R&D Outsourcing in an Innovation-driven Supply Chain

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Abstract

We consider R&D outsourcing in an innovation-driven supply chain. We find that there exists a threshold in the firm's R&D cost above which it prefers to outsource via a contest and that the suppliers may want to pay entry fee for participation. When hosting an R&D contest, we find that the firm benefits from inviting as many suppliers as possible (crowdsourcing) if the participation threshold is negligible. Otherwise, the firm may prefer to offer entry subsidies to increase the participation.

KEYWORDS: R&D outsourcing; R&D contest; innovation; crowdsourcing; entry incentives

1. Introduction

Today, we observe an increasing number of firms and governmental agencies rely on supplying their R&D via outsourcing. According to a survey conducted by R&D Magazine [2009], more than 83% of industry respondents in the U.S. use some sort of outsourcing to perform part of their R&D functions. For example, faced with plummeting drug approval rate and increasing pressure on cost reduction, many pharmaceutical firms are actively outsourcing R&D to third-party firms (e.g., in-licensing late-stage drugs from biotechs or conducting clinical trials using Contract Research Organizations) [Kaitin, 2010, Bunnage, 2011]. R&D outsourcing is becoming a common practice in other industries such as medical devices, agricultural products, and software developments. In 2012, the total R&D expenditure spent in the U.S. was estimated to be $436 billion, of which about 7% is captured by outsourcing or external firms [R&D Magazine, 2011, 2012].

In light of these developments, we first aim to understand the optimal R&D sourcing decision (the R&D “make-or-buy” decision) in the context of innovation-driven supply chain, a supply chain that heavily hinges on the innovation process in developing new products. The performance of an innovation-related activity such as R&D mostly depends on the first-time discovery and the firm’s profit is often directly determined by the quality of innovation. We capture such innovation process by considering random innovation arrival and
quality. In particular, we describe the random innovation arrival by a Poisson process akin to the search model introduced in Lippman and McCall [1976] in the job search context. In the search model, the optimal stopping policy for the search (that maximizes the expected return) can be characterized as a threshold in the job quality $\bar{x}$; accept the job if $x \geq \bar{x}$, otherwise continue to search. This search process (or its variant) has been often used in modeling technological discoveries during the innovation process [Lippman and McCardle, 1991, Lippman and Mamer, 1993, Kornish et al., 2011]. The main trade-off in this innovation process is between R&D effort (which incurs cost) and timing (expected R&D completion) that ultimately affects the firm’s sustainability.

When outsourcing R&D, firms often consider offering an R&D contest, also referred to as R&D tournaments, inviting multiple suppliers (agents contributing innovations to the firm) that compete against. In the R&D contest, the randomness in the innovation process (uncertain innovation time and quality) and suppliers’ ability to control the effort on the project lead to two opposing effects: (i) the firm may benefit from limiting the number of suppliers, otherwise stiff competition may discourage suppliers in exerting large efforts, effort-reducing effect; in contrast, (ii) the firm may solicit contributions from a larger group of suppliers to get the most out of competition and increase the likelihood of finding an extreme-value innovation, extreme-value effect. In general, the mainstream microeconomics literature is against free entry into contests cautioning the negative impact of excessive competition due to the effort-reducing effect [Fullerton and McAfee, 1999, Taylor, 1995, Che and Gale, 2003]. However, Terwiesch and Xu [2008] and Boudreau et al. [2011] recently show that the firm can benefit from increasing the participants when the degree of uncertainty in the problem is large enough, as the extreme-value effect dominates the effort-reducing effect. We contribute to this growing literature by studying the R&D contest on a dynamic setting taking into account the above mentioned trade-off between the R&D effort and timing. In search of optimal design of R&D contest, we also study how entry incentives (imposing entry fee or offering entry subsidy to the participating suppliers) can improve the firm’s profit as well as the entire supply chain profit.

The organization of this paper is as follows. In §2, we solve the R&D sourcing problem to characterize the optimal sourcing decision (When to outsource?). In §3, we study the R&D contest design, especially focusing on the number of suppliers to invite with entry incentives (How to outsource?). We conclude the paper in §4.

2. When to Outsource?

Consider an innovation search process (i.e., R&D) of which arrivals follow a homogeneous Poisson process with rate $\lambda$ if an effort rate $\lambda$ for the search is exerted. Thus, the inter-arrival time of each innovation, denoted by $T(\lambda)$, is an exponential random variable with rate $\lambda$. Associated with each innovation arrival, we assume that the random innovation quality $p \in [0, 1]$ is drawn from i.i.d. with a density function $f(\cdot) > 0$ on $[0, 1]$; 0 otherwise. For simplicity, we assume innovation quality is independent of the effort rate $\lambda$. However, this can be relaxed easily by thinning the Poisson process. We assume the cost of innovation searching (per unit time) is convex-increasing in the effort exerted (as in Terwiesch and Xu [2008]). To simplify the analysis, we consider the innovation searching cost is $c\lambda^2$ for effort rate $\lambda$. We denote the discount factor by $r$.

