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SYMPOSIUM

Outsourcing of innovation

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Abstract This paper looks at the outsourcing of research and development (R&D) activities. We consider cost reducing R&D and allow manufacturing firms to decide whether to outsource the project to research subcontractors or carry out the research in-house. We use a principal-agent framework and consider fixed and revenue-sharing contracts. We solve for the optimal contract under these constraints. We find that allowing for revenue-sharing contracts increases the chance of outsourcing and improves economic efficiency. However, the principal may still find it optimal to choose a

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contract that allows the leakage to occur—a second-best outcome when leakage cannot be monitored or verified. Stronger protection of trade secrets can induce more R&D outsourcing without inhibiting technology diffusion and increase economic efficiency, as long as it does not significantly lengthen the product cycle.

Keywords R&D outsourcing · Principal-agent problem · Fixed versus revenue-sharing contract

JEL Classification D21 · O31 · L14

1 Introduction

There is recent evidence that outsourcing research and development (R&D) activities is on the increase. For example, R&D magazine (January, 2001 issue) reports that according to a recent survey of their readers, "it is estimated that 25% of all R&D will be performed on contract with outside performers."[1] Despite its growing trend and increasing importance, outsourced R&D is still a relatively small fraction of total R&D. Why is R&D not outsourced as much as some manufacturing products (such as automobiles) or services (such as legal or advertising services)? We believe this is due largely to its major disadvantage—the possibility that outsourcing R&D will lead to the leakage of trade secrets in the absence of perfect contracting. In a 2003 survey conducted by the Shared Services and Business Process Outsourcing Association (SBPOA), a third (33%) of respondents stated that *a lack of control* and *loss of internal knowledge* are the main concerns when considering to whether or not to outsource. To our knowledge, there has not been any work that formally models the theoretical foundations of R&D outsourcing. Our paper fills that gap.

The outsourcing of production by firms has been considered by many authors (for example, Jones 2000, Grossman and Helpman 2002, 2005, and papers cited therein). This literature focuses primarily on the degree of production outsourcing based on the "theory of the firm". One reason there has been less attention paid to R&D outsourcing is, as Milgrom and Roberts (1992, Chap. 16) point out, R&D outsourcing is difficult to do because of the difficulty of writing a contract and monitoring the subcontractor. In this paper, we tackle this issue by considering a very simple R&D outsourcing problem using a principal–agent framework following the lead of Grossman and Hart (1983) and Myerson (1983).

We begin by supposing that there is a fixed number of firms producing differentiated products in the goods market, which we assume to be monopolistically competitive. As in product cycle theory, after the technology is standardized, the firms seek to lower the cost of production. One way is to engage in cost-reduction R&D. We use a principal-agent framework to analyze whether or not a production firm under monopolistic competition should outsource R&D or do it in-house. The principal in our problem is the owner of the production firm that produces output for this monopolistically

[1] Howells (1999) reports that outsourcing of R&D in the UK doubled in real terms between 1985 and 1995 and that outsourced R&D as a percentage of total R&D increased from 5.5 to 10% over the same period.

competitive market. The research firm is the agent. There is an unlimited supply of workers who can work as in-house researchers for the principal at a competitive wage.

Because of economies of scale, labor specialization, innovation speed, as well as knowledge spillovers, research subcontracting firms have a comparative advantage in R&D activities.[2] As a result, these firms innovate faster and more cheaply than the principal's in-house research employees. However, if R&D is outsourced then, information sharing takes place between the principal and the research firm. In the absence of perfect contracting, this organizational structure of subcontracting therefore facilitates information leakage.[3]

In general, the principal could be involved in two types of R&D, cost-reduction (or process innovation) research and new product innovation. We will analyze cost-reduction R&D and leave the extension to product innovation for future research.[4] So, in our model production firms either do in-house cost reduction research or outsource this job to a research firm.

Would R&D outsourcing always be the equilibrium outcome if the research firm can do research more cheaply and more quickly? Our answer is "No". The reason is that the information leakage problem will sometimes lead to research being done in-house even though it can be done more cheaply and effectively by an outside research firm. This is because useful information obtained by the research subcontractor could be sold to the production firm's competitors, leading to erosion of the production firm's market share.[5] Thus, because of the information leakage problem, R&D may not be outsourced even when it is efficient to do so.

Our major findings are, therefore, related to the information leakage problem, which distinguishes R&D outsourcing from production outsourcing. We find that the optimal outsourcing contract may or may not be revenue-sharing. In the first case, a revenue-sharing contract is the equilibrium outcome, and there is no information leakage. In the second case, the equilibrium features a lump-sum contract, and there will be information leakage. This is the second best outcome when information leakage cannot be monitored or verified. The allowance for revenue-sharing between the principal and the agent increases the likelihood of R&D outsourcing because it eliminates information leakage. Such a contractual arrangement therefore improves economic efficiency. Whether or not the optimal contract is revenue-sharing is endogenous. We find that

[2] Quinn (2000) emphasizes these advantages of outsourcing R&D from the business management point of view.

[3] It is suggested by business world observations delineated in the *R&D Magazine* (January 2001) that information leakage is much more severe in the absence of internal controls when R&D is outsourced. For example, Rhonda Hocker, the Chief Information Officer at San Jose-based software maker BEA Systems and a fan of outsourcing by any measure, stated clearly her limits: "We'll never outsource any of our IT architects," and "I would never envision putting them over there or outsourcing that to anyone" (C-Net news.com, May 5, 2004). Moreover, even by advocating the benefits of R&D outsourcing for U.S. information technology and pharmaceuticals industries, Hemphill (2005) still emphasizes the importance of retaining "core R&D" internally.

[4] Nonetheless, we can think of the innovation explored in this paper as increasing the value of the product (without changing the nature of the product).

[5] Another possibility is that the research firm could enter the industry as a competitor.

a revenue-sharing contract is more likely to be optimal when the agent's gain from information leakage is a smaller fraction of the principal's loss. This will occur, for example, when there is a larger number of firms in the output market. Even under this circumstance, revenue-sharing is optimal only when the principal's loss from leakage is not too small or too large.

Since leakage reduces the chance of outsourcing R&D, any government measure that reduces losses to the principal or the gains of the agent from appropriating the principal's proprietary information may improve economic efficiency. For example, increased protection of trade secrets should be one such measure that mitigates the information leakage problem. Stronger intellectual property protection encourages more R&D outsourcing and increases economic efficiency when it mitigates the principal's loss or reduces the agent's gain from information leakage, as long as it does not significantly lengthen product cycles.

1.1 Related literature

It is important to contrast our study with those modeling outsourcing of production by firms, particularly the more recent work regarding the make-or-buy outcome as an equilibrium phenomenon. Two seminal contributions by Grossman and Helpman (2002, 2005) focus on the incomplete contract (cf. Grossman and Hart 1986; Hart and Moore 1990) aspect of production outsourcing in two vertically linked economies. They highlight the trade-off between operating a larger organization with less specialization (in-house) and conducting costly search with contracting incompleteness (outsourcing). Another recent work by Antras (2005) explains that firms trade off the benefit of subcontracting (through incomplete contracting) against the cost arising from the hold-up problem. Internalization (in-house production) is optimal when the potential hold-up problem faced by the principal is serious, but then subcontracting occurs when this problem eases in the later stage of the product's cycle. Our paper tackles the fundamental agency problem associated with outsourcing R&D by emphasizing the trade-off between the cost arising from information leakage and the benefit from innovation specialization.

Our paper is also related to a seminal paper by Ethier (1986) and a more recent paper by Ethier and Markusen (1996). Ethier argues that in-house production will occur when information exchanges between the principal and the agent are complex. Arm's length contracting (such as outsourcing) emerges when information exchanges are simple. Thus, one can interpret the information leakage problem as a cause of increasing complexity, i.e., it makes exchange between the manufacturer and the subcontractor more difficult. Ethier and Markusen consider the organization of a manufacturing firm that produces a new product. The firm may produce the new good domestically and export or license it to a subsidiary abroad (outsourcing). While the benefit of a subsidiary arrangement is the saving of the transport cost of exporting, the cost is the possible dissipation of its proprietary asset. Although the focus and the framework of these papers are very different from ours, our paper shares the same view that information leakage is a major concern for firms that engage in outsourcing.

2 The basic setup

Consider a continuous-time environment in which each firm in the output market is an inventor of a differentiated product, the technology of which is already standardized. As in product cycle theory, the firms are seeking to reduce the cost of production through cost-reduction R&D. An output firm can carry out innovations in-house by hiring a researcher, or it can outsource the R&D.

The R&D we consider is cost-reduction R&D, though it can be interpreted as process innovation—invention of a process that lowers the cost of producing the output.[6] We assume that the unit production cost resulting from in-house R&D is c and that from outsourcing is $(1-\lambda)c$, where $\lambda \in (0, 1)$ is the unit cost reduction due to the higher quality of outsourced R&D.

In a monopolistically competitive product market with a fixed number of firms, each firm is faced with a downward sloping inverse demand curve $p(x)$. Although it is not essential for most of our findings, for expositional convenience we assume that the demand function takes the constant-elasticity form: $x = Ap^{-\epsilon}$, where $A > 0$ is a scaling factor that reflects the size of the market faced by the output firm and $\epsilon \in (0, 1)$ is the absolute value of the price elasticity of demand for goods. Thus, the value of sales of a typical firm is $R = xp(x) = Ap^{1-\epsilon}$.[7] There is a fixed number of producing firms with no entry or exit (as long as all firms make positive operating profits at all dates, which we assume to be the case). The product life starts at $t = 0$. The inception date of the research output is $t = I$ and the length of product cycle is T. That is, the product's life ends at $t = T$. Without discounting the future, the present-discounted value of sales over the entire product cycle is: $xp(x)\,(T - I)$.[8]

There are two possible ways to conduct R&D, one by hiring in-house researchers and the other via outsourcing to a subcontractor.[9] There is an unlimited supply of workers who can work as in-house researchers for the principal and receive a wage W^{IH} over the entire product cycle (with superscript IH denoting in-house) that is equal to the outside competitive wage W in equilibrium.[10] So, we shall use W^{IH} and W interchangeably in the rest of the paper. Research subcontracting firms are operated by cooperative workers who are able to cooperate with other research workers and thereby enjoy positive knowledge spillovers. These research subcontractors are the *agents*, serving the owners of goods production firms, or the *principals*.

6 We can easily extend the analysis to the case of quality enhancement innovation.

7 While we focus primarily on the simple case abstracting from uncertainty, the implications of demand uncertainty will be discussed in the concluding section.

8 With discounting, $T - I$ is replaced by $\int_I^T \mathrm{e}^{-rt}\mathrm{d}t = \mathrm{e}^{-rI}\int_0^{T-I}\mathrm{e}^{-rt}\mathrm{d}t$, where r is the discount rate. This would not fundamentally change the results.

9 One may regard in-house R&D as that examined in the conventional literature, such as Grossman and Helpman (1991) and Aghion and Howitt (1992).

