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ABSTRACT

We study the structure of an optimal management for innovative activities. The top management of a buyer hires a supplier for production. The production efficiency can be enhanced by investing in R&D before production. The buyer chooses between using its own subunit for the R&D, or outsourcing the task to the supplier (integration of R&D and production). Our analysis reveals that (*i*) when the R&D cost is small, the buyer prefers in-house R&D, (*ii*) when the R&D cost is intermediate, the buyer prefers outsourcing R&D, and (*iii*) when the R&D cost is large, the buyer prefers in-house or outsourcing R&D, depending on the parameter. Within the regime in which R&D outsourcing prevails, the optimal production levels may have "partial bunching" for successful yet less favorable R&D results, depending on the R&D cost. Thus, motivating R&D may require that less favorable R&D results be overly and equally appreciated, unless the R&D is a failure.

Keywords: Innovation, In-house R&D, Outsourcing R&D.

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1 Introduction

The issue of insourcing vs. outsourcing has constantly been considered important.[1] As the popularity of outsourcing grows,[2] organizations tend to outsource not only their production, but also upstream or innovative activities, such as R&D. For example, there are numerous firms that contract with suppliers such as Flextronics International Ltd. and Applied Engineering Inc. for various services, from OEM manufacturing to fully integrated services that involves R&D and design as well. For some government projects, their R&Ds are conducted in-house and only the manufacturing services are contracted with private companies, but for other projects, both R&D and manufacturing are completely outsourced. The examples for outsourcing only R&D task or both R&D and production tasks abound.

The objective of this paper is to analyze the structure of an optimal R&D policy in a buyer-supplier relationship. In particular, we want to study why the buyer (the project owner) sometimes purchases only the manufacturing service from the supplier, and sometimes both the R&D and the manufacturing services. We employ an agency framework in which the buyer chooses between in-house and outsourcing R&D, while the final output is always produced by the supplier.[3] If the buyer chooses in-house R&D, then the task is conducted by a subunit of the buyer, and the supplier engages in production using the R&D result delivered from the subunit. If the buyer chooses to outsource the R&D, the supplier conducts the R&D and uses the result to produce the final output. The buyer monitors the R&D effort, regardless of which party conducts the R&D. The buyer's monitoring is more efficient for in-house R&D in that, if the buyer's own subunit shirks, then it gets caught with a higher probability. The buyer cannot observe the R&D result in any case.[4]

When the R&D is conducted in-house, the buyer's only concern is the subunit's hidden action for the R&D effort. Since the subunit does not produce the output, thus not using the R&D result, it does not have any incentive to misreport the R&D result. However, the subunit has an incentive to shirk on the R&D effort so that it can privately reap the cost of R&D. Therefore, although there is no hidden information problem associate with the R&D result, the buyer must motivate its own subunit to engage in the R&D activity. And the supplier's production is always at the first-best level (the marginal benefit equals

[1] See Coase (1937) and Williamson (1985) for seminal works.

[2] See Harrison and Kelley (1993).

[3] Therefore, we are implicitly assuming that the buyer does not have the production capacity, or the opportunity cost of production for the buyer is too high.

[4] Our result does not change when the buyer observe the R&D result when the task is conducted in-house.

marginal cost), because he[5] has no private information about the R&D result.

When the R&D is conducted by the supplier, the buyer must cope with both hidden action and hidden information problem – the supplier has an incentive to shirk on the R&D effort, and since the supplier uses the R&D result in the production stage, he may have an incentive to misreport the R&D result to command information rent. Thus, unlike the case of in-house R&D, the optimal production levels when the supplier conducts the R&D are accompanied by distortions. Our analysis reveals that for a large R&D cost, the optimal production levels are not only distorted *upward*, but also *partially bunched* for the cases in which the R&D was successful, yet the result was less favorable. This result implies that, to induce the supplier to make a sincere effort for R&D, the buyer must *overly* and *equally appreciate* less favorable results of R&D, unless the R&D is a complete failure.

The magnitude and direction of the distortion depends on the cost of R&D when the supplier conducts the R&D. When the R&D cost is small enough, the supplier's incentive for the R&D effort is not an issue, since he wants to reap information rent associated with a successful R&D result. After conducting the R&D, the supplier has an incentive to understate the result. By doing so the supplier can exaggerate the cost of production for a higher compensation. As usual in the standard screening problem, the buyer distorts schedule of the production level downward to extract the supplier's information rent in such a case. As the cost of R&D becomes larger, however, the buyer faces a different incentive. To induce a sincere R&D effort when it is costly enough, the payment associated with successful R&D must be large. With a large payment for successful R&D, however, the supplier may pretend to have succeeded in R&D without conducting one. By doing so, the supplier can get away with a large payment and also save a large R&D cost. To discourage the supplier from claiming that R&D succeeded without conducting one, the buyer requires the supplier to over-produce when he reports that the R&D was successful.

With R&D outsourcing, a large enough R&D cost brings about not only the upward distortions, but also *partial bunching* in the production levels when the R&D was successful but the result is less favorable. If the supplier decides to report that R&D was successful without conducting one, he will report that although successful, the result is the least favorable (but still better than a failure). By doing so, the supplier can avoid suffering a large production level at the highest cost. To prevent such misreporting, the buyer increases the production level even further for that particular R&D result. This, however, attracts an understatement of the R&D result when the supplier in fact conducts the R&D and the

[5] The buyer refers to "she," the buyer's subunit "it," and the supplier "he."

result is successful. Consequently, when successful, the R&D results are treated equally for the less favorable states, and thus the optimal production levels have partial bunching.

We endogenize the optimal R&D policy by comparing in-house and outsourcing R&D.[6] When the cost of R&D is *small*, the buyer prefers *in-house R&D*. As mentioned above, with in-house R&D, the only incentive problem is the hidden action for the R&D effort. Therefore, although the buyer must give up some rent to its subunit for R&D effort, the supplier's production levels are at the first-best since the supplier captures no information rent. For a small R&D cost, the moral hazard problem associated with the subunit's R&D effort is not very costly to the buyer, and consequently, in-house R&D is preferred.

When the cost of R&D is *intermediate*, however, the buyer prefers *outsourcing R&D*. While the policy of in-house R&D has a merit of the first-best production levels, it has a disadvantage. Since the subunit does not use the R&D result for production, she can only motivate the subunit's effort by monitoring his effort. When the R&D and the production are integrated so that the supplier also conducts the R&D, the buyer has an additional device to motivate the supplier for his R&D effort – the level of production. When the R&D and the production are integrated, the supplier's incentive for the R&D effort is affected by his incentive to be privately informed at the production stage, and the buyer can manipulate the production levels to provide the right incentive to the supplier. As a result, when the R&D cost is not so small, in-house R&D becomes less attractive, and the buyer chooses to have more incentive devices by integrating the R&D and the production task.

