-reducing investment by the seller. While a long-term contract can typically prevent opportunistic behavior by parties and resolve the holdup problem, its rigidity imposes most of the risk on one party. Our first result implies that in the case of aggregate risk, sequential contracting, which is more flexible than long-term contracting, has an advantage in sharing risk between the parties.

A few studies have simultaneously analyzed both the holdup problem and the risk-sharing issue in incomplete contracts. Aghion et al. (1994) show that a long-term contract with a complex revelation mechanism achieves *ex ante* efficiency in a general environment where both the buyer and the seller make selfish investments, both parties are risk-averse, and the good to be traded is perfectly divisible. Their mechanism, however, cannot be observed in practice. In the same environment as Aghion et al. except that the buyer is risk-neutral, Chung (1991) provides some sufficient conditions under which a long-term contract prespecifying both the status quo and the parties' powers in *ex post* bargaining achieves *ex ante* efficiency: the seller's production cost is either independent of his investment or nonstochastic. These conditions prohibit us from analysing the trade-off between incentive provision and risk sharing.

The remainder of the paper is organized as follows. Section 2 presents the model. Section 3 characterizes the equilibrium outcome under each scheme and provides the sufficient conditions under which each scheme generates higher surplus than the other. Section 4 concludes. All proofs are in the Appendix.

2. The model

A risk-neutral buyer B procures one unit of product such as a plant. A risk-averse seller S has CARA utility function $u(\pi) = 1 - \exp(-r\pi)$, where $\pi \in \mathbb{R}$ and $r > 0$ is his coefficient of absolute risk aversion.

Valuation $v > 0$ for the product by B is common knowledge. S invests in design specifications before production of the product. With the design specifications, B can procure the product from either the seller S or a potential entrant E. Investment $a \in \mathbb{R}_+$ by S reduces the production costs for both S and E (c_S and c_E, respectively). Each $c_i(a, \theta_i)$ for $i = S, E$ is a function of both an investment level a and a random variable $\theta_i \in [\underline{\theta}, \bar{\theta}]$ representing exogenous factors in the cost. If S chooses an investment level a, which is equal to his investment cost, then his total cost is $a + c_S(a, \theta_S)$. We make the following assumptions.

Assumption 1. The function $c_i : \mathbb{R}_+ \times [\underline{\theta}, \bar{\theta}] \to \mathbb{R}_+$ is twice continuously differentiable in a, $\frac{\partial c_i(a,\theta_i)}{\partial a} < 0$, $\frac{\partial^2 c_E(a,\theta_E)}{\partial a^2} > \frac{\partial^2 c_S(a,\theta_S)}{\partial a^2} > 0$, $\lim_{a\to 0} \frac{\partial c_S(a,\theta_S)}{\partial a} = -\infty$, $\lim_{a\to 0} \frac{\partial c_E(a,\theta_E)}{\partial a} > -\infty$, and $\lim_{a\to\infty} \frac{\partial c_i(a,\theta_i)}{\partial a} = 0$, for all a, all θ_i, and all $i = S, E$.

Assumption 2. $v > c_E(a, \theta_E) > c_S(a, \theta_S)$ for all a and all θ_S, θ_E.

Assumption 3. $-\frac{\partial c_S(a,\theta_S)}{\partial a} > -\frac{\partial c_E(a,\theta_E)}{\partial a}$ for all a and all θ_S, θ_E.

Assumption 4. c_S is strictly increasing in θ_S.

Assumption 1 ensures a unique interior solution for the optimal investment levels. Assumptions 2 and 3 imply that S has an advantage in production over E. Assumption 2 also ensures that trade of the product between B and either seller (S or E) generates positive gains. Assumption 4 is almost without loss of generality.

The procurement game proceeds as follows. At date 0, B chooses between two contracting schemes: long-term contracting and sequential contracting. If B selects long-term contracting, then the game proceeds as follows. At date 1, B offers two fixed prices $(p_1, p_2) \in \mathbb{R}^2$ in exchange for both the design specifications and the product.[3] S then either accepts or rejects the offer. If S rejects the offer, the game ends and B and S obtain their reservation utilities 0. If S accepts the offer, the game continues. At date 2, S chooses an investment level a. At date 3, random variables (θ_S, θ_E) are realized and the game ends. If B selects sequential contracting at date 0, then the game proceeds as follows. At date 1, B offers a fixed price $p_1 \in \mathbb{R}$ in exchange only for the design specifications. The game continues in the same way as for long-term contracting until date 3. At date 4, in competitive bidding, S and E simultaneously submit a bid $p_2 \in \mathbb{R}$ for the right to produce and sell the product, with complete knowledge of the price p_1 and each other's production costs $c_S(a, \theta_S)$, $c_E(a, \theta_E)$. In a first-price auction, the seller who submits the lowest bid wins; when both sellers submit the same bid, S wins with his cost advantage. The game then ends.