10 One could include a constant "loyalty premium" $\rho \geq 0$ over the competitive wage W such that $W^{IH} = (1+\rho)W$. We assume that the loyalty premium is set high enough so that in-house researchers have no incentive to leak information.

We can now illustrate three important, easily identified features of R&D activities.

1. *Adaptability of the outsourced R&D to the production firm's environment* In-house R&D has no adaptability problem, since in-house researchers know the firm's operating environment. But outsourced R&D needs to be adapted to the host firm's operating environment, which takes time.[11] Therefore, adaptability is a disadvantage of outsourcing, as outsourcing delays the arrival of customized innovations.
2. *Specialization of the subcontractor* Since the subcontractor enjoys increasing returns to knowledge accumulation as well as increasing returns to scale, it is more efficient in the sense that it can develop the same innovation *faster* than in-house researchers at a given cost. Therefore, the speed of development is an advantage of outsourcing. In addition, outsourced innovation can produce more cost reduction benefits for the production firm than in-house R&D since specialization allows the subcontractor to produce higher quality research output than in-house researchers. The implications are that outsourcing shortens the innovation time for a given cost or effort and it produces more cost reduction benefit.
3. *Information leakage* Useful information about the operations of the production firm is obtained by the subcontractor.[12] Because the technology developed by the principal can be largely codified, internal control over employee activities can limit to a large extent its leakage.[13] For analytic convenience, we assume away the possibilities that in-house researchers may leak information.[14] We capture the fact, reported in the SBPOA Survey, that the subcontracting research firms can leak information and has an incentive to appropriate proprietary information of the output firm by (i) selling it to the potential competitors of the production firm; (ii) entering into the industry as a competitor, with the help of the information obtained.[15] Both of these would lead to erosion of the market share of the production firm and they can prevent R&D from being outsourced even when the advantages in Point 2 above outweigh the disadvantages in Point 1.[16]

In Points 1 and 2 above there are two effects that work in opposition. Adaptability means slower innovation from outsourced R&D while specialization leads to

[11] Although we do not model this effect explicitly, one could easily incorporate it by following the technology adoption setup in Chen and Shimomura (1998) and Chen et al. (2002).

[12] This could include, for example, information about design for manufacturing (DFM). For a discussion of DFM the reader is referred to Allen (2002). Balachandra (2005) argues that, "Outsourcing to other firms may be considered risky in terms of protecting firm's technology and intellectual propery and trade secrets."

[13] As mentioned above, in-house researchers may also receive a loyalty premium that reduces or eliminates their incentive to leak information.

[14] We could easily incorporate such possibilities but would generate complexity without yielding additional insights.

[15] A research activity can range from having very specific goals to having very uncertain ex post outcomes. This paper focuses on the former type. Because of the high specificity of the research outcome, the contract can specify clearly what outcome needs to be achieved, and so it is very difficult for the researcher to shirk by exerting less effort. Thus, the problem of shirking by the agent is assumed away and the agency problem we are dealing with here concerns only the leakage of information.

[16] In this aspect, the informational friction in our R&D outsourcing model is very different from that in the product outsourcing model developed by Grossman and Helpman (2002, 2004).

faster innovation. We assume that the benefit of outsourcing R&D (specialization) is more important than the adaptability delay so that the overall arrival time under R&D outsourcing is shorter than that under in-house research. We normalize by setting $I = 0$ for outsourcing and $I = L$ for in-house R&D, where L is the net delay of arrival of the innovation under in-house R&D. We impose:

Assumption 1 $L > 0$.

Thus, the advantage of specialization under outsourcing outweighs the disadvantage of adaptability. While lower adaptability of outsourced R&D or higher in-house innovative capability tends to lower L, the specialization effect of R&D outsourcing tends to increase L. The consideration of time delay $L > 0$ in addition to cost reductions $\lambda > 0$ enables us to study the the effect of the length of the product cycle (T) which directly influences the benefit of outsourcing from faster innovations (measured by $\frac{L}{T}$) but not the benefit from better innovations as a result of lower costs (measured by λ).

Point 3 above outlines the main incentive problem. The agent might have an incentive to leak information and that runs against the interests of the principal. We model this as a standard principal-agent problem as in Grossman and Hart (1983) and Myerson (1983). Accordingly, we assume that:

Assumption 2 Leakage of the principal's proprietary information by subcontractors cannot be monitored or verified.

More specifically, information leakage cannot be monitored by the principal or verified by a third party such as a court of law. There are several ways one can justify this assumption. There are situations in which both parties to an agreement know whether the agreement was satisfied but there is no way for a third party to verify whether it was or not (private information to third parties). It simply becomes one person's word against another person's word.[17] For example, observed market erosion could be a consequence of the principal's mismanagement or due to information leakage by the subcontracting agent. Even though the principal and the affiliated subcontractor know the true state of the world a third party would not. Moreover, one may argue that part of the information leaked can be of the general tacit knowledge type rather than purely related to the specific product manufactured by the principal. Spillovers of tacit knowledge can hardly be prohibited by the principal or the court.[18] Thus, given Assumption 2 it is not meaningful to write a contract that requires the agent not to leak information, since it would not be enforceable. Therefore, part of the principal's concern is to choose a contract that induces the agent to chose not to leak the information. It is also possible that the information leakage problem could be mitigated by intellectual property (IP) protection since stronger IP protection could *reduce the severity of the leakage problem* or *make leaked information less valuable*.

[17] An even simpler example is, suppose A robs B and there are no witnesses. A court cannot verify this even though both agents know the true state of the world.

[18] Alternatively, we could justify the lack of verifiability by assuming that there is intrinsic uncertainty of the sunspot type (though we do not model uncertainty explicitly). As a consequence, it is impossible for the court to identify the underlying source of a bad sales outcome.

To understand the basic incentives in this environment we use a very simple model of the leakage problem. Denote the binary-choice *action* of leakage by ϕ where $\phi = 0$ indicates no leakage and $\phi = 1$ indicates leakage occurs. As discussed in Point 3 above, the demand faced by the firm depends on whether there is a leakage of information. Specifically, we assume that informational leakage causes an inward shift of the demand curve faced by the production firm, or, more formally,

Assumption 3 Under R&D outsourcing, the goods demand is given by

$$X(p;\delta) \equiv \begin{cases} x(p) & \text{if } \phi = 0 \\ \delta x(p) & \text{if } \phi = 1 \end{cases}, \quad \text{where } \delta \in (0,1)$$

If $\phi = 0$ there is no leakage and demand is not affected. If information leakage occurs, the demand curve faced by the output firm shifts in by a fraction $1 - \delta$, which also captures the severity of information leakage. Notably, although the cost arising from information leakage is perfectly observable to the principal, the action of information leakage by subcontractors cannot be verified by third parties.

Let $B = \beta RT$ be the benefit of information leakage to the agent from selling information. It is reasonable to assume that $\beta \in (0, 1-\delta)$. This assumption guarantees that the principal's revenue loss is always more than the agent's gains when the agent appropriates proprietary information. Specifically, we assume $\beta = \beta_0(1 - \delta)$, with $\beta_0 \in (0, 1)$ being constant for any given market structure.[19] Then, the benefit of information leakage is given by

$$B = \beta RT = \beta_0(1 - \delta)RT \tag{1}$$

If outsourcing takes place then production firms and research firms must agree on a payment schedule for the outsourcing contract. The R&D contract (m, μ) specifies a fixed payment independent of sales (m) and a percentage fee based on the value of sales (a fraction μ). This type of contract is commonly seen in research subcontracting in practice.[20] It is also considered in Ghatak and Pandey (2000) concerning the

[19] Although it is not explicitly modeled in this paper, one can imagine that β_0 will be smaller when the output market is more competitive (i.e., when there are more firms in the output market). To justify $\beta_0 < 1$, or that the agent's gain from information leakage is less than the principal's revenue loss (i.e., $\beta + \delta < 1$), suppose that the R&D results in the principal having a monopoly in the product market. Now, with information leakage another firm can compete and the market becomes duopolistic. It is well-known that the sum of profits of two duopolists is less than the profit of a monopolist. Therefore, the gain of the agent must be less than the loss of the principal's profit, which is less than the principal's revenue loss. Moreover, as the number of firms in the output market increases, the ratio of the agent's gain to the principal's loss decreases. Therefore, β_0 decreases when there are more firms in the output market. At the end of Sect. 5, we shall return to this issue, by considering the case in which $\beta + \delta > 1$.

[20] There is anecdotal evidence that revenue sharing and fixed payment contracts both exist. In fact, the March 3, 2004 issue of BusinessWeek contains an article that describes a pair of firms engaged in R&D outsourcing that used both types of contracts at different points in time. The article is titled "An Unseen Peril of Outsourcing." This article tells the story of U.S. firm AM Communications which outsources R&D to India based NeST Group. The article describes the contracting arrangements as, "Between the end of 1998 and 2000, NeST billed more than \$1.8 million of outsourcing charges to AM, for which it was paid in AM warrants convertible to stock. Beginning in 2000 NeST began receiving cash for its outsourcing services ..."

agricultural sector and in Bajari and Tadelis (2001) concerning the construction industry. Assumption 2 effectively rules out the possibility of writing a more complicated contingent contract.[21]

The outside option wage faced by the agent, W, can be treated as the R&D cost for in-house research. Therefore, the gross profit (excluding the setup cost) over the entire product cycle of the production firm with in-house R&D is

$$\Pi^{IH} = x[p(x) - c](T - L) - W$$

With outsourcing it is

$$\Pi(\mu, m) = \begin{cases} x\,[p(x)(1-\mu) - (1-\lambda)c]\,T - m & \text{when } \phi = 0 \\ \delta x\,[p(x)(1-\mu) - (1-\lambda)c]\,T - m & \text{when } \phi = 1 \end{cases}$$

Note that the x and therefore $p(x)$ in each regime is to be chosen optimally by the principal in each circumstance, treating all other variables and parameters as given.

In the benchmark case, we bestow all bargaining power with the agent:

Assumption 4 The principal has no bargaining power in the sense that all the surplus accrues to the agent.

This is justified if, for example, there is a large number of production firms but a limited supply of potential agents (as assumed in our paper, there are few researchers who are able to cooperate with other researchers to form a subcontracting firm). Another interpretation of this assumption is that, given the various possible contracts offered by potential principals, the agent is the decisive player, selecting the contract she most prefers. If that contract yields her an income higher than her wage when employed in-house, she accepts the outsourcing contract. It is important to note that even if we relax Assumption 4 and allow the principal to have some or even all the bargaining power, the same qualitative results will be obtained.[22]

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[21] We can interpret a lump-sum contract as signifying an arm's length relationship between the principal and the agent, while a revenue-sharing contract as representing a more integrative, joint-venture type relationship. The consideration of more complex compensation contracts is beyond the scope of the present paper.