When the cost of R&D is *large*, the optimal R&D policy depends on the efficiency of the monitoring for the R&D effort. Again, with outsourcing R&D, the optimal production levels are distorted to provide the right incentive to the supplier. For a large R&D cost, the distortions in production levels are already very large, and therefore it is not optimal for the buyer to increase the distortions any further if the cost of R&D becomes larger. As the R&D cost increases, therefore, the buyer eventually stops increasing distortions in the production levels, and the buyer's marginal loss for an increase in the R&D cost becomes depending solely on the efficiency of the effort monitoring. Consequently, when the monitoring efficiency with in-house R&D is higher enough compared to the one with outsourcing R&D, the buyer's payoff is higher with *in-house R&D* for a large R&D cost.

According to our result, the optimal R&D policy for a small R&D cost is conducting the task in-house for removing the hidden information problem at the stage of production.

[6] In the concluding section, we also discuss the case in wihch the buyer hires a third party R&D firm.

The optimal policy for an intermediate R&D cost is outsourcing the task to the supplier for mitigating the hidden action problem at the stage of R&D. Finally, the optimal policy for a large R&D cost can again be in-house R&D for the efficiency of monitoring. We show that within the regime in which the policy of outsourcing R&D prevails, the optimal production schedule has the partial bunching for a successful yet less favorable R&D results, depending on the R&D cost. As mentioned above, therefore, it is implied that motivating a costly R&D may require that less favorable R&D results be overly and equally appreciated, unless the result is a complete failure.

Among numerous works on incentives for innovation,[7] studies more related to ours include Holmstrom (1989), Aghion and Tirole (1994, 1997), and Cornelli and Schankerman (1999). Holmstrom (1989) adopts a moral hazard model to analyze the optimal portfolio mix of horizontally different tasks. The author show that risky and innovative tasks should not be mixed with safe and routine task since it may lead to misallocation of risk. Aghion and Tirole (1994, 1997) employ an incomplete contract frameworks to show that providing a research unit with authority or property right over the outcome may allow the unit to misuse its right, but increases the unit's incentive to be engage in innovative activities. We take a complete contract approach with both moral hazard and adverse selection, and focuses on the issue of in-house vs. outsourcing innovation,[8] and production distortions. Cornelli and Schankerman (1999), like our paper, cope with both moral hazard and adverse selection. The authors argue that a uniform reward for innovation is suboptimal, whereas we demonstrate that partial uniform reward may be optimal to motivate innovation. The key difference is that, in their paper, the hidden information is not a result of R&D effort. In our paper, the hidden information is the R&D result, which is the product of R&D effort.

Lewis and Sappington (1993), in a pure adverse selection model, show that the optimal contract entails bunching in the production levels for a truthful report, if there is a chance that the supplier is uninformed. In our paper, the supplier's effort determines the production cost, and the bunching in the production schedule is to induce the supplier's effort as well as a truthful report. Lewis and Sappington (1997), like ours, adopts the framework with both moral hazard and adverse selection.[9] The authors argue that it is always optimal to separate the tasks of information gathering and production, if the contract to

[7]Unlike ours, much of the literature deals with inter-organizational situations such as oligopolistic competition. See, for example, Katz (1986), Segerstrom and Zolnierek (1999) and Cans and Stern (2000).

[8]See Ulset (1996) for an empirical study on R&D outsourcing.

[9]Other papers analyzing an optimal contracting problem with moral hazard and adverse selection include Cremer, Khalil and Rochet (1998[a], 1998[b]) and Dai, Lewis and Lopomo (2006).

the information gathering agent can be costlessly contingent on the production cost that is observable in the later stage. In practice, however, such contingency may be too costly to be designed and enforced: We take this approach, and integrating R&D and production can be optimal in the current paper.

Dewatripont and Tirole (1999) study a situation in which an innovative activity can be outsourced from multiple parties. The authors show that using multiple parties do not always provide the best incentive for such activities. Khalil, Kim and Shin (2006) show that it is optimal to "partially" separate the upstream and downstream tasks. In their paper, the buyer uses the same party for the upstream task, while she can use another party for the downstream task. Thus, separation/integration of the upstream and the downstream tasks is contingent on the report from the information gathering party. By contrast, in our paper, the buyer uses the same party for the downstream task, but she can use different party for the upstream task. As a result, separation/integration of the tasks cannot be contingent on the report of the R&D result, and optimal separation or integration of the upstream and down stream tasks is not partial in our paper for given parameters. Also, effort monitoring plays an important role in our paper – without monitoring the R&D effort, separation of the two tasks (in-house R&D) is never optimal in our model.[10]

The rest of the paper is organized as follows. We present the model in Section 2. In Section 3, we discuss the case in which the R&D is conducted in-house. The case in which the buyer outsources the R&D to the supplier is presented in Section 4. In Section 5, we compare the optimal outcomes in the previous two sections to endogenize the R&D policy. We conclude with some extensions in Section 6. All proofs are in Appendix.

2 Model

We consider a vertical relationship in which the top management of a monopsonistic buyer contracts with a supplier for the production level q of a good (alternatively, q can be interpreted as the size of the project). The buyer's valuation of the good is $V(q)$, an increasing concave function that satisfies the Inada condition. At the outset, both parties know that without R&D, the production cost is $\theta_0 q$, where θ_0 is the marginal cost of production. The buyer can use a subunit of the organization to conduct a cost-reduction

[10] The buyer constantly but imperfectly monitors the R&D effort in our model, and thus monitoring is not a choice variable. There are numerous studies that analyze optimal monitoring policies. See for example, Baron and Besanko (1984), Border and Sobel (1987), Mookherjee and Png (1989), Demougin and Fluet (2001), Dunne and Lowenstein (1995) among others.

R&D (in-house R&D), or let the supplier conducts the task (outsourcing R&D). The cost of conducting the R&D is denoted by C.

It is common knowledge that the R&D succeeds with probability p (therefore fails with probability $1-p$). When the R&D succeeds, the marginal cost of production is drawn from the range $\Theta = [\underline{\theta}, \overline{\theta}]$ according to the distribution $F(\theta)$ and the associated density function $f(\theta)$, where the standard assumption $F(\theta)/f(\theta) \geq 0$ holds. When the R&D fails, the marginal cost remains to be $\theta_0 (> \overline{\theta})$. We assume that C is not prohibitively large that the buyer wants to induce R&D by the supplier.