Under complete information, the equilibrium outcome of competitive bidding at date 4 is the same as that of Bertrand competition; in a unique equilibrium both S and E submit $p_2 = c_E(a, \theta_E)$ and S wins.[4] Thus, under either scheme, S produces the product in the equilibrium outcome.

Given prices (p_1, p_2), investment a, and the realization of (θ_S, θ_E), the payoff for B is $U_B = v - (p_1 + p_2)$ and that for S is $U_S = 1 - \exp\{-r[(p_1 + p_2) - a - c_S(a, \theta_S)]\}$.

We assume that investment a, realization of (θ_S, θ_E), and production costs $c_S(a, \theta_S)$, $c_E(a, \theta_E)$ are unverifiable. When B can offer an initial contract in which prices are contingent on both the investment a and the realization of θ_S (or both the investment a and the realization of $c_S(a, \theta_S)$), the *ex ante* efficient outcome is realized, in which (i) S chooses the *efficient investment level* $\tilde{a}$ that minimizes expected total cost $a + E[c_S(a, \theta_S)]$,[5] and (ii) B pays the realized total cost $\tilde{a} + c_S(\tilde{a}, \theta_S)$ for all θ_S to S. B then obtains the *first-best payoff* $v - \{\tilde{a} + E[c_S(\tilde{a}, \theta_S)]\}$.

3. Optimal contracting scheme

In this section, we explore the (pure strategy) subgame perfect equilibrium of the procurement game. We focus on the following two cases. Case (i): θ_S and θ_E are statistically independent. Case (ii): For any investment level a, production costs $c_S(a, \theta_S)$ and $c_E(a, \theta_E)$ have a perfect positive correlation and the same variance.

The first case may be plausible when each seller confronts his idiosyncratic risk, such

[3] B pays a total price $p_1 + p_2$ after both the design specifications and the product are delivered. We can assume instead that B pays each price just after S delivers the corresponding object.

[4] Whether or not the buyer knows the realized production costs does not affect the outcome. Even if each seller knows only his own production costs, the same outcome (S wins and the price is $c_E(a, \theta_E)$) can be obtained in a second-price auction; the pair of truth-telling strategies is a dominant strategy equilibrium.

[5] In this paper, $E[\cdot]$ and $\mathrm{Cov}(\cdot, \cdot)$ represent the expectation operator and the covariance operator of random variables, respectively.

as the availability of subcontractors. The second case may be plausible when both S and E confront aggregate risk, such as price fluctuations for raw materials for the plant or uncertain buyer requirements.

First, consider case (i). Before examining the equilibrium outcome, we characterize the *risk premium* for S. After S delivers the product, he obtains profit $\pi = (p_1 + p_2) - a - c_S(a, \theta_S)$ under long-term contracting with prices (p_1, p_2) and profit $\pi' = (p'_1 + p'_2) - a - c_S(a, \theta_S)$ under sequential contracting with prices $(p'_1, p'_2 = c_E(a, \theta_E))$. Competitive bidding determines the price as if the production costs for E are verifiable. These profits are random variables. The risk premium $\rho \geq 0$ for S for π is such that his expected utility $E[u(\pi)]$ is equal to $u(E[\pi] - \rho)$. His risk premium $\rho' \geq 0$ for π' is defined in the same way.

Lemma 1. Let ρ be the risk premium for S for $\pi = (p_1 + p_2) - a - c_S(a, \theta_S)$, and ρ' be that for $\pi' = (p'_1 + c_E(a, \theta_E)) - a - c_S(a, \theta_S)$. Then, in case (i), for any prices $(p_1, p_2), p'_1$ and any investment level a, $\rho' > \rho > 0$.

Lemma 1 shows that S bears even more risk under sequential contracting than under long-term contracting if the investment level a is the same under either scheme. This result is trivial. Since production costs $c_S(a, \theta_S)$ and $c_E(a, \theta_E)$ are statistically independent in case (i), S must bear an additional risk for the product price $p_2 = c_E(a, \theta_E)$ under sequential contracting.