[22] When the principal has some bargaining power, one may derive an optimal contract maximizing the joint surplus in a way similar to Burdett and Mortensen (1981) or Laing et al. (1995): $\max_{\mu,m}\,[V(\mu,m) - W]^b \left[\Pi(\mu,m) - \Pi^{IH}\right]^{1-b}$, where $b \in [0, 1]$ measures the relative bargaining power of the agent. For example, $b = 1$ under Assumption 4 and $b = 1/2$ when the two parties have symmetric bargaining power. The first-order conditions with respect to μ and m, respectively, are:

$$(\mu - \mu_C)\,[dV(\mu,m)/d\mu + d\Pi(\mu,m)/d\mu] = 0 \quad \text{for } \mu \geq \mu_C$$
$$\mu\,[dV(\mu,m)/d\mu + d\Pi(\mu,m)/d\mu] = 0 \quad \text{for } \mu < \mu_C$$

and

$$m\left[b\left(\Pi(\mu,m) - \Pi^{IH}\right) - (1-b)\,(V(\mu,m) - W)\right] = 0,$$

where each of the expressions in square brackets is non-positive. We will elaborate in Sect. 4.1 that such a generalization would not alter our main findings.

3 R&D outsourcing

We next turn to an analysis that uses a principal-agent framework to determine whether or not the production firm should hire the research firm to do its R&D. The production firm is the principal who offers the R&D contract (m, μ) which the agent (the research firm) may accept or reject. Once the contract is accepted, the agent must also decide, for a given R&D contract, whether to leak the information to the production firm's competitors. We focus on the case in which a match has been made between a production firm (principal) and a research firm (agent). Given that a match exists this becomes a three stage game depicted schematically in Chart 1.

To ensure subgame perfection, we solve this problem backward. In the third and final stage, the agent decides whether to leak the information (chooses ϕ) given the contract offered by the principal (m, μ). In the second stage, the principal, anticipating the decision on ϕ selects the optimal contract (m, μ). Finally, given the optimal contract and the existing outside wage, in the first stage the principal decides whether to do its R&D in-house or to outsource.

The solution to this game shows that the information leakage problem results in less outsourcing. Consequently, we are able to identify a distortion due to an informational asymmetry and as a result, resources are mis-allocated between in-house research and outsourced research. We begin by looking at the agent's decision.

3.1 Agent's decision on information leakage

We assume that the agent, a research firm, consists of several partners, each of whom deals with the R&D of one principal. Information sharing between partners occurs in the normal course of the research process. This information sharing facilitates

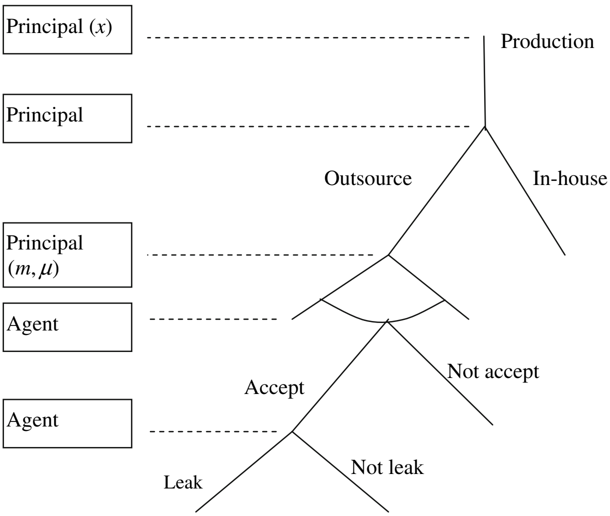

Chart 1 The game tree

information leakage. Clearly, the research firm only accepts contracts that yield a higher return than the market wage. Also, there is no uncertainty and hence, the agent does not have to evaluate risks.[23] For analysis of the third stage of the game, we assume that the agent does better as a subcontractor and accepts the principal's contract offer. We now turn to the question of whether the agent decides to leak the information or not.

Given an outsourcing contract (m, μ), the principal maximizes its profit by choosing x, given μ and m. Since the optimally chosen x is a function of μ, the periodic revenue without leakage R will also be a function—indeed a decreasing function—of μ (see Appendix A).[24] When there is no leakage, the revenue-sharing allows the agent to gain μRT (in addition to the lump-sum payoff m); with leakage it is reduced to $\delta\mu RT$. Therefore, when the agent leaks information about the principal, it loses revenue on account of the lowering of the demand for the principal's product and hence its revenue. The agent's value (or payoff) is therefore given by

$$V = \begin{cases} \mu RT + m & \text{when } \phi = 0 \\ \delta\mu RT + m + \beta_0(1-\delta)RT & \text{when } \phi = 1. \end{cases}$$

So, when the agent sells proprietary information there are two effects on her income. First, her income goes up due to the direct payment from the principal's rival(s) who pay(s) for the information, and also possibly due to her ability to enter the output market as a competitor. Second, since information leakage erodes the demand for the principal's products, the agent's payment from the principal is reduced as it is a function of the principal's revenue.[25] We can write,

$$V|_{\phi=1} = V|_{\phi=0} + \Delta V, \tag{2}$$

where $\Delta V = [\beta - (1-\delta)\mu]RT$ is the agent's valuation differential between leaking and not leaking. Define the critical value μ_C as the value of μ such that $\Delta V = 0$. One can easily compute : $\mu_C = \frac{\beta}{1-\delta} = \beta_0$. If the demand faced by the principal is constant elasticity it can be shown that $\Delta V > 0$ when $\mu < \mu_C$ and $\Delta V < 0$ when $\mu > \mu_C$. Moreover, ΔV decreases in μ until it reaches a value well beyond μ_C. Thus, for any $\mu > \mu_C$, $\Delta V < 0$, which means the value of not leaking is higher than the value of leaking. In this case, the performance-dependent contract payment is high enough to discourage leakage of information. On the other hand, for $\mu < \mu_C$, the agent would leak information leading to an erosion of the market share of the host production firm. We follow the literature by assuming that when an agent is indifferent (at $\mu = \mu_C$), he/she will not leak the information.

23 In a more sophisticated model with risks and uncertainty, we need to take into account the degree of risk aversion. We will discuss the implication of such possibilities in Sect. 6 below.

24 Note that R only depends on and not on ϕ because μ has contained the information about ϕ (when it is above the critical value μ_C, $\phi = 0$; otherwise, $\phi = 1$).

25 See Shell (1973) for a discussion of the importance of market share for inventive activities.

Summarizing, we have, in equilibrium,

$$\phi(\mu) = \begin{cases} 0 & \text{if } \mu \geq \mu_C \\ 1 & \text{if } \mu < \mu_C. \end{cases} \tag{3}$$

Thus, an agent's value can be rewritten as

$$V(m, \mu) = \begin{cases} \mu R(\mu)T + m & \text{when } \mu \geq \mu_C \\ \delta\mu R(\mu)T + m + \beta_0(1-\delta)R(\mu)T & \text{when } \mu < \mu_C. \end{cases} \tag{4}$$

3.2 The optimal outsourcing contract

In this subsection we determine what type of contract the principal (i.e., the production firm) will offer the agent (i.e., the research firm). As mentioned above, we assume that the contract payment has two components, a fixed payment m and a payment contingent on sales $\mu p(x)x$. So, the two parameters (m, μ) define the contract. For any particular response by the agent $\phi(\mu)$, the principal's gross profit over the entire product cycle under outsourcing with a contract (μ, m) is

$$\Pi(\mu, m) = \begin{cases} x(\mu)\left[p(x(\mu))(1-\mu) - (1-\lambda)c\right]T - m & \text{when } \mu \geq \mu_C \\ \delta x(\mu)\left[p(x(\mu))(1-\mu) - (1-\lambda)c\right]T - m & \text{when } \mu < \mu_C \end{cases} \tag{5}$$

which is locally decreasing in μ and discontinuous at $\mu = \mu_C$.

To determine the optimal contract consider the production firm's willingness to trade off between μ and m. For any given value of Π_0, we can define the iso-profit curve for each production firm as:

$$\Pi(\mu, m) = \Pi_0. \tag{6}$$

This relationship indicates the combinations of μ and m that leave the principal indifferent between outsourcing and conducting in-house R&D. We can then use (6) to find how μ and m vary along the iso-profit curve with gross profit equal to Π_0 (see Figs. 1 and 2). We show that the iso-profit curve must be downward sloping for constant elasticity demand since $\frac{d\Pi}{d\mu} = \frac{\partial\Pi}{\partial\mu} < 0$ by standard Envelope Theorem arguments. This is true whether $\mu > \mu_C$ or $\mu < \mu_C$.[26] An iso-profit curve closer to the origin is associated with a higher gross profit.

The iso-profit curves are all discontinuous at $\mu = \mu_C$. This discontinuity occurs because as μ increases to μ_C from below, information leakage is eliminated and the market share is restored from $\delta < 1$ to $\delta = 1$. Thus, the total revenues jump and the principal is able to increase the lump-sum contract payment (m) and still

[26] For illustrative purposes, these iso-profit curves are drawn as linear functions.

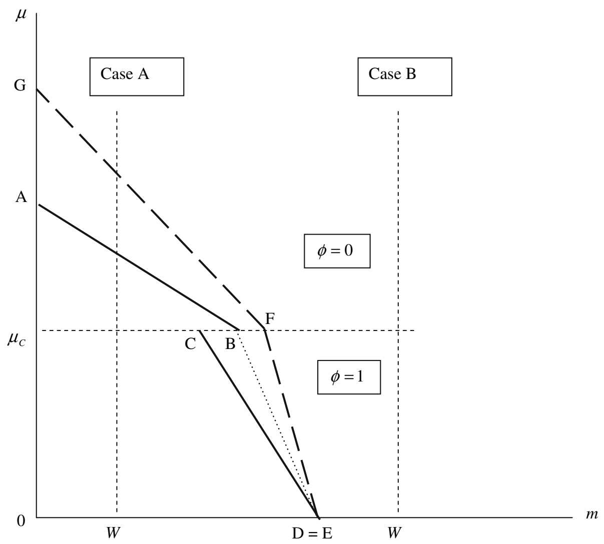

Fig. 1 Outsourcing with lump-sum contracts (OL) versus in-house (IH). Case A: $\overline{OE} > W$ Regime OL, Case B: $\overline{OE} < W$ Regime IH. Dashed line indicates indifference curve of the agent with payoff equal to V_o. Solid line indicates iso-profit curve of the principal with profit equal to Π^{IH}. Dotted line indicates convexified part of the iso-profit curve of the principal