The R&D effort, regardless of the conducting party (either the buyer's subunit or the supplier), is monitored constantly but imperfectly by the buyer.[11] This allows us to make our point in a simpler way because with the constant monitoring, we do not need to treat monitoring as the buyer's choice variable. As mentioned in the introduction, monitoring the R&D effort plays a key role when the R&D is conducted in-house. It is a well known result that, with an unbounded penalty, there is no incentive problem.[12] In our model, we rule out unbounded penalties – to illustrate our result in a simple way, we assume that one can quit or walk away anytime. The result of the R&D, i.e., the marginal cost of production $\theta \in \{\theta_0, \Theta\}$, is not observed by the buyer (the top management) in any case.[13] In this paper we assume that the following inequality holds:

$$\theta_0 - \overline{\theta} \geq \frac{1-p}{f(\overline{\theta})}. \tag{1}$$

The expression in (1) says that the gap between the state of failure and the state of the worst success is large enough, which assures that the usual monotonicity in the production levels is satisfied without the moral hazard problem in the R&D effort.

In-house R&D: As mentioned before, the R&D effort is monitored constantly but imperfectly. Therefore, if the subunit shirks on the R&D effort by not spending C for the R&D, it gets caught with probability μ^I (with probability $1-\mu^I$, therefore, the subunit gets

[11] It is implicitly assumed that the party that conducts the R&D is wealth-constrained and thus the buyer cannot sell the firm to the R&D conducting party.

[12] See, for example, Riordan and Sappington (1988) or Demougin and Garvie (1991).

[13] More generally, when the R&D is conducted in-house, the buyer might be able to imperfectly observe the R&D result. As becomes clear later, however, since the subunit does not use the R&D result for production, the moral hazard problem is the sole concern of the buyer when the R&D is conducted in-house. The buyer's information on the R&D result through monitoring simply affects the probability that the subunit gets caught when shirking. Therefore, in such a case, the effort monitoring in our model for in-house R&D can be interpreted as a result of monitoring both the R&D effort and the result.

away with shirking). When the R&D is conducted in-house, the R&D task is separated from production, and the top management's offer to the subunit specifies $t(\widehat{\theta}^I)$, where $\widehat{\theta}^I$ is the subunit's report of the R&D result $\theta \in \{\theta_0, \Theta\}$ and t is the transfer to the subunit contingent on his report.

The buyer's offer to the supplier for production specifies $\{q(\widehat{\theta}^I), T(\widehat{\theta}^I)\}$, the production level and the transfer contingent on the subunit's report on the R&D result. The timing is summarized below:

- The buyer offers $t(\widehat{\theta}^I)$ to its own subunit.
- The subunit decides whether or not to conduct R&D.
- The subunit learns $\theta \in \{\theta_0, \Theta\}$ privately, announces $\widehat{\theta}^I$ and receives $t(\widehat{\theta}^I)$.
- The buyer offers $\{q(\widehat{\theta}^I), T(\widehat{\theta}^I)\}$ to the supplier.
- The supplier engages in production and receives the transfer.

Outsourcing R&D: When the R&D task is outsourced, thus being conducted by the supplier, the R&D effort is monitored less efficiently compared to when the task is conducted in-house. If the supplier does not spend C for the R&D, then he gets caught with probability μ^S, where $\mu^S < \mu^I$. Here the R&D and production tasks are integrated, and the buyer's offer to the supplier specifies $\{q(\widehat{\theta}^S), T(\widehat{\theta}^S)\}$, where $\widehat{\theta}^S$ denotes the supplier's report of the R&D result $\theta \in \{\theta_0, \Theta\}$. The timing is as follows:

- The buyer offers $\{q(\widehat{\theta}^S), T(\widehat{\theta}^S)\}$ to the supplier.
- The supplier decides whether or not to conduct the R&D.
- The supplier learns $\theta \in \{\theta_0, \Theta\}$ privately and announces $\widehat{\theta}^S$.
- The supplier engages in production and receives the transfer.

As a benchmark, we present the optimal outcome under full information. Without hidden action (for the R&D effort) and hidden information (the R&D result), the optimal production schedule is characterized by:

$$V'(q^*(\theta)) = \theta.$$

With in-house R&D, the transfers are $t^*(\theta) = C$ to the subunit, and $T^*(\theta) = \theta q^*(\theta)$ to the supplier. With outsourcing R&D, the transfer to the supplier is $T^*(\theta) = \theta q^*(\theta) + C$.

Under full information, the supplier is required to produce the efficient level of output, and the buyer provides zero rent. For later use, we define:

$$\Phi_{\Theta}^{*} \equiv V(q^{*}(\theta)) - \theta q^{*}(\theta) \text{ for } \theta \in \Theta,$$

$$\Phi_{0}^{*} \equiv V(q^{*}(\theta_0)) - \theta_0 q^{*}(\theta_0) \text{ for } \theta = \theta_0.$$

3 In-house R&D

As described above, if the R&D is separated from the supplier and conducted in-house, the top management of the buyer offers its own subunit $t(\widehat{\theta}^{I})$, the transfer contingent on the subunit's report of the R&D result. After the R&D result is announced publicly, the buyer offers $q(\widehat{\theta}^{I})$ and $T(\widehat{\theta}^{I})$ to the supplier. In light of the backward induction, we present the optimal outcome from the end of the time line to the beginning.

Since the supplier has no private information, he receives zero rent, i.e., $T(\theta) = \theta q(\theta)$, where the true R&D result $\theta = \widehat{\theta}^{I}$ by the Revelation Principle. The optimal production schedule is the same as the one under full information:

$$q^{I}(\theta) = q^{*}(\theta).$$

When the buyer deals with its own subunit, she must cope with incentive issues. Since the subunit does not use the R&D result, the only way to remove the subunit's incentive to misreport θ is to make the transfer $t(\widehat{\theta}^{I})$ constant for all $\widehat{\theta}^{I} \in \{\theta_0, \Theta\}$, provided that no shirking is detected:

$$t(\widehat{\theta}^{I}) = t, \text{ for } \widehat{\theta}^{I} \in \{\theta_0, \Theta\}.$$

When shirking is detected, the transfer to the subunit is zero, due to the limited liability in our model. The condition below must be satisfied to induce the subunit's R&D activity:

$$t - C \geqslant (1 - \mu^{I})t. \tag{RD^I}$$

The participation requires that:

$$t - C \geq 0. \tag{PC^I}$$

The buyer's problem is to minimize t subject to constraints (PC^{I}) and (RD^{I}). Binding (RD^{I}) gives the transfer to the subunit when the R&D is conducted in-house:

$$t = C/\mu^{I}.$$

Our discussion in this section is summarized in the buyer's expected payoff presented in the following proposition.