We next characterize the equilibrium investment level under each scheme. Let a^* denote the equilibrium investment level in the subgame after B chooses long-term contracting at date 0, and a^{**} denote that for sequential contracting.

Lemma 2. In case (i), $a^* > a^{**}$.

This result is a version of the holdup problem. The investment by S is "relation-specific" since the investment is made to produce the product customized for B. Under long-term contracting, S can capture the full benefit from the relation-specific investment, with advance assurance of the product price and no room for renegotiation. However, under sequential contracting, an increase in investment induces aggressive bidding by E at date 4 and reduces the product price $p_2 = c_E(a, \theta_E)$ because of the positive externality for the production costs of E. Owing to the reduction in price $-\frac{\partial c_E(a, \theta_E)}{\partial a} > 0$, S has an incentive to lower the investment level compared to long-term contracting. We can interpret competitive bidding as opportunistic behavior by B.

However, we cannot generally say whether each equilibrium investment level is lower or higher than the efficient level $\tilde{a}$, since investment by S affects the riskiness of the production costs. Lemma 4 provides further details.

The equilibrium expected payoffs for B for long-term and sequential contracting are given by

$$EU_B^* = v - \left\{ a^* + \frac{1}{r} \ln\{E[\exp(rc_S(a^*, \theta_S))]\} \right\},$$

$$EU_B^{**} = v - \left\{ a^{**} + \frac{1}{r} \ln\{E[\exp(-r(c_E(a^{**}, \theta_E) - c_S(a^{**}, \theta_S)))]\} + E[c_E(a^{**}, \theta_E)] \right\},$$

respectively. The bracket terms are total payments to S. The following proposition shows that in the equilibrium outcome, B always chooses long-term contracting rather than sequential contracting.

Proposition 1. In case (i), for any coefficient of absolute risk aversion r, the optimal scheme for B is long-term contracting, which generates higher surplus than sequential contracting.

Figure 1 illustrates this result. Under sequential contracting, which imposes more risk on S than long-term contracting does, B must make a higher total payment. Therefore, in the case of idiosyncratic risk, the superiority of long-term contracting over sequential contracting holds even if S is risk-averse.

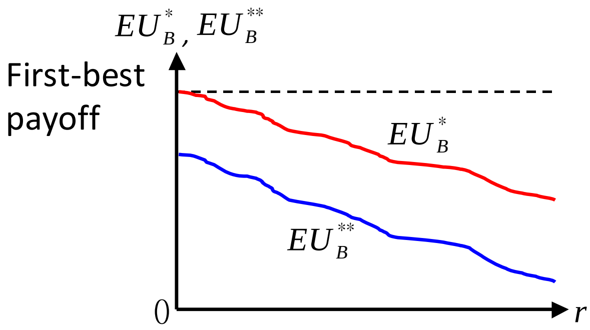

Figure 1: Illustration of Proposition 1.

Second, consider case (ii). In the same way as for case (i), we characterize the risk premium for S and the equilibrium investment levels a^* and a^{**} in the following lemmas.

Lemma 3. Let ρ be the risk premium for S for $\pi = (p_1 + p_2) - a - c_S(a, \theta_S)$, and ρ' be that for $\pi' = (p_1' + c_E(a', \theta_E)) - a' - c_S(a', \theta_S)$. Then, in case (ii), for any prices $(p_1, p_2), p_1'$ and any investment levels a, a', $\rho > \rho' = 0$.

Under long-term contracting in which prices are fixed in advance, S must bear all production cost risks. However, the assumption for case (ii) ensures that under sequential contracting, the contract price $p_2 = c_E(a, \theta_E)$ is determined to eliminate the risk that S must bear; when his production cost is high (low), the cost for his competitor E is also high (low) so that S can (must) submit a high (low) bid.

Lemma 4. In case (ii), $a^{**} < \tilde{a}$. In both cases,

$$a^* > \tilde{a} \quad \text{if} \quad -\frac{\partial c_S(a, \theta_S)}{\partial a} \text{ is increasing in } \theta_S, \tag{1}$$

$$a^* = \tilde{a} \quad \text{if} \quad -\frac{\partial c_S(a, \theta_S)}{\partial a} \text{ is independent of } \theta_S, \tag{2}$$

$$a^* < \tilde{a} \quad \text{if} \quad -\frac{\partial c_S(a, \theta_S)}{\partial a} \text{ is decreasing in } \theta_S. \tag{3}$$

Under long-term contracting, S has an incentive to decrease risk in production costs. If condition (1) (condition (3)) is satisfied, then an increase in investment changes the distribution of his production costs to a less (more) risky one, so that S has an incentive to overinvest (underinvest). If condition (2) is satisfied, so that an increase in investment only changes the expectation for the production costs of S, then there are no such distortions. However, under sequential contracting, S bears no risk, as explained in Lemma 3. Then, owing to the holdup problem, underinvestment occurs.