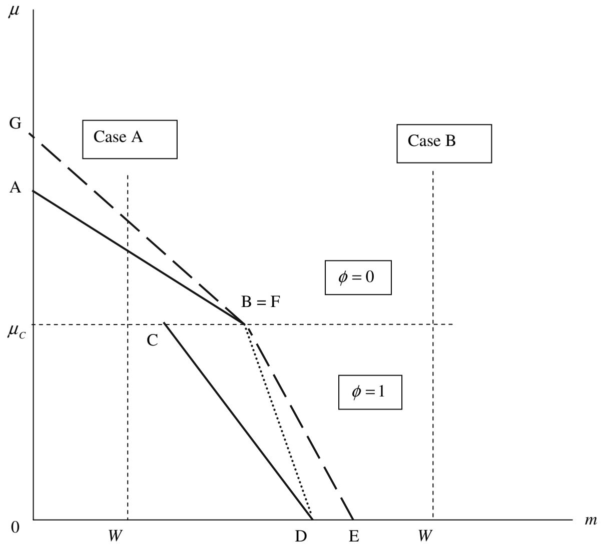

Fig. 2 Outsourcing with revenue-sharing contracts (OR) versus IH. Case A: $\overline{OE} > W$ Regime OR, Case B: $\overline{OE} < W$ Regime IH. Dashed line indicates indifference curve of the agent with payoff equal to V_o. Solid line indicates iso-profit curve of the principal with profit equal to Π^{IH}. Dotted line indicates convexified part of the iso-profit curve of the principal

maintain the same profit. Furthermore, totally differentiating (5) with respect to μ and m, we show in Appendix A that

$$\left|\frac{\mathrm{d}\mu}{\mathrm{d}m}\right|_{\Pi_0}^{\mu>\mu_\mathrm{C}} = \frac{1}{RT} < \frac{1}{\delta RT} = \left|\frac{\mathrm{d}\mu}{\mathrm{d}m}\right|_{\Pi_0}^{\mu<\mu_\mathrm{C}} \quad \text{at } \mu = \mu_\mathrm{C}$$

That is, the iso-profit curve is flatter if $\mu > \mu_\mathrm{C}$ (segment AB in Figs. 1, 2) than if $\mu < \mu_\mathrm{C}$ (segment CD in Figs. 1, 2) at least in the neighborhood of $\mu = \mu_\mathrm{C}$. Again, the difference in the slopes is entirely due to the reduced market share from information leakage ($\delta < 1$). The iso-profit curve is steeper for $\phi = 1$ than for $\phi = 0$ because the marginal effect of μ on $\Pi(\mu, m)$ is smaller when $\phi = 1$, and so the principal is willing to give up more μ for each one-dollar reduction in lump-sum payment.

If the principal does not outsource the R&D, then it has to pay the in-house researcher a wage of W. The gross profit of the principal when doing R&D in-house is therefore given by

$$\Pi^{IH} \equiv x^{IH}[p(x^{IH}) - c](T - L) - W \tag{7}$$

where $x^{IH} = \arg\max_x \{x[p(x) - c]\}$ is the optimal output of the firm when it conducts in-house R&D (see Appendix A for a derivation x^{IH}). Let $\underline{\Pi}$ denote the reservation profit of the principal. Throughout the paper, we assume that the participation constraint for in-house R&D is met, i.e., $\Pi^{IH} \geq \underline{\Pi}$. Voluntary participation by the principal in R&D outsourcing requires that the principal's payoff from R&D outsourcing be at least as high as her payoff under in-house R&D:

$$\Pi(\mu, m) \geq x^{IH}[p(x^{IH}) - c](T - L) - W$$

In the next section, we show how changes in parameters $\{W, \beta_0, \lambda, L/T\}$ affect the principal's decision on whether to outsource R&D in equilibrium.

4 Outsourcing versus in-house R&D

To understand the decision to outsource innovation versus carrying out the cost reduction innovation in-house, we begin by characterizing the indifference curve of the agent in (m, μ) space. The indifference curve is the locus of pairs of (m, μ) for which $V(m, \mu) = V_0$ (a constant). Referring to Fig. 1, note that, unlike the iso-profit locus of the principal, there is *no* discontinuity of the indifference curve where $\mu = \mu_\mathrm{C}$ (when ϕ switches from 0 to 1). This follows directly from (2), which shows that $V|_{\phi=1} = V|_{\phi=0}$ when $\mu = \mu_\mathrm{C}$. Alternatively, equation (4) shows that V is continuous in μ because it is the maximum of two continuous functions in μ.[27] Since V is continuous in μ, the indifference curve $V(m, \mu) = V_0$ is also continuous. Next, we compare the slopes of the indifference curve for $\mu > \mu_\mathrm{C}$ and for $\mu < \mu_\mathrm{C}$. Using

[27] Precisely, we have $V = \max\{\mu R(\mu)T + m,\ \delta\mu R(\mu)T + m + \beta_0(1 - \delta)R(\mu)T\}$.

(4), we totally differentiate $V(m, \mu) = V_0$ with respect to m and μ. Then, it can be shown (in Appendix A) that

$$\left|\frac{\mathrm{d}\mu}{\mathrm{d}m}\right|_{V_0}^{\mu>\mu_C} = \frac{1}{RT - \mu T\left|\frac{\mathrm{d}R}{\mathrm{d}\mu}\right|} < \frac{1}{\delta RT - \delta\mu T\left|\frac{\mathrm{d}R}{\mathrm{d}\mu}\right| - \beta T\left|\frac{\mathrm{d}R}{\mathrm{d}\mu}\right|} = \left|\frac{\mathrm{d}\mu}{\mathrm{d}m}\right|_{V_0}^{\mu<\mu_C} \quad \text{at } \mu = \mu_C$$

That is, the indifference curve is flatter when $\mu > \mu_C$ than when $\mu < \mu_C$, at least in the neighborhood of $\mu = \mu_C$. That means the indifference curve is kinked outward at $\mu = \mu_C$ (see curve EFG in Figs. 1, 2). The indifference curve is flatter when $\mu > \mu_C$ because when there is no leakage, the payoff of the agent is less tied to the revenue of the principal. The agent requires a smaller increase in μ to compensate her for each dollar reduction in m. Note that the indifference curve has higher utility in the northeast direction.[28] We next address the issue of bargaining power between the principal and the agent.

Under Assumption 4, the solution to our problem is straightforward. In particular, (i) when the payment to the subcontractor (μ, m) satisfying $\Pi(\mu, m) = \Pi^{IH}$ yields $V(\mu, m) \geq W$, the principal outsources R&D; (ii) otherwise, the principal conducts R&D in house. In this benchmark case, the agent solves:[29]

$$\max_{\mu,m} \quad V(\mu, m) \quad \text{s.t. } \Pi(\mu, m) = \Pi^{IH}$$

That is, the agent chooses the contract that maximizes her utility subject to the principal getting Π^{IH}. This contract is acceptable if it is more attractive than the researcher's best outside option—the in-house wage. That is, there will be outsourcing if $V(\mu, m) \geq W$.

It is shown in the Appendix A that

$$\left|\frac{\mathrm{d}\mu}{\mathrm{d}m}\right|_{V_0} > \left|\frac{\mathrm{d}\mu}{\mathrm{d}m}\right|_{\Pi_0} \quad \text{for any given } \mu$$

That is, the indifference curve is always steeper than the iso-profit curves for any given μ, as in Figs. 1 and 2. That is, for each dollar reduction in m, the agent requires a greater increase in μ than the principal is willing to yield. Finally, we can also conclude

[28] Again, the indifference curves in these diagrams are drawn as straight lines only for illustrative convenience. We have also depicted the indifference curve as downward sloping, which is not the case in general. In Appendix A, we show that the indifference curve may be upward sloping in (m, μ) space, meaning that an increase in μ leads to such a large decrease in R that the agent has to be compensated by being paid a higher lump-sum m to make her indifferent compared with before.

[29] Thus, the optimal contract obtained is an ex ante optimal incentive contract in the sense of Harris and Raviv (1979) and Milgrom (1988).

that the iso-profit curves and the indifference curves are convex in each of the zones $\mu < \mu_C$ and $\mu > \mu_C$.[30]

We will show shortly in the next four subsections that three types of equilibrium may emerge:

(i) equilibrium with in-house R&D (referred to as Regime IH),
(ii) outsourcing equilibrium with lump-sum contracts (referred to as Regime OL),
(iii) outsourcing equilibrium with revenue-sharing mixed contracts (referred to as Regime OR).

Before deriving the results formally, however, we would like to provide further insight into the determination of the equilibrium outcomes by comparing the "threat points" facing the principal and the agent. In doing so, we can see more clearly that our main findings do not rely on the assumption we make about the relative bargaining powers of the two parties (viz. Assumption 4). Specifically, the threat points facing the principal and the agent are, respectively, represented by a particular iso-profit curve, $\Pi(m, \mu) = \Pi^{IH}$, and a particular indifferent curve, $V(m, \mu) = W^{IH}$, because Π^{IH} and W^{IH} are the corresponding best outside options (from in-house production). Refer now to Fig. 3. Active participation in outsourcing activity requires that a contract (m, μ) be in the area on or below $\Pi(m, \mu) = \Pi^{IH}$ and on or above $V(m, \mu) = W^{IH}$ (that is, both the principal and the agent are at least as well off as when R&D is conducted in-house).

Depending on the relative positions of the two threat-point curves, there are four scenarios:

(a) $\Pi(m, \mu) = \Pi^{IH}$ is entirely below $V(m, \mu) = W^{IH}$;
(b) $\Pi(m, \mu) = \Pi^{IH}$ is entirely below $V(m, \mu) = W^{IH}$ for $\mu \geq \mu_C$ but at least part of $\Pi(m, \mu) = \Pi^{IH}$ is above $V(m, \mu) = W^{IH}$ for $\mu < \mu_C$;
(c) $\Pi(m, \mu) = \Pi^{IH}$ is entirely below $V(m, \mu) = W^{IH}$ for $\mu < \mu_C$ but at least part of $\Pi(m, \mu) = \Pi^{IH}$ is above $V(m, \mu) = W^{IH}$ for $\mu \geq \mu_C$;
(d) at least part of $\Pi(m, \mu) = \Pi^{IH}$ is above $V(m, \mu) = W^{IH}$ for both $\mu < \mu_C$ and $\mu \geq \mu_C$ (including the case where $\Pi(m, \mu) = \Pi^{IH}$ is entirely above $V(m, \mu) = W^{IH}$).

In scenario (a), outsourcing is inferior to both the principal and the agent regardless of the assumption of the relative bargaining powers. Thus, Regime IH always arises where the equilibrium outcome must be in-house R&D. For the other three scenarios, there are joint surpluses accrued as a result of outsourcing R&D and hence, in equilibrium, R&D must be subcontracted. While Regime OL arises where R&D is outsourced with a lump-sum contract ($\mu = 0$) in scenario (b), Regime OR occurs featuring a revenue-sharing mixed outsourcing contract with $\mu = \mu_C$ in scenario (c). In scenario (d), whether the outsourcing contract is lump-sum or revenue-sharing depends on the

[30] Note that even if the indifference curve is upward sloping or partially upward sloping $\left(\text{when the indifference curve is upward sloping, } \left.\frac{d\mu}{dm}\right|_{V_0} > 0 > \left.\frac{d\mu}{dm}\right|_{\Pi_0}\right)$, the indifference curve EF must always be to the right of the iso-profit curve DC in Fig. 1, as long as D and E are the same point. This ensures that the equilibrium contract will either be at point B or point D (i.e. $\mu = 0$ or μ_C). There is no possibility of an equilibrium at any point between $\mu = 0$ and $\mu = \mu_C$.