Proposition 1 *When the R&D is conducted in-house, the buyer's expected payoff is:*

$$p\int_{\Theta}\Phi_{\Theta}^{*}dF(\theta)+(1-p)\Phi_{0}^{*}-C/\mu^{I}.$$

Note that, without the R&D effort being monitored, the buyer cannot induce the subunit's R&D activity, because the subunit does not use R&D result for production. As mentioned above, after the subunit announces the R&D result, the buyer offers the supplier the contract under full information since no information rent needs to be provided to the supplier when the R&D is conducted in-house.

4 Outsourcing R&D

We now analyze the case in which the R&D task and the production tasks are integrated: The supplier conducts the R&D before he engages in production. As in the previous section, we present the buyer's constraints from the end of the time line to the beginning.

Once the R&D is conducted, the supplier privately learn $\theta \in \{\theta_0, \Theta\}$. As the revelation principle applies, the following incentive compatibility condition must be satisfied for the supplier to truthfully announce the R&D result:

$$\theta \in \arg\max_{\widehat{\theta}^S} U(\widehat{\theta}^S|\theta) \text{ for } \forall\widehat{\theta}^S, \theta \in \{\theta_0, \Theta\},$$

where $U(\widehat{\theta}^S|\theta) \equiv T(\widehat{\theta}^S|\theta) - \theta q(\widehat{\theta}^S|\theta)$. A necessary condition for the above incentive compatibility condition gives the following expression for the supplier's rent when the R&D is successful:

$$U(\theta) = U(\overline{\theta}) + \int_{\theta}^{\overline{\theta}} q(\tau)d\tau, \text{ for } \theta \in \Theta, \qquad (IC_{\theta}^{S})$$

where $U(\theta) \equiv U(\theta|\theta)$. The optimal contract must also satisfy the following incentive compatibility constraints that prevent the supplier from reporting that the R&D has failed when the R&D is actually successful and vice versa:

$$U(\overline{\theta}) \geq U(\theta_0) + (\theta_0 - \overline{\theta})q(\theta_0), \qquad (\overline{IC}^{S})$$

$$U(\theta_0) \geq U(\overline{\theta}) - (\theta_0 - \overline{\theta})q(\overline{\theta}), \qquad (IC_{0}^{S})$$

Notice that, together with (IC_{θ}^{S}) which prevents misreporting within the range of $\theta \in \Theta$, (IC_{0}^{S}) is sufficient to prevent the supplier from any misreport of the result when $\theta = \theta_0$.

Next, we present the condition that induces the R&D. The supplier's expected payoff when he conducts the R&D is:

$$p \int_{\Theta} U(\theta) dF(\theta) + (1-p) U(\theta_0).$$

Using the expressions for $U(\theta)$ in (IC_θ^S), and integrating by parts, the supplier's expected (net) payoff when he conducts the R&D is:

$$p \left\{ \int_{\Theta} q(\theta) F(\theta) d\theta + U(\overline{\theta}) \right\} + (1-p) U(\theta_0) - C \tag{2}$$

If the supplier does not conduct the R&D, then $\theta = \theta_0$ with certainty. If the supplier shirks on the R&D activity and gets caught, then the buyer pays $T^*(\theta_0) = \theta_0 q^*(\theta_0)$ and the supplier produces $q^*(\theta_0)$, since the supplier can choose to quit. Suppose the supplier did not conduct the R&D and reports $\widehat{\theta}^S$. The supplier receives zero information rent when his shirking is detected by the buyer, but receives a rent of $T(\widehat{\theta}^S) - \theta_0 q(\widehat{\theta}^S)$ if he is not caught. Therefore, the supplier's expected net payoff is $(1-\mu^S)\left[T(\widehat{\theta}^S) - \theta_0 q(\widehat{\theta}^S)\right]$ if the supplier decides not to conduct the R&D. With incentive compatibility conditions (IC_θ^S) and (IC_0^S), the supplier also reports that $\theta = \theta_0$ if he does not conduct R&D. Then, using (2), we can write the constraint that assures that the supplier will choose to conduct R&D:

$$p \left\{ \int_{\Theta} q(\theta) F(\theta) d\theta + U(\overline{\theta}) \right\} + (1-p) U(\theta_0) - C \geq (1-\mu^S) U(\theta_0). \tag{RD^S}$$

The supplier learns θ before the production takes place, so his payoff must be greater than his reservation payoff for all θ in order to engage in the production. Thus, the contract must satisfy the following participation condition for the supplier:

$$U(\theta) \geq 0, \text{ for } \theta \in \{\theta_0, \Theta\}. \tag{3}$$

With (IC_θ), $(\overline{IC})$ and (IC_0), (3) is implied by:

$$U(\theta_0) \geq 0. \tag{PC^S}$$

Using (IC_θ), the buyer's expected payoff,

$$p \int_{\Theta} \left[V(q(\theta)) - T(\theta) \right] dF(\theta) + (1-p)[V(q_0) - T(\theta_0)],$$

can be rewritten as:

$$\begin{aligned} &p \left\{ \int_{\Theta} \left[V(q(\theta)) - \left(\theta + \frac{F(\theta)}{f(\theta)} \right) q(\theta) \right] dF(\theta) - U(\overline{\theta}) \right\} \\ &+(1-p)[[V(q_0) - \theta_0 q_0 - U(\theta_0)]. \end{aligned} \tag{$\mathcal{P}$}$$

The buyer's problem is to maximize her expected payoff in ($\mathcal{P}$) subject to (PC^S), (RD^S), ($\overline{IC}^S$), and (IC_0^S).

The moral hazard issue in the supplier's R&D effort depends on the cost of R&D. In other words, the constraint that induces R&D effort, (RD^S), can be binding or non-binding, depending on the size of C. When C is very small, the supplier's incentive associated with conducting the R&D is not the buyer's concern since the supplier's expected information rent from successful R&D gives the supplier enough incentive to conduct the R&D. When C is sufficiently large, however, the supplier's incentive for the R&D effort becomes an issue. That is, the amount of rent provided to the supplier to induce a truthful report of the R&D result is not enough to induce his sincere R&D effort. Below, we identify the buyer's optimal production schedule for three different ranges of the R&D cost: small ($C < C^-$), intermediate ($C^- < C < C^+$), and large ($C > C^+$).