The following proposition presents the main result. To specify the supremum of the total payment under long-term contracting, let $\bar{a}^*$ denote the optimal investment level for the infinitely risk-averse S under the scheme; the Appendix shows that $\bar{a}^* = \arg\min_a[a + c_S(a, \bar{\theta})]$ and the supremum of the total payment is $\bar{a}^* + c_S(\bar{a}^*, \bar{\theta})$.

Proposition 2. Consider case (ii). If $\bar{a}^* + c_S(\bar{a}^*, \bar{\theta}) \leq a^{**} + E[c_S(a^{**}, \theta_S)]$, then the optimal scheme for B is long-term contracting, which generates higher surplus than sequential contracting, for all r. Otherwise, there exists a threshold $\hat{r} > 0$ such that the optimal scheme for B is long-term contracting, which generates higher surplus than sequential contracting, for all $r < \hat{r}$, and sequential contracting, which generates higher surplus than long-term contracting, for all $r > \hat{r}$.

Figure 2 illustrates this result. Under sequential contracting, although S bears no risk so that B only pays the expected total cost $a^{**} + E[c_S(a^{**}, \theta_S)]$, the investment level a^{**} is lower than the efficient level. Under long-term contracting, as S is more risk-averse, B must pay a higher risk premium to induce S to participate in this trade. In particular, if S is infinitely risk-averse, then B must compensate the highest production cost $c_S(\bar{a}^*, \bar{\theta})$ as if B faces a limited liability constraint. Therefore, in the case of aggregate risk, if the externality on the production cost for E is sufficiently low so that under sequential contracting S optimally chooses an investment level close to the efficient level, then B optimally chooses sequential contracting for sufficiently large r.

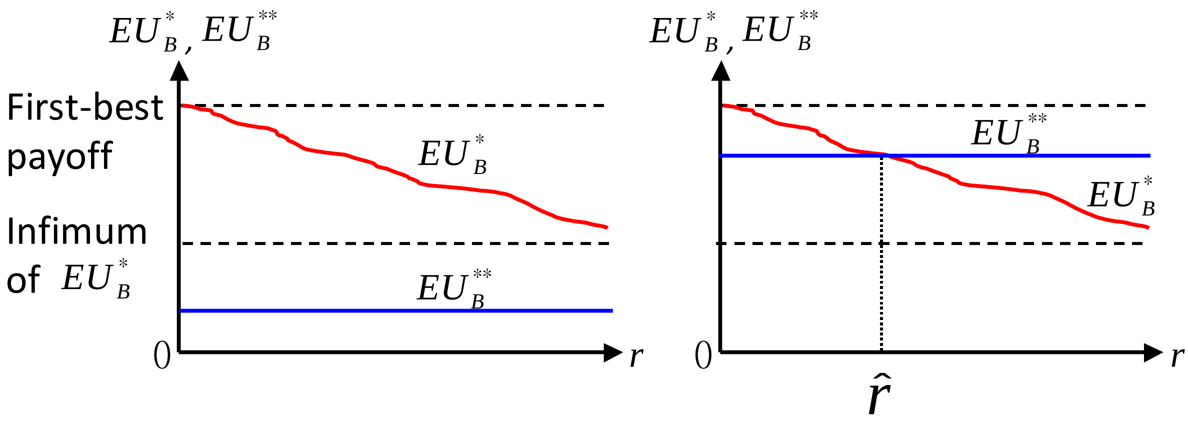

Figure 2: Illustration of Proposition 2.

4. Concluding remarks

We compared two types of fixed-price contracting schemes, long-term contracting and sequential contracting, and established sufficient conditions under which each scheme generates higher surplus than the other. Sequential contracting may be more incomplete than long-term contracting, for which the product characteristic must be described in advance. A risk-sharing issue may induce the buyer to endogenously choose a more incomplete contract, provided that only these two schemes are feasible.

Sequential contracting is so flexible that the buyer may be able to use procurement mechanisms other than competitive bidding, such as negotiated contracts (see Bajari et al., 2008, for an empirical analysis of private-sector building contracts). Investigation of the optimality of sequential contracting with other mechanisms is left for future research.