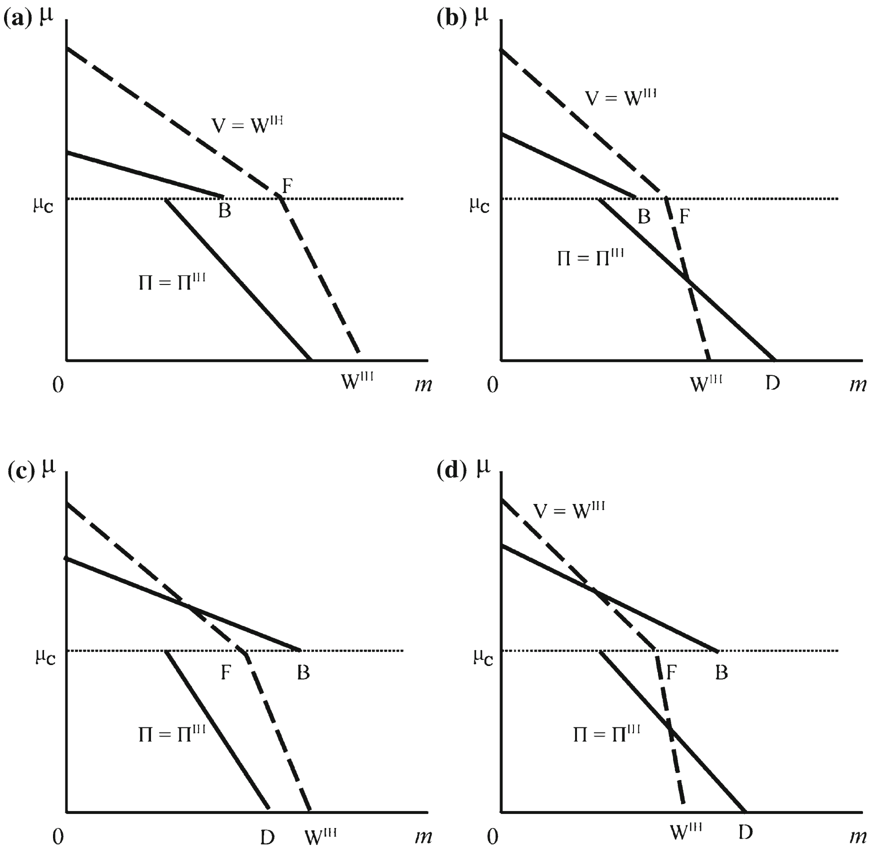

Fig. 3 Outsourcing versus IH from the point of view of the threat points facing the principal ($\Pi = \Pi^{\mathrm{IH}}$) and the agent ($V = W^{\mathrm{IH}}$). **a** In-house, **b** outsource with $\mu = 0$, **c** outsource with $\mu = \mu_C > 0$ **d** outsource with either $\mu = 0$ or $\mu = \mu_C$

relative magnitude of $\overline{BF}$ versus $\overline{OD} - W^{IH}$ (see panel (d) of Fig. 3). It is clear that the optimal forms of the contract as well as the main findings concerning the role of performance-based contracts in alleviating the agency problem remain unchanged for different assumptions about the relative bargaining power.[31]

4.1 Lump-sum versus revenue-sharing contracts

If outsourcing does occur in equilibrium, which forms of outsourcing contracts will be chosen depends crucially on the relative slopes of the agents's indifference curve to the principal's iso-profit curve. Particularly, we have:

[31] Specifically, while μ always takes on the value 0 or μ_C, the relative bargaining power only affects the equilibrium value of m (and hence only the boundary between Regimes OL and OR). Regardless of the relative bargaining power, leakage still occurs in the case where $\mu = 0$ (Regime OL), whereas under $\mu = \mu_C$ (Regime OR) the agency problem is completely alleviated.

Proposition 1 *Under Assumptions 1–4 and constant elastic output demand, if R&D is outsourced in equilibrium, then the optimal contract is* (i) *lump-sum when* δ *or* β_0 *is sufficiently large and* (ii) *revenue-sharing when* δ *or* β_0 *is sufficiently small.*

When δ or β_0 is sufficiently large, the agent's willingness to substitute lump-sum payments (m) for performance-based payments (μ) is high and the principal's profit gap between leaking and no leaking is small. Thus, we have a corner solution under outsourcing at point D in Fig. 1, and the agent would rather take a lump-sum contract that is tolerable by principal. When δ or β_0 is sufficiently small, the agent's willingness to substitute lump-sum payments (m) for performance-based payments (μ) is low and the principal's profit loss from leakage by the agent is large. An interior solution under outsourcing arises at point B in Fig. 2 where the agent is willing to take a revenue-sharing contract that is preferred by the principal. (See Appendix B for a more detailed illustration based on Figs. 1 and 2.)

The fact that the potentially leakage-deterring performance-based contract is not necessarily optimal is a consequence of its opposing effects on the principal's incentives. On the one hand, a higher value of μ discourages the agent from leaking information. On the other hand, it weakens incentives by the principal to invest in output (lower x) as a result of the diminished rate of net profit. This tradeoff gives rise to the possibility that a performance-based contract may in some circumstances be dominated by a lump-sum contract that does not affect the principal's incentives to invest in output.[32]

In Appendix C, we derive the boundary between the cases associated with the two different forms of outsourcing contracts explicitly. Essentially, the calculation of this boundary is based on comparing the tradeoffs between lump-sum payments and performance-based payments. It is shown in Appendix C that this boundary is given by

$$D(\beta_0, \delta) \equiv (1-\beta_0)^{\frac{\alpha}{1-\alpha}} - \alpha\,(1-\beta_0)^{\frac{1}{1-\alpha}} - \beta_0(1-\delta) - (1-\alpha)\delta = 0 \qquad (8)$$

where $\alpha = 1 - 1/\epsilon$. An outsourcing contract will be lump-sum if $D(\beta_0, \delta) < 0$; otherwise, it is performance-based. This boundary is plotted in (β_0, δ) space: see the AEC locus in Fig. 4. To the northeast of AEC (δ or β_0 is large), we have lump-sum outsourcing contracts and to the southwest of AEC (δ or β_0 is small), we have revenue-sharing mixed contracts.[33]

In the next two subsections, we describe in detail the transition between in-house R&D and outsourcing under each type of contract.

[32] One may wonder whether our performance-based contract is a simple threshold bonus and whether revenue-sharing is always optimal if moral hazard were more continuous in nature. We have checked such possibilities and found that, as long as there is a minimum threshold for the leaked information to have any market value (which is realistic), revenue-sharing need not be optimal.

[33] It is noted that, when $\beta_0 > 1-\alpha$, performance-based outsourcing contracts can never arise in equilibrium.

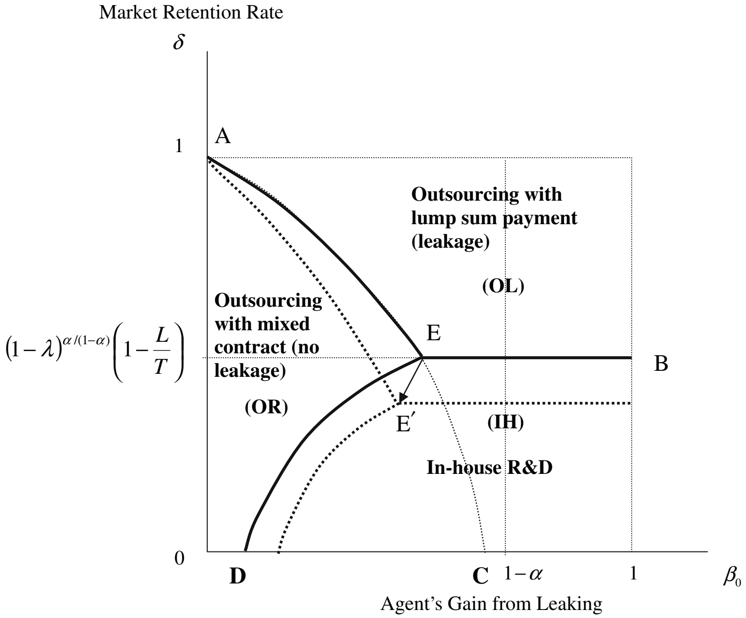

Fig. 4 The boundary between in-house R&D and outsourcing R&D: an increase in α leads to a shift of point E to point E'

4.2 In-house versus outsourcing with lump-sum contracts

To better understand how the parameters in the model determine whether research is outsourced, we derive the boundary between outsourcing and in-house research. Consider first the case with sufficiently large δ or β_0 so that the optimal contract is lump-sum if R&D is outsourced. We can show that

Proposition 2 *Under Assumptions 1–4, constant elastic output demand, and the scenario that the optimal contract is lump-sum if outsourcing does occur, R&D is outsourced in equilibrium if* $\delta > (1-\lambda)^{\frac{\alpha}{1-\alpha}}(1-L/T)$; *otherwise, it is conducted in-house. Changes in W or β_0 have no effect on who carries out R&D in equilibrium in this case.*

From Fig. 1, R&D is outsourced iff $\overline{OE}(=\overline{OD}) > W$; otherwise, it is conducted in-house. It is shown in Appendix C that the boundary along which it is indifferent between outsourcing and in-house in $(\delta, L/T)$ space (given λ and α) satisfy:

$$\delta = (1-\lambda)^{\frac{\alpha}{1-\alpha}}\left(1-\frac{L}{T}\right) \tag{9}$$

Since this boundary is independent of β_0, it is horizontal in (β_0, δ) space (see Fig. 4).

The first part of the Proposition is very intuitive. Basically, it says that if the advantage of R&D outsourcing (values of δ and λ) and/or the disadvantage of in-house R&D (value of L/T) are/is larger, R&D outsourcing will be the equilibrium outcome.

The interesting effects are those of W and β_0. An increase in W causes Π^{IH} to decrease, which in turn causes $\overline{OD}$ to increase by the same amount. In the end, W has no effect on $\overline{OD} - W$, and therefore it has no effect on the mode of R&D. The fact that changes in W have no effect on who carries out R&D in equilibrium is quite surprising, since one would expect an increase in the wage to induce agents to become employees rather than partners in subcontracting firms. This argument is incorrect because it ignores the fact that an increase in W raises the principal's willingness to pay for outsourcing R&D as Π^{IH} decreases. Thus, both $\overline{OD}$ and W increase by the same amount. In other words, though the subcontractor gets a higher wage while working as the principal's employee, she also receives more fees from the principal through outsourcing. Thus, it would not change the value of $\overline{OD} - W$, and so it would not change who carries out R&D in equilibrium. The effects of β_0 are even simpler. Since β_0 does not affect Π^{IH}, it has no effect on $\overline{OD}$. Therefore, changes in β_0 does not affect $\overline{OD} - W$.