As shown in Lippman and McCall [1976], the above optimal policy for the R&D process is given by a threshold policy: stop the innovation search by accepting the first innovation such that its quality exceeds a certain threshold. The threshold in innovation quality is a decision variable for the firm. We denote the innovation threshold by $\tilde{p}$ and the probability of innovation exceeding the threshold $\tilde{p}$, excess probability,
by $\xi(\bar{p}) = P(p > \bar{p})$. We assume $\bar{p} < 1$ to retain our attention to a nontrivial case. For brevity of notation, we suppress $\xi(\bar{p})$ by $\xi$ if there is no risk of confusion. We assume the revenue gained by commercializing the R&D (into a service or a product) is linear in the innovation quality $p$, and thus, normalize it to $p$ itself. The innovation quality can be interpreted as a market success probability which in turn determines the firm’s revenue. Finally, we denote the expected surplus on innovation $p$ given threshold $\bar{p}$ by $\eta(\bar{p}) = E[p - \bar{p}|p > \bar{p}]$. This is also suppressed to $\eta$ if its meaning is clear from the context.

**In-sourcing (Vertical Integration).** We first consider an in-sourcing supply chain, the case in which the firm conducts the R&D itself. Since only the innovations with quality greater than $\bar{p}$ are relevant, we consider a thinned Poisson process adjusted by the excess probability $\xi$. Hence, a profit-maximizing firm who determines the R&D exerting effort rate $\lambda$ and the innovation threshold $\bar{p}$ solves the following problem:

$$
\Pi = \max_{(\bar{p}, \lambda)} \mathbb{E}\left[ p e^{-rT(\lambda \xi)} - c\lambda^2 \int_0^{T(\lambda \xi)} e^{-rt} dt | p > \bar{p} \right] = \max_{(\bar{p}, \lambda)} \left\{ \left( \eta + \bar{p} \right) \frac{\lambda \xi}{r + \lambda \xi} - \frac{c\lambda^2}{r + \lambda \xi} \right\}.
$$

(1)

**Lemma 1.** For the R&D in-sourcing case, the firm’s optimal profit is given by $\Pi = \bar{p}^*$, where the optimal threshold in innovation $\bar{p}^*$ is the unique solution to the following implicit equation:

$$
4cr\bar{p} = E\left[(p - \bar{p})^2\right].
$$

(2)

Further, the optimal effort rate is given by $\lambda^* = E[(p - \bar{p}^*)^2] / (2c) = 2r\bar{p}^* / E[(p - \bar{p}^*)^2] = \sqrt{r\bar{p}^* / c}$, and the expected time to innovation is given by $\tau^* = (\lambda^* \xi^*)^{-1}$ where $\xi^* = \xi(\bar{p}^*)$.

**Proof.** For notational simplicity, let us denote the maximand in (1) by $h(\bar{p}, \lambda)$. First, we claim that the optimal $(\bar{p}^*, \lambda^*)$ satisfy $\bar{p}^* \in (0, 1)$ and $\lambda^* > 0$. Indeed, as $\bar{p}$ approaches 1, $\xi \to 0$ and thus $\lim_{\bar{p} \to 1} h(\bar{p}, \lambda) \leq 0$. Also, it is clear that $h(\bar{p}, 0) = 0$. Now suppose that $\bar{p} = 0$. Then, $h(0, \lambda) = \lambda (\mu - c\lambda) / (r + \lambda)$ where $\mu = E[p]$. One can easily check that the optimal effort rate when $\bar{p} = 0$ is $\lambda_o = -r + \sqrt{r^2 + \mu r / c}$. However, we note that

$$
\frac{\partial h}{\partial \bar{p}} (0, \lambda_o) = \frac{f(0) \lambda_o^2}{(r + \lambda_o)^2} (\mu - c\lambda_o) > 0.
$$

This implies the existence of a positive $\bar{p}$ such that $h(\bar{p}, \lambda_o) > \max_{\lambda} h(0, \lambda)$. Our first claim is now proved.

Since the optimum is obtained at an interior point, it is sufficient to check the first order optimality conditions: $\partial h / \partial \bar{p} = \partial h / \partial \lambda = 0$. Direct calculations yield the following equations:

$$
\frac{\partial h}{\partial \bar{p}} = \frac{f(\bar{p}) \lambda}{(r + \lambda \xi)^2} \left\{ \eta (r + \lambda \xi) - r (\eta + \bar{p}) - c \lambda^2 \right\} = 0 \implies c \lambda^2 - \eta \xi \lambda + r \bar{p} = 0,
$$

$$
\frac{\partial h}{\partial \lambda} = \frac{1}{(r + \lambda \xi)^2} \left\{ (\eta + \bar{p}) r \xi - 2c \lambda (r + \lambda \xi) + c \xi \lambda^2 \right\} = 0 \implies c \xi \lambda^2 + 2cr \lambda - (\eta + \bar{p}) r \xi = 0.
$$