Proposition 2 *When the R&D with $C < C^-$ is conducted by the supplier, the optimal production levels are characterized by:*

$$V'(q^S(\theta)) = \begin{cases} \theta + \frac{(1-\lambda)F(\theta)}{f(\theta)}, \ \textit{for } \theta \in \Theta, \\ \theta_0 + \frac{p(1-\lambda)}{1-p}\left(\theta_0 - \overline{\theta}\right), \ \textit{for } \theta = \theta_0, \end{cases}$$

where λ is the Lagrange multiplier associated with (RD^S) and $1 > \lambda \geqslant 0$.

The downward distortions in the production levels here are well known[14] – in the optimal contract, a production level for given θ is distorted downward, and the distortion increases in θ. In this regime, the main incentive problem is exaggerating the cost of production. Therefore, by distorting the production levels downward and increasing the degree of distortion in θ, the buyer can reduce the transfer schedule to the supplier. This limits the supplier's information rent, and thus discourages the supplier from exaggerating the cost of production.

When C is very small, $\lambda = 0$ and (RD^S) and (IC_0^S) are slack. As mentioned above, the supplier's expected information rent from the R&D is sufficient to induce the R&D effort when the cost of R&D is small enough. This means that the buyer does not need to reward the supplier for a successful R&D. Consequently, when the R&D fails the supplier has no incentive to misreport that the R&D result. As C increases, (RD^S) becomes binding ,i.e., $\lambda > 0$, and the amount of rent that induces a truthful report of R&D result is no longer sufficient to induce the R&D effort. The buyer must increase the supplier's rent to

[14] See Baron-Myerson (1982).

induce his R&D effort, and accordingly the production level must go up. Eventually, as C approaches to a critical level C^{-}, the production level approaches to the first-best level.

Proposition 3 *When the R&D with $C^{-} < C < C^{+}$ is conducted by the supplier, the optimal production levels are characterized by:*

$$V'(q^S(\theta)) = \theta, \text{ for } \theta \in \{\theta_0,\ \Theta\}.$$

As the cost of R&D increases, so does the reward to the supplier for a successful R&D. The buyer optimally reduces the downward distortion in the production schedule and increases the supplier's expected information rent from a successful R&D. When $C^{-} < C < C^{+}$, the buyer no longer restricts the supplier's information rent from successful R&D through downward distortion in the output schedule. The supplier is required to produce the efficient level of output based upon the R&D result, and the buyer adjusts the transfer payment, $T(\theta)$, to provide the supplier just sufficient information rent to conduct R&D. Although the optimal production schedule is at the first best, the buyer must provide a large amount of rent to the supplier in this regime to provide a R&D incentive.

As the R&D cost becomes yet larger, the buyer faces a different incentive issue. Again, the transfer to the supplier for a successful R&D must increase as the R&D cost goes up. Therefore, when C is large enough, i.e., $C > C^{+}$, the reward for the successful R&D becomes so large that the supplier has an incentive to misreport that the R&D was successful without actually conducting one. Consequently, the optimal production schedule needs to be distorted again in this regime. The following proposition presents the optimal production levels for $C > C^{+}$.

Proposition 4 *When the R&D with $C > C^{+}$ is conducted by the supplier, the optimal output schedule is characterized by:*

$$V'(q^S(\theta)) = \begin{cases} \theta + (1-\lambda)\frac{F(\theta)}{f(\theta)}, \text{ for } \theta \in [\underline{\theta}, \theta^{+}), \\ \overline{\theta} + (1-\lambda)\left[\frac{1}{f(\overline{\theta})} + \left(\theta_0 - \overline{\theta}\right)\right] \text{ for } \theta \in [\theta^{+}, \overline{\theta}], \\ \theta_0, \text{ for } \theta = \theta_0, \end{cases}$$

where λ is the Lagrange multiplier associated with (RD) and $1/\mu^S \geqslant \lambda > 1$.

As the supplier faces a large R&D cost, the reward for a successful R&D in this regime must also be large. As in the previous regime, the best way to reward for a successful R&D is to increase the output level for $\theta \in \Theta$, and in the current regime, the amount of necessary rent to induce R&D is so large that the production schedule associated with a successful R&D is distorted upward ($q^S(\theta) \geq q^*(\theta)$ for $\theta \in \Theta$).

Figure 1 below shows the optimal output schedule in this regime. Note that there is a "partial bunching" in the production schedule, i.e., $q^S(\theta)$ is constant for $\theta \in [\theta^+, \overline{\theta}]$. The intuition behind this result is as follows. Again, the reward for successful R&D is large in this regime. The supplier has an incentive to report that the R&D was successful (instead of reporting that it failed) without actually conducting R&D. By doing so, the supplier can save the large R&D cost, while getting a large reward from the buyer. And when the supplier report that the R&D is successful without even conducting one (hence $\theta = \theta_0$), he will report that $\theta = \overline{\theta}$ so he will produce the least amount of output required for a successful R&D. To discourage the supplier from shirking on R&D and pretending that the R&D result is $\overline{\theta}$, the buyer requires even higher level of production when the supplier reports that R&D succeeded and $\theta = \overline{\theta}$. Then again, there is another hidden information problem. After a successful R&D ($\theta \in \Theta$), the increased production level at $\overline{\theta}$ increases the supplier's incentive to exaggerate the production cost by misreporting θ as $\overline{\theta}$. To prevent such a misrepresentation, the buyer requires a constant level of production for $\theta \in [\theta^+, \overline{\theta}]$.