4.3 In-house versus outsourcing with revenue-sharing contracts

We next derive the boundary between outsourcing and in-house research for the case with sufficiently small δ or β_0 so that the optimal contract is performance-based if R&D is outsourced. We have:

Proposition 3 *Under Assumptions 1–4 and constant elastic output demand, the condition that supports outsourcing under lump-sum contracts also supports outsourcing under performance-based contracts. However, even under the condition that in-house R&D is chosen over outsourcing with lump-sum contracts, outsourcing with revenue-sharing contracts may still arise as an equilibrium outcome.*

From Fig. 2, R&D is outsourced iff $\overline{OE} > W$ (in this case, $\overline{OD} < \overline{OE}$). Using this condition, we show in Appendix C that the boundary between outsourcing and in-house R&D (given λ and α) is given by

$$\Gamma\left(\beta_0, \delta, \frac{L}{T}\right) \equiv (1-\beta_0)^{\frac{\alpha}{1-\alpha}} - \alpha\,(1-\beta_0)^{\frac{1}{1-\alpha}} - \beta_0(1-\delta) - (1-\alpha)\,(1-\lambda)^{\frac{\alpha}{1-\alpha}}\left(1-\frac{L}{T}\right) = 0 \tag{10}$$

where Γ measures the net benefit of outsourcing R&D. That is, R&D will be outsourced iff $\Gamma > 0$; otherwise, it will be conducted in-house. It is clear that outsourcing is more likely to occur as δ or L/T gets larger, or as β_0 gets smaller. The projection of this boundary is upward sloping in (β_0, δ) space (given $\frac{L}{T}$, λ and α), depicted as the ED locus in Fig. 4.

In this case, $\overline{OD} < \overline{OE}$, that is, the maximum lump-sum-equivalent that the principal is willing to give up so as to maintain its gross profit of Π^{IH} is smaller than the maximum lump-sum-equivalent that the agent can extract from the principal under outsourcing. Since there is outsourcing iff $\overline{OE} - W > 0$, a sufficient *but not necessary* condition for outsourcing is that $\overline{OD} - W > 0$. In other words, we have weaker conditions in Proposition 3 than Proposition 2 for outsourcing to be the equilibrium outcome.

Intuitively, when outsourcing does not entail a lump-sum contract, there exists some wage level which is higher than the maximum lump-sum the principal is willing to pay the agent, but the agent is still willing to do R&D for the principal. This is because the agent is able to extract a mixed contract from the principal which yields a higher payoff to the agent than the wage. Therefore, allowing for a revenue-sharing component in the outsourcing contract can increase the likelihood of outsourcing. This is possible when β_0 is sufficiently small so that the agent can only gain a small fraction of what the principal loses in case of leakage. The possibility of writing a mixed contract explains why the outsourcing region in the case with performance-based contracts shown in Fig. 4 extends beyond the region $\delta > (1-\lambda)^{\frac{\alpha}{1-\alpha}}(1 - L/T)$ (which is the condition defining the outsourcing region in the case with lump-sum contracts). As β_0 gets smaller, the range of δ that supports outsourcing in equilibrium gets larger.

4.4 Characterization of the equilibrium

Combining the arguments in the three previous subsections, the boundaries that divide three regimes in (β_0, δ) space, in-house (IH), outsourcing with lump-sum contracts (OL) and outsourcing with revenue-sharing contracts (OR), are depicted in Fig. 4. Straightforward comparative-static exercises lead to:

Proposition 4 *Under Assumptions 1–4 and constant elastic output demand, the equilibrium possesses the following properties.*

(i) *R&D is outsourced when the degree of market erosion due to information leakage is low (δ large), the subcontractor's benefit from leaking is not too high (β_0 small), or the output demand faced by the principal is sufficiently elastic (α high); otherwise, R&D is conducted in-house.*

(ii) *Revenue-sharing is the optimal contractual arrangement only when the subcontractor's benefit from leaking (β_0) is sufficiently small; given that β_0 lies in a range where revenue-sharing and in-house R&D are both supportable as equilibrium, revenue-sharing is optimal only when the degree of market erosion due to information leakage $(1-\delta)$ is not too large or too small.*

It is worthwhile going through the intuition for the impact of a reduction in β_0 using Fig. 4. From (9), we see that β_0 has no effect on who carries out R&D if the optimal outsourcing contract is lump-sum. However, it does have an effect if the optimal outsourcing contract is performance-based. Start from a point in the IH region and now decrease β_0 (by keeping δ constant). Recall that $\mu_C = \beta_0$, so a reduction in β_0 reduces μ_C. This, therefore, raises the possibility that one can mitigate the effects of information leakage by writing a performance-based contract because there are smaller gains for the agent to leak information. By reducing the agent's gain from leakage, it makes R&D outsourcing more likely. We thus enter into the OR region.

Figure 4 essentially contains all the major results of this paper regarding the characterization of equilibrium outcomes. First, it shows that we have the IH regime only when β_0 is large and δ is small. This is intuitive because it implies that when the principal's loss and the agent's gain from leakage are both high, outsourcing is unlikely. Second, it shows that the OR regime with revenue-sharing outsourcing contracts arises in equilibrium only when β_0 is sufficiently small. Intuitively, when β_0 is sufficiently large, the agent's "price" of leaking is smaller than the willingness of the agent to substitute m for μ, and so she always prefers leaking in case of outsourcing. Third, given that β_0 is sufficiently small so that there is the possibility of revenue-sharing outsourcing (but not so small as to completely inhibit in-house R&D), there are three subcases, depending on the value of δ. The OR regime emerges only when δ is not too large or too small. When δ is too small, the disadvantage of outsourcing is too big, and so Regime IH is the optimal choice. When δ is too large, though there is outsourcing, there is no revenue-sharing since leakage does not cause too much loss to the principal; so the equilibrium features Regime OL. Only when δ is intermediate in value would outsourcing and revenue-sharing (to prevent leakage) be both beneficial to the principal.

Finally, our results show that, as the output demand faced by the principal gets more elastic (α gets larger), the IH regime gets smaller, and the OL regime (with leakage) gets larger (see Fig. 4 where point E shifts southwest to E'). When α is close to 1 (output demand is very elastic), the probability of outsourcing with lump-sum contract (and leakage) is close to one. Intuitively, when the differentiated goods become more substitutable with each other, a given reduction in cost by a firm can induce more quantity demanded, thereby generating more profit for the firm, making outsourcing more attractive.

5 Intellectual property protection and R&D outsourcing

Does R&D outsourcing result in higher economic welfare? Suppose there is no information leakage. Because the research firm can do R&D faster and better, R&D outsourcing is *more efficient* than in-house research and thus is associated with higher welfare. Therefore, to the extent that it inhibits outsourcing of R&D, information leakage causes the production firm to *under-outsource* R&D compared to a socially coordinated outcome. Moreover, since $\beta + \delta < 1$, leakage reduces economic efficiency, as the principal's losses outweigh the agent's gains. Under these circumstances, actions that *mitigate information leakage* arising from outsourcing R&D will generate an efficiency gain.

The above discussion suggests a role for policy. Can appropriate policies alleviate the economic inefficiency resulting from the information leakage problem? Suppose policy makers have no direct control over the actions of research firms. Now consider an intellectual property (IP) policy of tighter protection of trade secrets. Such a policy may reduce the principal's loss associated with information leakage (i.e., δ increases while β_0 stays constant) and/or lower the agent's marginal gain from information leakage (i.e., β_0 decreases while δ stays constant).[34] For example, it would be easier for the principal to stop intellectual property (IP) rights infringement or seek compensation after the trade information is leaked by the agent, even though one cannot verify whether the agent indeed leaked the information (Assumption 2). Proposition 4 states that this effect increases the likelihood of R&D outsourcing, which is an economically more efficient "institutional arrangement" to conduct R&D (as compared to in-house R&D). Therefore, stronger protection of trade secrets tends to improve economic efficiency on this account.

Does stronger IP protection necessarily inhibit technology diffusion? Our answer is "No". Consider first the case where IP protection only reduces the principal's loss (higher δ). If β_0 is sufficiently small so that stronger IP protection induces more R&D outsourcing with no leakage, it does not inhibit or enhance diffusion of the developed technology. This is represented by an upward movement from Regime IH to Regime OR crossing the DE locus in Fig. 4. If β_0 is sufficiently large for stronger IP protection to induce more R&D outsourcing with leakage, it actually enhances technology diffusion.[35] This latter case is represented by an upward movement from Regime IH to Regime OL crossing the EB line in Fig. 4. Consider next the case where IP protection only reduces the agent's marginal gain (lower β_0). Although stronger IP protection can induce more R&D outsourcing by moving from the IH to the OR regimes (crossing the DE locus in Fig. 4), it does not affect technology diffusion as no leakage would occur in equilibrium. In the conventional IP protection literature, the optimal degree of IP protection balances the marginal benefit of inducing more R&D investment against the deadweight loss arising from inhibiting imitation or technology diffusion [see Grossman and Lai (2004) and papers cited therein]. In contrast, the benefit of IP protection in our model does not arise from increased R&D investment, but rather, from a better institutional arrangement of R&D (i.e., outsourcing versus in-house). In this context, we show that increased IP protection induces more efficient R&D *without* necessarily inhibiting technology diffusion.

One may inquire what happens if the product cycle is lengthened (i.e., T increases). Under our framework, it makes the relative disadvantage from delayed arrival of conducting R&D in-house less severe (as L/T is lower), making in-house R&D more attractive. Stronger IP protection can lead to longer product cycles. One explanation is offered by Green and Scotchmer (1995) and O'Donaghue et al. (1998), where they argue that wider patent breadth stifles future quality-improvement innovations by making them more costly to conduct. This slows down the creative destruction process and lengthens the product cycle. The lengthened duration of monopoly power of the incumbent discourages R&D outsourcing and thus decreases economic efficiency.[36]

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[34] More generally, let $\beta(\tau) = \beta_0(\tau)[1 - \delta(\tau)]$ where τ represents strength of IP protection, δ is increasing in τ, and β_0 is decreasing in τ. Thus, an strengthening of IP protection in either form will reduce the agent's net gain from leaking trade secrets.

[35] Should stronger IP protection increase the number of technologies that are diffused, but decrease the extent to which each one of them diffuses, the net effect would be ambiguous.

[36] To be more specific, lengthening the product cycle induces the production firm to undertake R&D in-house. This is because the principal can now enjoy no leakage for a larger fraction of the product's life if it keeps R&D in-house. Thus, lengthening product cycles hurts welfare on two counts: R&D is not outsourced and the duration of monopoly power of the incumbent is increased.