From these two equations, we obtain $\lambda^* = r \xi^* (\eta^* + 2\bar{p}^*) / (\eta^* \xi^* + 2cr)$ where $\xi^* = \xi(\bar{p}^*)$ and $\eta^* = \eta(\bar{p}^*)$. Plugging this back into the first equation of the above optimality equations and re-arranging terms, we obtain

$$
4cr\bar{p}^* = \eta^* \xi^* + 2 = E\left[(p - \bar{p}^*)^2\right].
$$

(3)
From this result, we get \( \lambda^* = \eta^* \xi^* / (2c) = \sqrt{r \bar{p}^*/c} \). Now we can easily see that (3) has a unique solution because the left hand side (as a function of \( \bar{p}^* \)) is strictly increasing while the right hand side is strictly decreasing, crossing exactly at a single point.

Lastly, the optimal profit of the firm is computed as

\[
\Pi = \left( \eta^* + \bar{p}^* \right) \frac{\lambda^* \xi^*}{r + \lambda^* \xi^*} - \frac{c \lambda^2}{r + \lambda^* \xi^*} \frac{\xi^* (\eta^* + 2 \bar{p}^*)}{2cr + \eta^* \xi^*} = \frac{c \lambda^2}{r} = \frac{\eta^* \xi^*}{4cr} = \bar{p}^*.
\]

The remaining statement about the arrival time \( \tau^* \) is trivial.

It is interesting to note that the firm’s optimal expected profit is identical to the innovation threshold \( \bar{p}^* \). This implies that the firm sets the innovation threshold \( \bar{p} \) such that its expected R&D cost equals the expected surplus on innovation at time \( \tau^* \) (since the firm’s expected revenue is \( E[p|p > \bar{p}] = \eta + \bar{p} \)). From (2), we can infer how the optimal effort rate \( \lambda^* \) interacts with other parameters and \( \bar{p}^* \). For instance, decreases in \( c \) and \( r \) (changes in the R&D cost and the discount rate in firm’s favor) lead to an increase in innovation threshold \( \bar{p} \) (thus, the firm’s profit). However, the effect of \( c \) and \( r \) result in the opposite direction for the optimal effort rate \( \lambda^* \); a decrease in \( c \) yields an increase in \( \lambda^* \), whereas a decrease in \( r \) yields a decrease in \( \lambda^* \). A similar trend can also be observed for the expected time to innovation. We note that this result can also be obtained in other papers in the literature albeit differences in model setting; e.g., Lippman and McCardle [1991].

**Outsourcing (Decentralization).** We now consider the option of outsourcing via R&D contest in a decentralized supply chain. The firm invites \( n \) homogeneous suppliers who compete for a fixed reward \( w \) which will be awarded to the one first delivering the qualified innovation (innovation quality that exceeds the threshold). The suppliers may have a different cost structure compared to the firm, as the chosen suppliers are likely to have better expertise in the field and incur cheaper costs in conducting the R&D. We denote the supplier’s innovation searching cost coefficient by \( c_s \). We assume the suppliers are risk-neutral and that there is a participation threshold in the contest reward, \( \delta \); hence, the supplier participates the contest only if the expected profit of each supplier is no less than \( \delta \). The participation constraint can be interpreted as an initial setup cost or an opportunity cost for forgone alternatives. While other forms of contract may also be used in the R&D contest (e.g., revenue-sharing contract), we limit to a simplest form for tractability. In this section, we first assume that the number of suppliers \( n \) is exogenously given so as to understand the firm’s sourcing decisions. Later in §3, we consider the participation threshold \( \delta \) more explicitly as it will act as a factor determining the optimal number of participants in the R&D contest.

We assume the firm informs the \( n \) suppliers the desired innovation threshold \( \bar{p} \) along with a fixed reward \( w \) which will be rewarded upon the successful completion of the R&D project. Given \((\bar{p}, w)\), the suppliers then decide the effort rate \( \lambda \) to exert, which determines the arrival rate of the innovation. Let us define the time of the first innovation exceeding \( \bar{p} \) of the \( i \)th supplier by an exponential random variable \( T(\lambda^{(i)} \xi) \) or \( T^{(i)} \) where \( \lambda^{(i)} \) is the effort rate per unit time. Then, the firm’s revenue from an innovation quality \( p (> \bar{p}) \) is realized at the time \( \min_{j=1,...,n} T(\lambda^{(j)} \xi) \), where \( \xi = \xi(\bar{p}) = P(p > \bar{p}) \) is the excess probability. Therefore, the firm’s problem can be formulated as follows:

\[
\Pi_i = \max_{(\bar{p}, w)} \mathbb{E} \left[ e^{-r \min_{j=1,...,n} T^{(j)} (p - w)} \bigg| p > \bar{p} \right].
\]
The problem faced by each supplier is then to determine the optimal effort rate taking into consideration that the revenue is realized only when she is the first one to deliver an innovation greater than quality \( \bar{p} \):

\[
V^{(i)}(\bar{p}, w) = \max_{\lambda^{(i)}} \mathbb{E} \left[ we^{-r \min_i T^{(i)}} \mathbf{1}_{\{T^{(i)} = \min_i T^{(j)}\}} - c_s(\lambda^{(i)})^2 \int_0^{\min_i T^{(i)}} e^{-rt} \, dt \right].
\]