Appendix

Proof of Lemma 1. In case (i), $c_S(a,\theta_S)$ and $c_E(a,\theta_E)$ are statistically independent. Thus,

$$\rho' - \rho = E[c_E(a,\theta_E)] + \frac{1}{r}\ln\{E[\exp(-rc_E(a,\theta_E))]\} > 0.$$

This follows from a simple calculation and Jensen's inequality. □

Proof of Lemma 2. The expected utility for S on choosing a at date 1 is $E[1-\exp\{-r[(p_1+p_2)-a-c_S(a,\theta_S)]\}]$ under long-term contracting, and $E[1-\exp\{-r[p_1-a+c_E(a,\theta_E)-c_S(a,\theta_S)]\}]$ under sequential contracting. The necessary and sufficient first-order conditions for a^* and a^{**} are given by

$$-\frac{E\left[\frac{\partial c_S(a^*,\theta_S)}{\partial a}\cdot\exp(rc_S(a^*,\theta_S)\right]}{E[\exp(rc_S(a^*,\theta_S)]} = 1, \tag{4}$$

$$-\frac{E\left[\left(\frac{\partial c_S(a^{**},\theta_S)}{\partial a}-\frac{\partial c_E(a^{**},\theta_E)}{\partial a}\right)\cdot\exp(-r(c_E(a^{**},\theta_E)-c_S(a^{**},\theta_S)))\right]}{E[\exp(-r(c_E(a^{**},\theta_E)-c_S(a^{**},\theta_S)))]} = 1. \tag{5}$$

Since $c_S(a,\theta_S)$ and $c_E(a,\theta_E)$ are statistically independent in case (i), condition (5) is

$$-\frac{E\left[\frac{\partial c_S(a^{**},\theta_S)}{\partial a}\cdot\exp(rc_S(a^{**},\theta_S)\right]}{E[\exp(rc_S(a^{**},\theta_S)]} = 1-\frac{E\left[\frac{\partial c_E(a^{**},\theta_E)}{\partial a}\cdot\exp(rc_E(a^{**},\theta_E)\right]}{E[\exp(rc_E(a^{**},\theta_E)]}. \tag{6}$$

The second term on the right-hand side of (6) is strictly positive, so we have $a^* > a^{**}$ by comparing (4) with (6). □

Proof of Proposition 1. Since $c_S(a,\theta_S)$ and $c_E(a,\theta_E)$ are statistically independent,

$$E[\exp(-r(c_E(a,\theta_E)-c_S(a,\theta_S)))] = E[\exp(-rc_E(a,\theta_E))]E[\exp(rc_S(a,\theta_S))].$$

Thus, $EU_B^{**} = v-\left\{a^{**}+\frac{1}{r}\ln\{E[\exp(rc_S(a^{**},\theta_S))]\}+\frac{1}{r}\ln\{E[\exp(-rc_E(a^{**},\theta_E))]\}+E[c_E(a^{**},\theta_E)]\right\}$. By Jensen's inequality, $\frac{1}{r}\ln\{E[\exp(-rc_E(a^{**},\theta_E))]\} > -E[c_E(a^{**},\theta_E)]$. In addition, $a^* = \arg\min\{a+\frac{1}{r}\ln\{E[\exp(rc_S(a,\theta_S))]\}\}$. Therefore, $EU_B^* = v-\left\{a^*+\frac{1}{r}\ln\{E[\exp(rc_S(a^*,\theta_S))]\}\right\} > EU_B^{**}$ for all r. □

Proof of Lemma 3. Under long-term contracting, the distribution of $\pi = (p_1+p_2)-a-c_S(a,\theta_S)$ is nondegenerate so that the risk premium ρ for π is positive. Under sequential contracting, in case (ii), since there exists a function $c(a)$ such that $c_E(a',\theta_E) = c_S(a',\theta_S)+c(a')$, the risk premium ρ' for S for $\pi' = p_1'-a'+c(a')$ is zero. □

Proof of Lemma 4. The necessary and sufficient first-order condition for $\tilde{a} = \arg\min[a+E[c_S(a,\theta_S)]]$ is given by

$$-E\left[\frac{\partial c_S(\tilde{a},\theta_S)}{\partial a}\right] = 1. \tag{7}$$