One may therefore argue, that the Trade-Related Aspects of Intellectual Property Rights (TRIPS) agreement, which strengthens IP protection of many less developed countries, could result in less R&D outsourcing from the North to the South if it greatly lengthens product cycles.[37]

These results are summarized in:

Proposition 5 *Under Assumptions 1–4,*

(i) *Strengthening IP protection to reduce the principal's loss increases economic efficiency by encouraging more R&D outsourcing—it enhances technology diffusion if the equilibrium features a lump-sum outsourcing contract (β_0 is large), but it does not inhibit or enhance technology diffusion if the equilibrium features a mixed contract (β_0 is small);*

(ii) *Strengthening IP protection to reduce the agent's marginal gain from leakage increases economic efficiency by encouraging more R&D outsourcing, but does not inhibit or enhance technology diffusion;*

(iii) *If a strengthening of IP protection leads to longer product cycles, it tends to reduce the incentive to outsource R&D and hence, lowers economic efficiency.*

A straightforward policy prescription is therefore to protect trade secrets by preventing production firms from suffering information-leakage-based losses and by reducing subcontractor's potential gains from selling such information, but that conclusion is tempered if such policy significantly lengthens the product cycle.

Finally, what if the agents' gain from leakage exceeds the principal's loss ($\beta+\delta > 1$)? If the R&D outsourcing takes place within a country then leakage will actually increase efficiency, as the agent's gain outweigh the principal's loss. However, if outsourcing takes the form of offshoring, then leakage lowers welfare from the home (source) country point of view since the increased profits of foreign subcontractors do not enter into the home country's welfare calculation. Nonetheless, from the point of view of world welfare, leakage increases welfare when $\beta + \delta > 1$.

6 Concluding remarks

This paper is among the first to explore the economics of R&D outsourcing. We believe a principal-agent framework is appropriate for this purpose because the central issue in R&D outsourcing is the possibility of the leakage of trade secrets and the subsequent erosion of the competitive advantage of the principal. These leakage problems might prevent R&D from being outsourced even though it is economically efficient to do so. Here, a very simple model reveals a rich array of principles. By solving for and characterizing the optimal contract which best mitigates these leakage problems, we find that the optimal outsourcing contract may or may not involve revenue-sharing. With revenue-sharing, there is no leakage of information.

Interestingly, under certain circumstances, manufacturing firms outsource R&D with a lump-sum contract, despite knowing that leakage will occur. In-house R&D is

[37] This is more likely when the information leaked is of the general tacit knowledge type that is difficult to protect.

the optimal institutional arrangement only if the principal's loss and the agent's gain from leakage are both large. Outsourcing with revenue-sharing is optimal only when the agent's gain from leakage is sufficiently small and the principal's loss from leakage is neither too large nor too small. As the output demand faced by the principal gets more elastic, the probability of outsourcing with a lump-sum contract (and leakage) increases. Stronger intellectual property protection encourages more R&D outsourcing and increases economic efficiency when it mitigates the principal's loss or reduces the agent's gain from information leakage, as long as it does not significantly lengthen product cycles.

What happens if we introduce demand uncertainty (or, what is mathematically equivalent, uncertainty in the relative cost reduction measured by λ)? If both the principal and the agent have linear value functions, our findings remain the same. Suppose the research firm (the agent) is risk averse. Then, under the same outside competitive wage, the principal must provide an outsourcing contract with higher compensation in order to maintain the agent's indifference. The resulting increase in the compensation cost therefore discourages the principal from outsourcing R&D. Moreover, since a revenue-sharing contract generates uncertain rewards to the agent, it must provide a higher share of revenue to compensate the agent for each unit reduction in lump-sum payment. The outsourcing contract must therefore be more likely to be lump-sum. Comparing to the case without demand or cost-reduction uncertainty, the introduction of uncertainty therefore increases the likelihood of in-house R&D and reduces the likelihood of R&D outsourcing with a revenue-sharing contract. This suggests an additional explanation for the reluctance of manufacturing firms to outsource R&D despite its advantages of speed and specialization.

Appendix A

This appendix proves that the slope of the agent's indifference curve is always steeper than that of the iso-profit curve of the principal at any given μ. We can easily show that $R = x^{\alpha} A^{1-\alpha}$.

With in-house R&D, profit-maximization implies $\frac{\mathrm{d}\Pi^{IH}}{\mathrm{d}x} = 0$, which in turn implies that

$$\begin{aligned} x^{IH} &= \left(\frac{\alpha}{c}\right)^{\epsilon} A \\ p^{IH} &\equiv p(x^{IH}) = \frac{c}{\alpha} \\ R^{IH} &\equiv x^{IH} p^{IH} = \left(\frac{\alpha}{c}\right)^{\epsilon-1} A. \end{aligned} \tag{A1}$$

Under R&D outsourcing, we can see from (5) that in both cases of $\phi = 0$ and $\phi = 1$, profit-maximization by the principal yields the same x, p, and R as a function of μ. In choosing the optimal x, the principal treats m, μ, λ, c and T as parametric. Profit-maximization implies $\frac{\mathrm{d}\Pi}{\mathrm{d}x} = 0$, which in turn implies that

$$
\begin{aligned}
x &= \left[\frac{(1-\mu)\alpha}{(1-\lambda)c}\right]^{\epsilon} A \\
p &= \frac{(1-\lambda)c}{(1-\mu)\alpha} \\
R &= \left[\frac{(1-\mu)\alpha}{(1-\lambda)c}\right]^{\epsilon-1} A
\end{aligned}
\tag{A2}
$$

where $\frac{\mathrm{d}R}{\mathrm{d}\mu} = -A\left(\frac{\alpha}{1-\alpha}\right)\left[\frac{\alpha}{(1-\lambda)c}\right]^{\frac{\alpha}{1-\alpha}}(1-\mu)^{\frac{2\alpha-1}{1-\alpha}} < 0$. This explains why $\Delta V(\mu)$ decreases with μ in (2) for any μ less than a critical value that is beyond μ_C. Note that x_0 and $p_0 \equiv p(x_0)$ can be obtained by setting $\mu = 0$.

Now, from (4) we obtain, for $\phi = 0$,

$$
\left|\frac{\mathrm{d}\mu}{\mathrm{d}m}\right|_{V_0} = \left|\frac{\mathrm{d}V(0)/\mathrm{d}m}{\mathrm{d}V(0)/\mathrm{d}\mu}\right| = \frac{1}{RT + \mu T\frac{\mathrm{d}R}{\mathrm{d}\mu}} = \frac{1}{RT - \mu T\left|\frac{\mathrm{d}R}{\mathrm{d}\mu}\right|} \tag{A3}
$$

Note that $RT - \mu T\left|\frac{\mathrm{d}R}{\mathrm{d}\mu}\right|$ needs not be positive. In other words, the indifference curve may be upward sloping in (m, μ) space, meaning that an increase in μ leads to such a decrease in R that the agent has to be compensated by being paid a higher lump-sum m to make her indifferent compared with before. However, even in this case, our main results would not change; therefore, we will focus primarily on the case with downward sloping indifference curves throughout the rest of our analysis.

[Refer again to (5). Invoking envelope theorem (since $\partial\Pi/\partial x = 0$ due to profit maximization), for $\phi = 0$ (i.e. $\mu \geq \mu_C$),]

$$
\frac{\mathrm{d}\Pi}{\mathrm{d}\mu} = \frac{\partial\Pi}{\partial\mu} + \frac{\partial\Pi}{\partial x}\cdot\frac{\partial x}{\partial\mu} = \frac{\partial\Pi}{\partial\mu} = -RT
$$

Therefore, for $\phi = 0$,

$$
\left|\frac{\mathrm{d}\mu}{\mathrm{d}m}\right|_{\Pi_0} = \left|\frac{\mathrm{d}\Pi/\mathrm{d}m}{\mathrm{d}\Pi/\mathrm{d}\mu}\right|_{\phi=0} = \frac{1}{RT} \tag{A4}
$$

Comparing (A3) and (A4), for $\phi = 0$,

$$
\left|\frac{\mathrm{d}\mu}{\mathrm{d}m}\right|_{V_0} = \frac{1}{RT - \mu T\left|\frac{\mathrm{d}R}{\mathrm{d}\mu}\right|} > \frac{1}{RT} = \left|\frac{\mathrm{d}\mu}{\mathrm{d}m}\right|_{\Pi_0} \quad \text{for a given } \mu.
$$

That is, the indifference curve is always steeper than the iso-profit curve for any given μ for $\phi = 0$. Similarly, we can prove from (4) and (5) that, for $\phi = 1$,

$$
\left|\frac{\mathrm{d}\mu}{\mathrm{d}m}\right|_{V_0} = \frac{1}{\delta RT - \delta\mu T\left|\frac{\mathrm{d}R}{\mathrm{d}\mu}\right| - \beta T\left|\frac{\mathrm{d}R}{\mathrm{d}\mu}\right|} > \frac{1}{\delta RT} = \left|\frac{\mathrm{d}\mu}{\mathrm{d}m}\right|_{\Pi_0} \quad \text{for a given } \mu.
$$

That is, the indifference curve is always steeper than the iso-profit curve for any given μ for $\phi = 1$.

Finally, it is clear that

$$\left|\frac{\mathrm{d}\mu}{\mathrm{d}m}\right|_{V_0}^{\mu<\mu_C} > \left|\frac{\mathrm{d}\mu}{\mathrm{d}m}\right|_{V_0}^{\mu>\mu_C} \quad \text{in the neighborhood of } \mu = \mu_C$$

Appendix B

This appendix provides detailed illustration for the optimal forms of outsourcing contracts, if outsourcing does occur in equilibrium. Refer to Figs. 1 and 2. Since the area below the iso-profit curve $ABCD$ is not convex, it proves convenient to construct a "convexified" iso-profit curve ABD, where BD is a straight line. We can use this convexification because the parts of the iso-profit curve inside the convexified curve are irrelevant to the analysis, since they are not candidates for tangent points with the agent's indifference curves. Consequently, which outsourcing contract occurs depends on whether the curve EF is steeper than the convexified portion of the iso-profit curve BD. Figure 1 presents the case where the indifference curve is steeper than the convexified iso-profit curve, whereas Fig. 2 presents the opposite scenario. Since an increase in δ or β_0 reduces the gap CB and the slope of BD and raises the relative slope of the curve EF, it will make the case presented in Fig. 1 more likely to occur.

(i) δ or β_0 is sufficiently large so that EF is steeper than BD: there are two types of equilibrium that may arise.

  (A) When $W < \overline{OE}$ in Fig. 1, i.e., the wage is less than the lump-sum equivalent of the researcher's payoff under outsourcing, we have regime OL. In this case, there is outsourcing, since the wage of the researcher when she works in-house is less than her payoff when she subcontracts research work from the principal. The outsourcing contract entails a lump-sum payment without revenue sharing. As a result, there is leakage of information of the principal by the agent. Given this outsourcing contract, the agent strictly prefers leaking, since the payoff from leakage is equal to βRT. The principal, on the other hand, prefers no leakage, but can do nothing to prevent it, because it is impossible to monitor or verify leakage, according to Assumption 2. This regime would take place when, within this case, δ is relatively large (and, within this case, β_0 is irrelevant for whether outsourcing would arise).