We do not consider the case of having multiple winners since the probability of such event given that times to deliver innovations are independent exponential random variables is 0. The solution to each supplier’s problem can be found via direct calculations or the associated Hamilton-Jacobi-Bellman equation. Since participating suppliers share the same characteristics, their optimal choice of effort rates must be the same. With identical \( \lambda^{(i)} \)'s, we can obtain a quadratic equation for the optimal effort rate \( \tilde{\lambda}_n = \lambda_n(\bar{p}, w) \):

\[
\tilde{\lambda}_n(\bar{p}, w) = \frac{1}{2c_s(2n-1)} \left\{ (n-1)w^2 - 2c_s r + \sqrt{(2c_s r - (n-1)w^2)^2 + 4c_s r w^2} \right\},
\]

which is a nonnegative solution to \((2n-1)c_s \lambda^2 + (2c_s r - (n-1)w^2) \lambda - rw = 0\). Also, we get the corresponding expected profit of each supplier given by \( V_n = V_n(\tilde{\lambda}_n, w) = w - 2c_s \lambda_n(\bar{p}, w). \)

**Lemma 2.** For the \( n \) supplier R&D contest, the firm’s optimal reward is given by \( w^*_n = \eta(\tilde{\lambda}_n) / 2 \), where \( \tilde{\lambda}_n \) is the optimal innovation threshold that is strictly positive.

**Proof.** Recall that the firm’s problem is to maximize the following function for \( w \geq 0 \) and \( \tilde{\lambda} \in [0, 1] \):

\[
h_n(\tilde{\lambda}, w) := \mathbb{E} \left[ e^{-r \min_i T^{(i)}(\lambda^{(i)})} (p - w) \mid p > \bar{p} \right] = (\eta + \tilde{\lambda} - w) \frac{n \tilde{\lambda} w}{r + n \tilde{\lambda} w}.
\]

We first show the optimal \( \tilde{\lambda}_n \) is obtained at an interior point, \( \tilde{\lambda}_n \in (0, 1) \), and then show that \( w^*_n = \eta(\tilde{\lambda}_n) / 2 \).

Note that \( \lim_{\tilde{\lambda} \uparrow 1} h_n(\tilde{\lambda}, w) = 0 \). This is because \( \lim_{\tilde{\lambda} \uparrow 1} \eta = 0 \) and \( P(p > 1) = 0 \). If \( w = 0 \), then clearly \( \tilde{\lambda}_n = 0 \) and \( h_n(\tilde{\lambda}, 0) = 0 \) for any \( \tilde{\lambda} \). If \( w = 1 \), then \( \lambda > 0 \) but \( h_n(\tilde{\lambda}, 1) \leq 0 \). Hence the optimum is obtained in the region \( \{ (\tilde{\lambda}, w) : 0 \leq \tilde{\lambda} < 1, 0 < w < 1 \} \). On the other hand, when \( \tilde{\lambda} = 0 \), then \( \xi = 1 \), \( \eta = \mu \), and thus

\[
h_n(0, w) = (\mu - w) \frac{n \tilde{\lambda}(w)}{r + n \tilde{\lambda}(w)}, \quad \tilde{\lambda}(w) = \frac{1}{2c_s(2n-1)} \left( (n-1)w - 2c_s r + \sqrt{(2c_s r + (n-1)w^2)^2 + 4c_s r w^2} \right).
\]

Let us denote any maximizer of \( h_n(0, w) \) by \( w^* \), which is in \((0, 1)\). If we show that \( (\partial / \partial \tilde{\lambda}) h_n(0, w^*) \) is positive, then there is a \( \tilde{\lambda} > 0 \) such that \( h_n(\tilde{\lambda}, w^*) > \max_{w \in [0, 1]} h_n(0, w) \). This proves our first claim.