Since $c_E(a,\theta_E)-c_S(a,\theta_S)$ is independent of the realization of (θ_S,θ_E) in case (ii), condition (5) is

$$-E\left[\frac{\partial c_S(a^{**},\theta_S)}{\partial a}\right] = 1-E\left[\frac{\partial c_E(a^{**},\theta_E)}{\partial a}\right]. \tag{8}$$

The second term on the right-hand side of (8) is strictly positive, so we have $\tilde{a} > a^{**}$ by comparing (7) with (8). We can rewrite condition (4) as

$$-E\left[\frac{\partial c_S(a^*, \theta_S)}{\partial a}\right] = 1 - \frac{\text{Cov}\left(-\frac{\partial c_S(a^*,\theta_S)}{\partial a}, \exp(rc_S(a^*, \theta_S))\right)}{E[\exp(rc_S(a^*, \theta_S))]}. \tag{9}$$

If condition (1) (condition (3)) in Lemma 4 is satisfied, then the fact that the covariance between two positively (negatively) covarying variates is positive (negative) implies that the covariance term in (9) is positive (negative), so that $a^* > \tilde{a}$ ($a^* < \tilde{a}$) by comparing (7) with (9). If condition (2) is satisfied, then $a^* = \tilde{a}$ since the covariance term in (9) is zero. □

Proof of Proposition 2. As above, $c_E(a, \theta_E) - c_S(a, \theta_S)$ is independent of the realization of (θ_S, θ_E) in case (ii). Thus, $EU_B^{**} = v - \{a^{**} + \frac{1}{r}\ln\{\exp(-rE[c_E(a^{**}, \theta_E) - c_S(a^{**}, \theta_S)])\} + E[c_E(a^{**}, \theta_E)]\} = v - \{a^{**} + E[c_S(a^{**}, \theta_S)]\}$. Now, a^{**} determined by (8) does not depend on r, so that EU_B^{**} does not depend on r as well.

We then show that (a) EU_B^* converges to the first-best payoff as $r \to 0$, (b) EU_B^* is decreasing in r, and (c) EU_B^* has an infimum.

(a) Since the optimal investment for S depends on his coefficient of absolute risk-aversion, we denote $a^* = a^*(r)$. Then, $EU_B^* = v - a^*(r) - E[c_S(a^*(r), \theta_S)] - \rho(a^*(r), r)$, where $\rho(a^*(r), r) = -E[c_S(a^*(r), \theta_S)] + \frac{1}{r}\ln\{E[\exp(rc_S(a^*(r), \theta_S))]\}$ is the risk premium. As $r \to 0$, $a^*(r) \to \tilde{a}$ since the covariance term in (9) converges to 0, and the risk premium $\rho(a^*(r), r)$ converges to 0. Therefore, as $r \to 0$, EU_B^* converges to $v - \{\tilde{a} + E[c_S(\tilde{a}, \theta_S)]\}$.

(b) Using the envelope theorem, $\frac{dEU_B^*}{dr} = -\frac{\partial\rho(a^*(r),r)}{\partial r}$. From Theorem 1 of Pratt (1964), as the coefficient of absolute risk-aversion is greater, the risk premium is greater. Thus, $\frac{\partial\rho(a^*(r),r)}{\partial r} > 0$, so that $\frac{dEU_B^*}{dr} < 0$.

(c) The certainty equivalent for S for $\pi = (p_1 + p_2) - a - c_S(a, \theta_S)$, from which he obtains the same utility as $E[u(\pi)]$, is $(p_1 + p_2) - a - \frac{1}{r}\ln\{E[\exp(rc_S(a, \theta_S))]$. Since c_S is increasing in θ_S, the highest production cost given a is $c_S(a, \bar{\theta})$. Thus, as $r \to \infty$, his certainty equivalent converges to $(p_1 + p_2) - a - c_S(a, \bar{\theta})$. Then the infinitely risk-averse S optimally chooses $\bar{a}^*$ determined by $-\frac{\partial c_S(\bar{a}^*,\bar{\theta})}{\partial a} = 1$. Since $\lim_{a\to\infty} \frac{\partial c_S(a,\bar{\theta})}{\partial a} = 0$, $\bar{a}^*$ is finite. Therefore, as $r \to 0$, EU_B^* converges to $v - \left\{\bar{a}^* + c_S(\bar{a}^*, \bar{\theta})\right\} > 0$. This is the infimum of EU_B^*.

Comparing the infimum of EU_B^* with $EU_B^{**} = v - \{a^{**} + E[c_S(a^{**}, \theta_S)]\} > 0$, which is less than the first-best payoff. This completes the proof. □

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