  (B) When $W > \overline{OE}$ in Fig. 1, we have regime IH. In this case, there is always in-house R&D, because the wage the agent earns from working as the principal's employee is higher than the payoff she gets if she works as a subcontractor of the principal. This regime would prevail when, within this case, δ is relatively small (and, again, β_0 is irrelevant within this case).

(ii) δ or β_0 is sufficiently small so that BD is steeper than EF: there are also two types of equilibrium that may arise.

(A) When $W < \overline{OE}$ in Fig. 2, we have regime OR, where there is outsourcing with a mixed contract (m, μ) with $\mu = \mu_C$ and $m > 0$. There will be no information leakage. Under this contract, the agent strictly prefers not leaking information (albeit with only a slight preference), and the principal also strictly prefers no leakage (with a strong preference) since the loss from leakage is positive and non-trivial. Within this case, this regime would take place when δ is relatively large or β_0 is relatively small.

(B) When $W > \overline{OE}$ in Fig. 2, we again have regime IH and there is in-house R&D. Within this case, this regime would take place when δ is relatively small and β_0 is relatively large.

Appendix C

This appendix derives the boundaries between the three regimes: IH, OL and OR.

(I) Boundary between the OL and the OR regimes

All iso-profit curves have the same slope for any given μ. Similarly, all indifference curves have the same slope for any given μ. Let point B in Figs. 1 and 2 be represented by $(m, \mu) = (m_0, \mu_C)$, point D in Figs. 1 and 2 by $(m, \mu) = (m_1, 0)$, and point E in Fig. 2 by $(m, \mu) = (m_2, 0)$.

Since a typical iso-profit curve $\Pi(\mu, m) = \Pi_0$ passes through both (m_0, μ_C) and $(m_1, 0)$, we can apply (5), (A2) and $\mu_C = \beta_0$ to obtain:

$$\begin{aligned}\Pi_0 &= x(\mu_C)\left[p(x(\mu_C))(1-\mu_C) - (1-\lambda)c\right]T - m_0\\ &= AT\left[\frac{\alpha}{(1-\lambda)c}\right]^{\frac{\alpha}{1-\alpha}}(1-\alpha)\,(1-\beta_0)^{\frac{1}{1-\alpha}} - m_0\end{aligned}$$

$$\Pi_0 = \delta x(0)\left[p(x(0)) - (1-\lambda)c\right]T - m_1 = AT\left[\frac{\alpha}{(1-\lambda)c}\right]^{\frac{\alpha}{1-\alpha}}(1-\alpha)\delta - m_1$$

Eliminating Π_0 yields,

$$m_1 - m_0 = AT\left[\frac{\alpha}{(1-\lambda)c}\right]^{\frac{\alpha}{1-\alpha}}(1-\alpha)\left[\delta - (1-\beta_0)^{\frac{1}{1-\alpha}}\right] \tag{B1}$$

Similarly, consider an indifference curve that passes through (m_0, μ_C) and $(m_2, 0)$ and let $V(m_0, \mu_C) = V(m_2, 0) = V_0$. Therefore, from (4), we can eliminating V_0 to get:

$$m_2 - m_0 = AT\left[\frac{\alpha}{(1-\lambda)c}\right]^{\frac{\alpha}{1-\alpha}}\beta_0\left[(1-\beta_0)^{\frac{\alpha}{1-\alpha}} - (1-\delta)\right] \tag{B2}$$

Note that there is no need for $m_2 - m_0$ to be positive since the indifference curve can be upward sloping or partially upward sloping, and the results of the paper would not be affected.

Combining (B1) and (B2), we obtain:

$$\begin{aligned} & m_2 - m_1 \\ & = AT\left[\frac{\alpha}{(1-\lambda)c}\right]^{\frac{\alpha}{1-\alpha}}\left\{\beta_0\left[(1-\beta_0)^{\frac{\alpha}{1-\alpha}}-(1-\delta)\right]-(1-\alpha)\left[\delta-(1-\beta_0)^{\frac{1}{1-\alpha}}\right]\right\} \\ & = AT\left[\frac{\alpha}{(1-\lambda)c}\right]^{\frac{\alpha}{1-\alpha}}\left[(1-\beta_0)^{\frac{\alpha}{1-\alpha}}-\alpha\,(1-\beta_0)^{\frac{1}{1-\alpha}}-\beta_0(1-\delta)-(1-\alpha)\delta\right] \end{aligned} \tag{B3}$$

By setting $m_1 = m_2$, we obtain the boundary between these two cases given by (8).

Concerning the function $D(\beta_0, \delta)$ in (8), we have $D(\beta_0, 1) = (1-\beta_0)^{\frac{\alpha}{1-\alpha}} [1-\alpha\,(1-\beta_0)] - (1-\alpha) \leq 0$ (the equality holds as $\beta_0 = 0$). So, we have Regime OL when $\delta \to 1$. We can easily show: $\frac{\partial D}{\partial \beta_0} = -\frac{\alpha}{1-\alpha}\beta_0\,(1-\beta_0)^{\frac{\alpha}{1-\alpha}-1} - (1-\delta) < 0$. Therefore, Regime OR becomes more likely as β_0 gets smaller. For example, we have $D(0,\delta) = (1-\alpha)(1-\delta) > 0$, under which Regime OR arises. Moreover, $\frac{\partial D}{\partial \delta} = \beta_0 - (1-\alpha) < 0$ if $\beta_0 < 1-\alpha$. Since $D(1-\alpha, \delta) = \alpha^{\frac{\alpha}{1-\alpha}}(1+\alpha) - 1 < 0$, $D(1,\delta) = -(1-\alpha\delta) < 0$ and $\frac{\partial D}{\partial \delta} > 0$ for $\beta_0 \in (1-\alpha, 1]$, Regime OR cannot arise if $\beta_0 > 1-\alpha$. When β_0 is sufficiently small (less than β_0^* where β_0^* satisfies $D(\beta_0^*, 0) = 0$), Regime OR becomes more likely to emerge as δ gets smaller. In summary, the boundary between the two regimes OL and OR in (β_0, δ) space is downward sloping with horizontal intercept at $\beta_0^* < 1-\alpha$ and vertical intercept at 1, as depicted by AEC in Fig. 4.

(II) Boundary between the IH and the OL regimes

In this case, $\Pi(\mu, m) = \Pi^{IH}$ implies:

$$\Pi^{IH} = \Pi_0 = AT\left[\frac{\alpha}{(1-\lambda)c}\right]^{\frac{\alpha}{1-\alpha}}(1-\alpha)\delta - m_1 \tag{B4}$$

By substituting (B4) into (7), we have:

$$W = W^{IH} = A\left(\frac{\alpha}{c}\right)^{\frac{\alpha}{1-\alpha}}(1-\alpha)\,(T-L) - AT\left[\frac{\alpha}{c(1-\lambda)}\right]^{\frac{\alpha}{1-\alpha}}(1-\alpha)\delta + m_1$$

which implies,

$$m_1 - W = AT\left[\frac{\alpha}{c(1-\lambda)}\right]^{\frac{\alpha}{1-\alpha}}(1-\alpha)\left[\delta - (1-\lambda)^{\frac{\alpha}{1-\alpha}}\left(1-\frac{L}{T}\right)\right] \tag{B5}$$

Setting it to zero, we obtain the boundary given by (9), and is depicted by EB in Fig. 4.

(III) Boundary between the IH and the OR regimes

In this case, $\Pi(\mu, m) = \Pi^{IH}$ implies:

$$\Pi^{IH} = \Pi_0 = AT\left[\frac{\alpha}{(1-\lambda)c}\right]^{\frac{\alpha}{1-\alpha}}(1-\alpha)(1-\beta_0)^{\frac{1}{1-\alpha}} - m_0 \tag{B6}$$

By substituting (B6) into (7), we have:

$$W = W^{IH} = A\left(\frac{\alpha}{c}\right)^{\frac{\alpha}{1-\alpha}}(1-\alpha)(T-L) - AT\left[\frac{\alpha}{(1-\lambda)c}\right]^{\frac{\alpha}{1-\alpha}}(1-\alpha)(1-\beta_0)^{\frac{1}{1-\alpha}} + m_0$$

which implies,

$$m_0 - W = AT\left[\frac{\alpha}{c(1-\lambda)}\right]^{\frac{\alpha}{1-\alpha}}(1-\alpha)\left[(1-\beta_0)^{\frac{1}{1-\alpha}} - (1-\lambda)^{\frac{\alpha}{1-\alpha}}\left(1-\frac{L}{T}\right)\right] \tag{B7}$$

Utilizing (B2) and (B7), we obtain:

$$\begin{aligned} m_2 - W &\\ &= (m_2 - m_0) + (m_0 - W) \\ &= AT\left[\frac{\alpha}{(1-\lambda)c}\right]^{\frac{\alpha}{1-\alpha}} \\ &\quad\times\left[(1-\beta_0)^{\frac{\alpha}{1-\alpha}} - \alpha(1-\beta_0)^{\frac{1}{1-\alpha}} - \beta_0(1-\delta) - (1-\alpha)(1-\lambda)^{\frac{\alpha}{1-\alpha}}\left(1-\frac{L}{T}\right)\right] \end{aligned}$$

Thus, setting it to zero yield the boundary between IH and OR given by (10). This is curve DE in Fig. 4.

Since from (B3) outsourcing arises when $(1-\beta_0)^{\frac{\alpha}{1-\alpha}} - \alpha(1-\beta_0)^{\frac{1}{1-\alpha}} - \beta_0(1-\delta) > (1-\alpha)\delta$, we have:

$$\Gamma\left(\beta_0, \delta, \frac{L}{T}\right) > (1-\alpha)\left[\delta - (1-\lambda)^{\frac{\alpha}{1-\alpha}}\left(1-\frac{L}{T}\right)\right]$$

Thus, if R&D is outsourced under lump-sum contracts (the RHS of the above inequality is positive), it must be so arranged under mixed contracts. It is straightforward to show that $\frac{\partial\Gamma}{\partial\beta_0} = \frac{\partial D}{\partial\beta_0} < 0$, $\frac{\partial\Gamma}{\partial\delta} > 0$ and $\frac{\partial\Gamma}{\partial L/T} > 0$. So the boundary (10) is upward sloping in (β_0, δ) space and downward sloping in $(\frac{L}{T}, \delta)$ space. In (β_0, δ) space, $\Gamma(\beta_0^*, \delta, \frac{L}{T}) = \delta - (1-\lambda)^{\frac{\alpha}{1-\alpha}}\left(1-\frac{L}{T}\right)$ and $\Gamma(0, \delta, \frac{L}{T}) \equiv (1-\alpha)\left[1-(1-\lambda)^{\frac{\alpha}{1-\alpha}}\left(1-\frac{L}{T}\right)\right] > 0$ (implying the boundary must have a positive horizontal intercept). Combining (9) and (10), we have the kinked boundary between outsourcing and in-house as depicted by DEB in Fig. 4.

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