The following two equations are obtained from the first order optimality equation for \( w^* \) and from the definition of \( \tilde{\lambda}(w) \) above:

\[
(\mu - w^*) r \tilde{\lambda}'(w^*) = \tilde{\lambda}(w^*) (r + n \tilde{\lambda}(w^*)), \quad \tilde{\lambda}'(w^*) = \frac{(n-1)\tilde{\lambda}(w^*) + r}{\sqrt{(2c_s r + (n-1)w^*)^2 + 4c_s r w^*}}.
\]

As for \( (\partial / \partial \tilde{\lambda}) h_n(0, w^*) \), we proceed as follows: using \( \eta'(\tilde{\lambda}) = -1 + \eta(f(\tilde{\lambda}) / \xi) \) and \( \lambda_n := \tilde{\lambda}(w^*) \),

\[
\frac{\partial h_n}{\partial \tilde{\lambda}}(0, w^*) = \mu f(0) \frac{n \lambda_n}{r + n \lambda_n} + (\mu - w^*) \left( \frac{rn}{(r + n \lambda_n)^2} \frac{\partial (\lambda \xi)}{\partial \tilde{\lambda}} \bigg|_{\tilde{\lambda} = 0, w = w^*} \right).
\]
\[
\begin{align*}
&= \frac{n f(0)}{(r+n\lambda_w)^2} \left\{ \mu \lambda_w (r+n\lambda_w) - (\mu - w^o) r \frac{((n-1)\lambda_w + r)2w^o}{\sqrt{(2c_r r + (n-1)w^o)^2 + 4c_s r w^o}} \right\} \\
&= \frac{n f(0)}{(r+n\lambda_w)^2} \frac{((n-1)\lambda_w + r) r}{\sqrt{(2c_r r + (n-1)w^o)^2 + 4c_s r w^o}} (\mu - w^o)(\mu - 2w^o).
\end{align*}
\]

Here, the second equality comes from straightforward calculations for the partial derivative of \( \lambda \xi \) and the third equality is obtained by applying two equations in (5). It is left to us to show that \((\mu - w^o)(\mu - 2w^o) > 0\).

We note that (5) implies that \( \mu > w^o \). To see \( \mu > 2w^o \), we equate two equations in (5) to get

\[
(\mu - w^o) r \frac{((n-1)\lambda_w + r)}{\sqrt{(2c_r r + (n-1)w^o)^2 + 4c_s r w^o}} = \lambda_w (r+n\lambda_w).
\]

For simplicity, let us denote the square root term by \( \Theta \). Suppose that \( \mu \leq 2w^o \). Then, the right hand side would be less than or equal to \( w^o r ((n-1)\lambda_w + r) / \Theta \). However, if we look at

\[
\lambda_w (r+n\lambda_w) - w^o r ((n-1)\lambda_w + r) / \Theta = \lambda^2_w + (r + (n-1)\lambda_w) \{ \lambda_w - w^o r / \Theta \},
\]

then this turns out to be positive, which contradicts the assumption \( \mu \leq 2w^o \). Indeed, we observe that

\[
\begin{align*}
\lambda_w \Theta - r w^o &= \frac{1}{2c_s(2n-1)} \left\{ (n-1) w^o \Theta - 2cw \Theta + \Theta^2 - 2c_s(2n-1) r w^o \right\} \\
&= \frac{1}{2c_s(2n-1)} \left\{ (n-1) w^o \Theta - 2c_r r \Theta + 4c_s^2 r^2 + (n-1)^2 (w^o)^2 + 2c_s r w^o \right\} \\
&= \frac{1}{2c_s(2n-1)} \left\{ 2c_r (2c_s r + mw^o - \Theta) + (n-1) w^o ((n-1) w^o - 2c_s r + \Theta) \right\}.
\end{align*}
\]

Now it is an easy matter to show that each term in the bracket is positive.

Since we showed that an optimum is achieved at an interior point, we only need to consider the first order conditions: \( \partial h_n / \partial \bar{p} = \partial h_n / \partial w = 0 \). It is then a tedious but straightforward task to arrive at \( -\eta f(\bar{p}) = \partial (\lambda_n \xi) / \partial \bar{p} \) by comparing two first order optimality equations. On the other hand, recall the quadratic equation below (4) that \( \lambda_n \) satisfies. One can easily compute \( \partial (\lambda_n \xi) / \partial \bar{p} \) and \( \partial \lambda_n / \partial w \), and compare two expressions to see \( -2w f(\bar{p}) = \partial (\lambda_n \xi) / \partial \bar{p} \). Combining these two results, we can conclude that \( \xi(\bar{p}_n^*) = 2w^o n^* \) because \( f(\cdot) \) is assumed to be nonzero.

From the above result, the firm’s profit becomes \( \Pi_n = \max_{\bar{p}} h_n(\bar{p}, \eta / 2) \). The first order optimality equation for the function \( h_n(\bar{p}, \eta / 2) \) then yields an optimal solution \( \bar{p}_n^* \). We denote associated function values \( \eta(\bar{p}_n^*), \xi(\bar{p}_n^*), \lambda_n(\bar{p}_n^*, w_n^*), V_n(\bar{p}_n^*, w_n^*) \) by \( \eta^*, \xi^*, \lambda_n^*, \) and \( V_n^* \), respectively for notational simplicity.