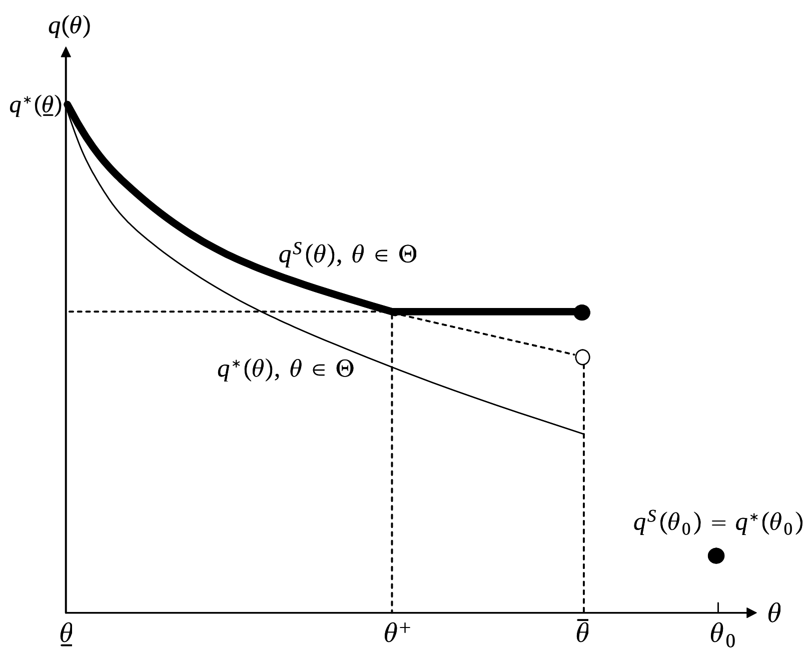

Figure 1: Optimal Production Levels with Outsourcing R&D when $C > C^+$.

If the R&D cost C continues to increase in this regime, λ reaches its maximum possible value $1/\mu^S$. Once C reaches the level such that $\lambda = 1/\mu^S$, no further distortion in the production schedule takes place. Instead, the buyer simply increases the transfer to the supplier. In other words, to provide an R&D incentive from a mere increase the transfer is cheaper than the incentive provision from increasing the distortion once C reaches a certain level. Note that λ is the marginal decreases in the buyer's payoff with respect to C. Also, recall from Proposition 1 that $t_s = C/\mu^I$. Thus, when the R&D is conducted in-house, the marginal decrease in the buyer's payoff with respect to C is constantly $1/\mu^I$. Under the R&D outsourcing, therefore, $\lambda = 1/\mu^S$ implies that the buyer's "additional cost" from an increase in C is solely from the supplier's hidden action in the R&D effort.

5 In-house vs. Outsourcing R&D

In this section, we endogenize the buyer's R&D policy by comparing her payoffs from in-house and outsourcing R&D. With the in-house R&D, the buyer provides no information rent to the supplier and achieves production efficiency. However, despite the efficiency in the production stage, the buyer can only use effort monitoring and transfer as the incentive devices for R&D when its subunit conducts the R&D. On the other hand, when the supplier conducts the R&D, although the supplier captures information rent from the R&D result, the buyer has another device to motivate the supplier's R&D effort – the level of production. When R&D and production tasks are integrated, the buyer can pair the reward for a successful R&D with a high level of output, which helps deter the supplier from pretending that the R&D is successful without actually conducting R&D. This trade-off between separation and integration of R&D and production leads to the following proposition.

Proposition 5 *Let $\Delta\mu \equiv \mu^I - \mu^S$. Then, there exists $\Delta\overline{\mu}$ such that:*

- *For $\Delta\mu < \Delta\overline{\mu}$, the buyer prefers in-house R&D if the cost of R&D is small enough, and prefers outsourcing R&D otherwise.*
- *For $\Delta\mu > \Delta\overline{\mu}$, the buyer prefers in-house R&D if the cost of R&D is small or large enough, and prefers outsourcing R&D otherwise.*

As presented in Proposition 1, the buyer's payment to its subunit is C/μ^S, so the subunit captures a expected rent of $C(1/\mu^S - 1)$. When C is sufficiently small, the information rent and production inefficiency under integrated R&D exceeds the payment to the subunit. Consequently, the buyer prefers the in-house R&D to separate the R&D task from production. As C increases, however, the buyer must increase the amount of rent to its subunit at a fixed rate. On the other hand, when R&D and production are integrated so that the supplier conducts R&D, initially the R&D constraint is not binding as C increases. Therefore, initially the information rent and production inefficiency do not increase as the cost of R&D increases. When C is not small and the R&D constraint is binding, the buyer uses additional incentive device to motivate R&D: Increasing the production levels (therefore reducing downward production distortion) for a successful R&D. Consequently, when C is at a intermediate level, the expected payment to the subunit under the in-house R&D exceeds the information rent and production inefficiency under the R&D outsourcing, and the buyer prefers integrating R&D with production.

When C becomes sufficiently large, however, the merit of having additional incentive device under R&D outsourcing becomes less attractive. Indeed, with a large enough C such that $\lambda = 1/\mu^S$, there will be no further manipulation of the production level to incentivize the R&D effort for an increase in C. As mentioned above, $1/\mu^S$ is the marginal decrease in the buyer's payoff with respect to C in such a case. Since such a marginal cost with in-house R&D is $1/\mu^S$, if the gap between the two monitoring efficiencies is large enough, the buyer prefers in-house R&D for a large enough R&D cost. In Figure 2 below, we illustrate the result for $\Delta\mu > \Delta\overline{\mu}$: We denote by Φ^{IN} the buyer's payoff with in-house R&D, Φ^{OUT} her payoff with outsourcing R&D, and $\Phi^{NO}(\equiv V(q_0^*) - \theta_0 q_0^*)$ her payoff with no R&D.

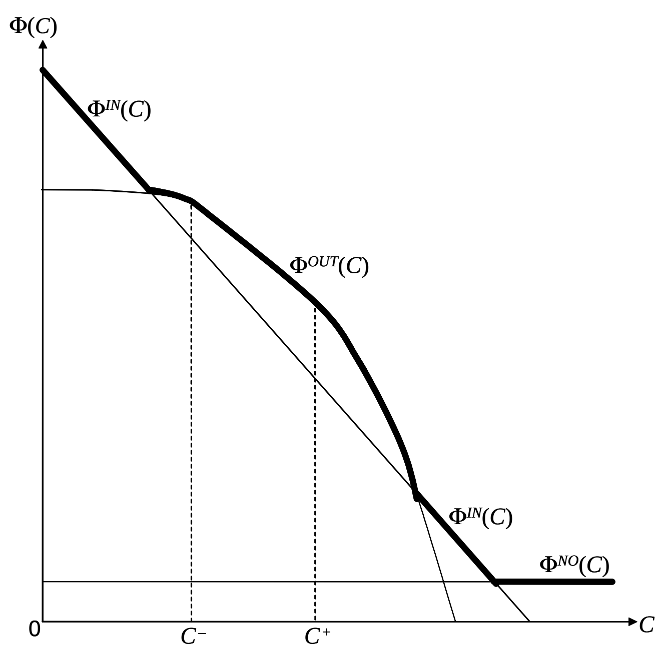

Figure 2: The Buyer's Payoffs with In-house and Outsourcing R&D.

In summary, there can be three regions regarding the optimal R&D policy: (i) In-house R&D when the R&D cost is small, (ii) outsourcing R&D when the R&D cost is intermediate, and (iii) when the R&D cost is large, in-house or outsourcing R&D, depending on $\Delta\mu$. As have identified, each of the R&D policy depending on the cost of R&D has different reasoning for its optimality. The in-house R&D in (i) is to mitigate the hidden information problem, the R&D outsourcing in (ii) is to mitigate the hidden action problem, and the in-house R&D in (iii) is for the monitoring efficiency.

6 Concluding Remarks

In this paper, we have analyzed how to motivate a costly innovation in a vertical relationship. Before the supplier engage in production, the buyer decides whether to conduct a efficiency enhancing R&D in-house or letting the supplier to conduct the R&D. According to our result, the buyer prefers in-house R&D when the cost of R&D is small, but she prefers outsourcing R&D when the cost of R&D is in the intermediate range. With a large R&D cost, the buyer's preference depends on the gap between the monitoring efficiencies of the two R&D policies. Within the regime in which the buyer prefers outsourcing R&D, the optimal production schedule has a partial bunching for a successful, but less favorable R&D results, depending on the R&D cost.

Our analysis can be extended to several directions. First, the binary R&D effort can be extended to a continuum. For example, the supplier determines the probability of the successful R&D, $p \in [0,1]$, and the R&D cost is realized by $C(p)$, with $C' > 0$ and $C'' > 0$. Then, when the R&D is outsourced, the supplier chooses p to maximize $pE_{\Theta}[U(\theta)] + (1-p)U(\theta_0) - C(p)$, and the first order condition with respect to gives:

$$E_{\Theta}[U(\theta)] - U(\theta_0) = C'(p),$$

which is essentially the same as (RD^S) in our model.[15] In this setting, how much the buyer values the R&D determines each regime in our model. When the buyer wants a very high probability of success in R&D, there will be over-production with partial bunching.

Second, the buyer may be able to monitor the R&D result in addition to the R&D effort. With in-house R&D, as have pointed out, the top management's information on R&D result simply affects the probability that the subunit gets caught when shirking, and it does not affect our qualitative results. With outsourcing R&D, the buyer's information on R&D

[15] In more sophisticated models, $F(\theta)$ can be determined by the effort level. See Szalay (2009), for example.

results helps alleviate both the moral hazard problem (hidden effort) and the adverse selection problem (hidden information), and the distortion in the optimal production schedule will be reduced. It implies that outsourcing R&D becomes relatively more desirable when the buyer can imperfectly monitor the R&D result.

Finally, when the R&D task is separated from the production task, the buyer may want to hire a third party R&D firm, instead of using its own subunit. As in the case of in-house R&D, the buyer then faces no hidden information problem because the third party R&D firm has no chance to use the R&D result. Therefore, provided that the buyer's monitoring for the R&D effort is more accurate when the R&D is conducted in-house, hiring a third party firm for the R&D is dominated by in-house R&D policy in our model.

Appendix

Proof of Propositions 2∼4.

The Lagrangian of the buyer's problem is given by:

$$\begin{aligned} L \; = \; & p\left\{\int_{\Theta}[V(q(\theta)) - (\theta + \frac{F(\theta)}{f(\theta)})q(\theta)]dF(\theta) - U(\overline{\theta})\right\} + (1-p)[V(q(\theta_0)) - \theta_0 q(\theta_0) - U(\theta_0)] \\ & +\lambda\left\{p[\int_{\Theta}F(\theta)q(\theta)d\theta + U(\overline{\theta})] - [(1-\mu^S) - (1-p)]U(\theta_0) - C\right\} + \lambda_0 U(\theta_0) \\ & +\lambda_1\left\{U(\overline{\theta}) - [U(\theta_0) + (\theta_0 - \overline{\theta})q(\theta_0)]\right\} + \lambda_2\left\{U(\theta_0) - [U(\overline{\theta}) - (\theta_0 - \overline{\theta})q(\overline{\theta})]\right\}, \end{aligned}$$

where λ, λ_0, λ_1, and λ_2 are the Lagrangian multipliers for constraints (RD^S), (PC^S), $(\overline{IC}^S)$, and (IC_0^S), respectively. The first derivatives of the Lagrangian with respect to $q(\theta_0)$, $U(\theta_0)$, $q(\overline{\theta})$, $U(\overline{\theta})$, and $q(\theta)$ are given by:

$$L_{q(\theta_0)} = (1-p)[V'(q(\theta_0)) - \theta_0] - \lambda_1(\theta_0 - \overline{\theta}) = 0, \qquad (A1)$$

$$L_{U(\theta_0)} = -(1-p) - \lambda[(1-\mu^S) - (1-p)] + (\lambda_2 - \lambda_1) + \lambda_0 = 0, \qquad (A2)$$

$$L_{q(\overline{\theta})} = p\left\{V'(q(\overline{\theta})) - \overline{\theta} - (1-\lambda)\frac{F(\overline{\theta})}{f(\overline{\theta})}\right\} + \lambda_2[\theta_0 - \overline{\theta}] = 0, \qquad (A3)$$

$$L_{U(\overline{\theta})} = -p(1-\lambda) + (\lambda_1 - \lambda_2) = 0, \qquad (A4)$$

$$L_{q(\theta)} = pf(\theta)\left\{V'(q(\theta)) - \theta - (1-\lambda)\frac{F(\theta)}{f(\theta)}\right\} = 0, \text{ for } \theta \in \Theta. \qquad (A5)$$

From $(A4)$, $\lambda_1 - \lambda_2 = p(1-\lambda)$. Substituting it into $(A2)$ provides that:

$$\lambda_0 = 1 - \lambda\mu^S. \qquad (A6)$$

Since the function $V(\cdot)$ is strict concave and constraint (RD^S) is linear in $q(\cdot)$ and in C, the buyer's optimization problem is convex, and its Lagrangian L is concave in C. Moreover, by strict concavity of $V(\cdot)$, the buyer's problem has a unique solution and $\lambda(C) = -L'(C)$. Thus, λ is increasing in C, as L is concave in C.