**In-sourcing vs. Outsourcing.** With the optimal solutions for both in-sourcing and outsourcing cases (Lemmas 1 and 2), we shall now obtain the firm’s optimal R&D sourcing decision.

**Proposition 1.** Consider the \( n \) supplier R&D contest with fixed constant \( c_s \).

(a) There exist a set of thresholds \( \bar{c}_n < \bar{c}_n \) in the firm’s cost \( c \) such that: (i) \( \Pi_n \geq \Pi \) if and only if \( c \geq \bar{c}_n \) and (ii) \( \Pi_n + n V_n^* \geq \Pi \) if and only if \( c \geq \bar{c}_n \).
Proof. The eq. (2) says \( c = \Psi(\bar{p}^\ast) \) where \( \Psi(\bar{p}) := \mathbb{E} \left[ \frac{[(\rho - \bar{p})^+)^2}{4r\bar{p}} \right] \). The function \( \Psi \) is strictly decreasing in \( \bar{p} \) such that \( \lim_{\bar{p}\downarrow 0} \Psi(\bar{p}) = \infty \) and \( \lim_{\bar{p}\uparrow 1} \Psi(\bar{p}) = 0 \). Let us denote the firm’s optimal profit by \( \Pi(c) \) to express its dependency on \( c \). Since \( \Pi(c) = \bar{p}^\ast \), we have \( \lim_{c\downarrow 0} \Pi(c) = 1 \) and \( \lim_{c\uparrow \infty} \Pi(c) = 0 \). Therefore, one can find \( \bar{c}_n < \bar{c}_n \) such that \( \Pi(\bar{c}_n) = \Pi_n + nV_n^\ast \) and \( \Pi(\bar{c}_n) = \Pi_n \). Then, the statement easily follows.

As for part (b), observe that \( \Pi_n = (\eta_n^\ast / 2 + \bar{p}_n^\ast) (1 - r/(r + n\lambda_n^\ast \xi_n^\ast)) \). It is easy to check that each of two terms in \( \Pi_n \) are increasing in \( \bar{p}_n^\ast \) and \( n\lambda_n^\ast \xi_n^\ast \), respectively. Hence, \( \Pi_n \) increases with \( n \). From its definition, we see that \( \bar{c}_n \) decreases in \( n \). The last statement about \( \tau_n^\ast \) is trivial as the collective innovation arrival rate is \( n\lambda_n^\ast \xi_n^\ast \) and the arrival time is exponentially distributed.

Proposition 1(a) obtains the critical R&D cost thresholds for the firm’s sourcing decision and its impact on the supply chain profit. Specifically, the firm prefers to outsource its R&D if and only if \( c > \bar{c}_n \) holds. Further, if \( c > \bar{c}_n \) holds, R&D outsourcing yields a greater supply chain profit than in-sourcing. Since \( \bar{c}_n < \bar{c}_n \), this implies that, under \( \bar{c}_n < c < \bar{c}_n \), the firm does not outsource although doing so improves the entire supply chain profit. Thus, the firm’s outsourcing decision is not aligned with the supply chain perspective. Although there is no simple closed form expressions, Proposition 1(b) suggests how the firm would behave as the number of participating suppliers increases. Given that the innovation threshold \( \bar{p}_n^\ast \) increases and the expected time to innovation \( (n\lambda_n^\ast \xi_n^\ast)^{-1} \) decreases with \( n \), which can be shown numerically and proven asymptotically, we observe that the firm is more likely to outsource its R&D as \( n \) increases. These results are driven by the competition among the suppliers (extreme-value effect). Therefore, we can infer that, although the firm may not consider R&D outsourcing unless the supplier’s cost is cheap enough, outsourcing to multiple suppliers (R&D contest) can potentially be a superior option for the firm even if the suppliers’ costs are not necessarily cheaper than the firm’s.

As shown in Proposition 1(a), the firm’s R&D sourcing decision is not aligned with the supply chain when \( \bar{c}_n < c < \bar{c}_n \). Under such condition, imposing an entry fee to each participating supplier can be considered.

**Corollary 1.** Suppose that \( \bar{c}_n < c < \bar{c}_n \). Then, the \( n \) suppliers can pay the entry fee \( \theta / n \) (hence, collectively \( \theta \)) to make R&D outsourcing more profitable than in-sourcing for any \( \theta \in (\Pi - \Pi_n, nV_n^\ast) \).

**Proof.** From \( \bar{c}_n < c < \bar{c}_n \), it follows that \( \Pi_n < \Pi < \Pi_n + nV_n^\ast \). If each supplier pays such entry fee \( \theta \), then the condition means that \( \Pi < \Pi_n + \theta \) while \( V_n^\ast - \theta / n > 0 \); that is, each supplier enjoys positive expected profit. Hence, it is profitable for the firm to host the \( n \) supplier R&D contest.

Entry fee is generally considered as a mechanism for deterring the entry to limit the number of participation (e.g., Fullerton and McAfee [1999]) or for identifying inferior players (e.g., Kaplan and Sela [2010]). Corollary 1 shows that the entry fee can also be used as a channel for transferring the surplus from the suppliers to the firm to align the incentives in the R&D sourcing decision. More specifically, the suppliers can decrease the outsourcing threshold \( \bar{c}_n \) by collectively transferring \( \theta \) to offset the firm’s loss \( (\Pi - \Pi_n) \) from altering its decision (in-sourcing to outsourcing).
3. How to Outsource?

In this section, we study the structure of optimal R&D contest. To this end, we now consider the supplier number endogenously by incorporating the participation constraint \((V_n(\bar{p}, w) \geq \delta)\) in the model and call a contest feasible if the constraint is satisfied. In the following, we first focus on the optimal number of suppliers to invite for the R&D contest. Then, we study the optimal R&D contest design with entry incentives.

Optimal Number of Suppliers to Invite. To facilitate the analysis, we obtain the following lemma.

Lemma 3. If \(\delta = 0\), any R&D contest with given \((\bar{p}, w)\) and \(n\) yields a strictly positive profit for the suppliers. If \(\delta > 0\), there is an upper bound on the number of participating suppliers \(n\).

Proof. We start by re-writing the left hand side of the quadratic equation below (4) by \(Q_n(\lambda)\) after re-scaling:

\[
\tilde{Q}_n(\lambda) = Q_n(\lambda) + \gamma = (2n - 1)\lambda^2 + (\alpha - (n - 1)\beta) \lambda
\]

where \(\alpha = 2r/\xi, \beta = w\xi/c_s, \gamma = \alpha\beta/2\) are all positive constants. From the definition of \(V^{(i)}\), it is not difficult to compute that \(V_n = (w\xi\lambda_n - c_s\lambda_n^2)/(r + n\lambda_n\xi)\). To see \(V_n > 0\), it is enough to show that \(w\xi/c_s > \lambda_n\), and this is in turn verified if \(\lambda = w\xi/c_s\) makes the quadratic equation \(Q_n(\cdot)\) positive. This is because it has one negative and one positive solution \(\lambda_n\). Indeed,

\[
(2n - 1)c_s\xi \left(\frac{w\xi}{c_s}\right)^2 + (2c_s r - (n - 1)w\xi^2) \frac{w\xi}{c_s} - rw\xi = \frac{nw^2\xi^3}{c_s} + rw\xi > 0.
\]

Hence, if \(\delta = 0\), then the firm can invite any number of suppliers.

Next, note that the non-zero root of \(\tilde{Q}_n(\lambda) = 0\), say \(\tilde{\lambda}_n\), is increasing in \(n\) because \(\tilde{\lambda}_n = ((n-1)\beta - \alpha)/(2n-1)\) and \(\tilde{\lambda}_{n+1} - \tilde{\lambda}_n = (2\alpha + \beta)/((2n-1)(2n+1)) > 0\). On the other hand, \(\tilde{Q}_n(\lambda) = \tilde{Q}_{n+1}(\lambda)\) only at \(\lambda = 0\) or \(\lambda = \beta/2 > 0\). These observations imply that the solution \(\lambda_n\) to \(Q_n(\lambda) = 0\) is increasing in \(n\) if \(\gamma < \tilde{Q}_n(\beta/2) = \tilde{Q}_{n+1}(\beta/2)\). This is because \(\lambda_n\) is nothing but the positive intersection point of \(\tilde{Q}_n(\cdot)\) and the horizontal line \(y = \gamma\). Indeed, one can see that \(\tilde{Q}_n(\beta/2) > \gamma\). Since \(V_n = w - 2c_s\lambda_n/\xi\), it is decreasing in \(n\).

The asymptotic behaviors are then readily found. The slope of \(\tilde{Q}_n(\lambda)\) decreases linearly in \(n\) whereas the function value at \(\lambda = \beta/2\) is fixed at \(\beta^2/4 + \gamma\). Thus, the positive intersection point of \(\tilde{Q}_n(\cdot)\) and the horizontal line \(y = \gamma\) approaches the value \(\lambda = \beta/2\). This also can be checked via direct calculations of \(\lambda_n\). In addition, \(\lim_n \lambda_n = \beta/2\) is immediately translated into \(\lim_n V_n = 0\). This implies that \(n\) cannot be arbitrarily large due to the participation constraint \(V_n \geq \delta\).

This shows the feasibility of hosting an R&D contest for a given contract with \(n\) suppliers. In particular, if the participation threshold \(\delta\) is negligible, then any number of suppliers can be invited while satisfying the participation constraint; that is, suppliers adjust their effort rates with respect to \(n\) to insure the non-negative expected profit (effort-reducing effect). However, if the participation threshold is non-negligible, \(\delta > 0\), then the firm cannot arbitrary increase the number of participants in the contest.