(i) $0 \leq \lambda < 1$ $(C < C^-)$**:** As a part of proof, we first conjecture that when C is small enough $\lambda = 0$, and show that this in fact is that case. With $\lambda = 0$, we have $\lambda_0 = 1$ from $(A6)$, which implies that $U(\theta_0) = 0$. Also from $(A4)$, we have $\lambda_1 - \lambda_2 = p(1-\lambda)$ or $\lambda_1 = \lambda_2 + p > 0$. Moreover, with (1), constraint (IC_0^S) is not binding and therefore $\lambda_2 = 0$. From $(A1)$, $(A3)$, and $(A5)$, we have:

$$V'(q(\theta)) = \theta + \frac{F(\theta)}{f(\theta)}, \text{ for } \theta \in \Theta,$$

$$V'(q(\theta_0)) = \theta_0 + \frac{p}{1-p}\left(\theta_0 - \overline{\theta}\right), \text{ for } \theta = \theta_0.$$

Since λ is non-negative and increasing in C, there exists a cutoff point of C^* such that $\lambda = 0$ if $C < C^*$. For $1 > \lambda > 0$, from $(A6)$, we have $\lambda_0 = 1 - \lambda\mu^S > 0$, and therefore we have $U(\theta_0) = 0$. Also, $\lambda_1 = \lambda_2 + p(1-\lambda) > 0$ from $(A4)$. Again, with (1), constraint (IC_0^S) is not binding and therefore $\lambda_2 = 0$. From $(A1)$, $(A3)$, and $(A5)$, we have:

$$V'(q(\theta)) = \theta + (1-\lambda)\frac{F(\theta)}{f(\theta)}, \text{ for } \theta \in \Theta,$$

$$V'(q(\theta_0)) = \theta_0 + \frac{p(1-\lambda)}{1-p}\left(\theta_0 - \overline{\theta}\right), \text{ for } \theta = \theta_0.$$

Since λ is increasing in C, there exists C^- such that $0 < \lambda < 1$ if $C^* < C < C^-$.

(ii) $\lambda = 1$ $(C^- < C < C^+)$**:** From $(A6)$, we have $\lambda_0 = 1 - \mu^S > 0$, and thus $U(\theta_0) = 0$. From $(A4)$, $\lambda_1 = \lambda_2$. With condition (1), constraint (IC_0^S) is again not binding and therefore $\lambda_1 = \lambda_2 = 0$. Then, $(A1)$, $(A3)$, and $(A5)$ give the following expression:

$$V'(q(\theta)) = \theta, \text{ for } \theta \in \{\theta_0, \Theta\}.$$

Since λ is increasing in C, there exists C^+ such that $\lambda = 1$ if $C^- < C < C^+$.

(iii) $1 < \lambda \leq 1/\mu^S$ $(C^+ < C)$**:** From $(A6)$, $\lambda_0 = 1 - \lambda\mu^S \geq 0$, implying that $U(\theta_0) \geq 0$. From $(A5)$, again we have:

$$V'(q(\theta)) = \theta + (1-\lambda)\frac{F(\theta)}{f(\theta)} < \theta, \text{ for } \theta \in \Theta. \tag{A7}$$

Moreover $\lambda_2 = \lambda_1 + p(\lambda - 1) > 0$ from $(A4)$, implying that (IC_0^S), the constraint that prevents the supplier from exaggerating θ when $\theta = \theta_0$, is binding.

Now, suppose $\lambda_1 > 0$. Then the the two incentive compatibility constraints require $q(\theta_0) = q(\overline{\theta})$. However, $(A1)$ with $\lambda_1 > 0$ implies that $V'(q(\theta_0)) > \theta_0$, and $(A7)$ with $\lambda > 1$ implies that $V'(q(\overline{\theta})) < \overline{\theta}$, and together, $q(\overline{\theta}) > q(\theta_0)$ is indicated. The contradiction suggests that $\lambda_1 > 0$ cannot hold in this case. Thus, $\lambda_1 = 0$. Then $\lambda_2 = p(\lambda - 1)$, and $(A4)$ provides

$$V'(q(\overline{\theta})) = \overline{\theta} + (1 - \lambda)\left[\frac{F(\overline{\theta})}{f(\overline{\theta})} + (\theta_0 - \overline{\theta})\right]. \qquad (A8)$$

The expression in $(A8)$ indicates that the monotonicity condition regarding $q(\theta)$ is binding in the neighborhood of $\overline{\theta}$. Consequently, there exist a θ^+ such that $q(\theta)$ is constant for $\theta \in [\theta^+, \overline{\theta}]$. Moreover, $(A1)$ provides $V'(q(\theta_0)) = \theta_0$. Since λ is increasing in C, there exists a cutoff point C^{**} such that $1 < \lambda < 1/\mu^S$ if $C^+ < C < C^{**}$. The value of λ cannot be greater than $1/\mu^S$, because the buyer can always choose to motivate R&D solely by effort monitoring as in the case of in-house R&D, in which case, $L'(C) = 1/\mu^S$. ■

Proof of Proposition 5.

With in-house R&D, the buyer's expected payment for the R&D is C/μ^I. However, the buyer gives no information rent to the supplier and achieves production efficiency. When C is sufficiently small, the information rent and production inefficiency associated with outsourcing integrated R&D exceeds C/μ^I. Recall that the information rent and production inefficiency does not vary in C when C is sufficiently small. Therefore, the buyer prefers in-house R&D to outsourcing R&D when C is sufficiently small. Next, we show that for $C^- < C < C^+$, the buyer prefers outsourcing R&D to in-house R&D. For $C^- < C < C^+$, with integrated R&D, the supplier produces the efficient level of output and receives zero expected rent – his expected ex post information rent is just sufficient to compensate the cost of R&D, C. On the other hand, with in-house R&D, the buyer's expected payment is C/μ^I which leaves its R&D subunit an expected rent of $C(1/\mu^I - 1)$. Therefore, the buyer's payoff with outsourcing R&D is higher than her payoff with in-house R&D in this case. Moreover, with outsourcing R&D, $L'(C) = -\lambda(C)$, and $\lambda(C)$ is non-decreasing in C and $0 \leqslant \lambda(C) \leqslant 1/\mu^S$; with in-house R&D, $L'(C) = 1/\mu^I$. Thus, there exists $\widetilde{C} < C^-$ such that the buyer prefers in-house R&D for $C < \widetilde{C}$. Again, as shown in Proof of Proposition 4, when C is large enough, the buyer's marginal loss with respect to C is $\lambda = 1/\mu^S$ with outsourcing R&D. Since such a marginal loss with in-house R&D is $1/\mu^I$, for μ^I sufficiently greater than μ^S, the buyer's payoff with in-house R&D is higher than the one with outsourcing R&D when C is sufficiently larger than C^+. ■

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