Proposition 2. Consider the R&D contest.

(a) If \(\delta = 0\), it is optimal to invite as many suppliers as possible. More specifically, we have \(\lim_n \bar{p}_n = 1\), \(\lim_n \lambda_n^* = 0\), and \(\lim_n n\lambda_n^* \xi_n = \infty\). In addition, \(\lim_n \{\Pi_n + nV_n^*\} = \lim_n \Pi_n = 1\).
(b) If $\delta > 0$, there exists an integer $n_\delta$ such that the $n$ supplier R&D contest is feasible if and only if $n \leq n_\delta$. Therefore, an R&D contest with a finite number of suppliers is optimal.

**Proof.** **Part (a):** Since we assume the existence of a density function, $E[(p - \bar{p})^+]$ is a continuous function of $\bar{p}$ ranging between 0 and $\mu = E[p]$. For each $n$, we solve $E[(p - \bar{p}_n)^+] = n^{-1/3} \mu$. This implies that $\bar{p}_n \to 1$ and that $nE[(p - \bar{p}_n)^+]^2 = \mu^2 n^{1/3} \to \infty$. On the other hand,

$$n\eta_n \xi_n^2 = n\xi_n^2 \int_{\bar{p}_n}^1 (x - \bar{p}_n) f(x) dx \geq nE[(p - \bar{p}_n)^+]^2 \to \infty,$$

where $\eta_n = \eta(\bar{p}_n)$ and $\xi_n = \xi(\bar{p}_n)$. This makes the left hand side increase to infinity and consequently $n\lambda_n \xi_n$ to infinity when we take $\lambda_n = \lambda_n(\bar{p}_n, \eta_n/2)$.

Note that this choice of threshold $\bar{p}_n$ (converging to 1) and reward $\eta_n/2$ is suboptimal for the firm’s problem. Nevertheless, we have

$$h_n(\bar{p}_n, \eta_n/2) = \left( \frac{\eta_n}{2} + \bar{p}_n \right) \left( 1 - \frac{r}{r + n\lambda_n \xi_n} \right) \leq \Pi_n \leq \max \left( \frac{\eta_n}{2} + \bar{p}_n \right)$$

and the left hand side converges to 1 as $n$ increases. On the other hand, the right hand side is maximized at $\bar{p} = 1$ with the maximum 1. Therefore, $\lim_n \Pi_n = 1$. Indeed, if the limit of $\bar{p}_n$ were less than 1, then we arrive at a contradiction because, first, $\Pi_n \leq (\eta_n^2/2 + \bar{p}_n^2)$ and, second, the right hand side would converge to some value strictly less than 1 as $\eta/2 + \bar{p}$ is a strictly increasing function of $\bar{p}$. To prove $\lambda_n^* \to 0$, we re-write (4) as

$$\lambda_n^* = \frac{1}{2c_s(2n - 1)\xi_n} - \frac{(2c_s r + (n - 1)w \xi_n^2 + 4c_s r w \xi_n^2 - ((n - 1)w \xi_n^2 - 2c_s r))^2}{\sqrt{\lambda_n^* - ((n - 1)w \xi_n^2 - 2c_s r)}}$$

where $\lambda_n$ denotes the term inside the square root in (4) for notational simplicity. We observe that this expression converges to 0 as $\bar{p}$ approaches 1. Hence, $\lim_n \lambda_n^* = 0$.

Next, we see that $\lim_n n\lambda_n^* \xi_n^2 = \infty$. This can be simply proved as follows. Suppose that this is not true, say $\lim_k n_k \lambda_k^* \xi_k^2 \leq M < \infty$ for some positive number $M$ and a subsequence $\{n_k\}$. Then,

$$\lim_k \Pi_{n_k} = \lim_k \left( \frac{\eta_k^2}{2} + \bar{p}_k^* \right) \left( 1 - \frac{r}{r + n_k \lambda_k^* \xi_k^2} \right) \leq \lim_k \left( \frac{\eta_k^2}{2} + \bar{p}_k^* \right) \left( 1 - \frac{r}{r + M} \right) < \sup_{\bar{p}} \left( \frac{\eta_n}{2} + \bar{p} \right) = 1.$$ 

Since this is a contradiction to $\lim_n \Pi_n = 1$, the claim is proved.

Lastly, we prove that $\lim_n nV_n^* = 0$. From the definitions of the supplier’s and the firm’s problems, we get

$$\Pi_n + nV_n^* = E \left[ e^{-\int_0^T (n\lambda_n^* \xi_n^2) p - nc_s(\lambda_n^*)^2} e^{-\int_0^T \xi_n^2} dt \right] = (\eta_n^2 + \bar{p}_n^* \frac{n\lambda_n^* \xi_n^2}{r + n\lambda_n^* \xi_n^2}$$

where we used the symmetry of suppliers. Note that this implies $\lim_n (\Pi_n + nV_n) \leq \lim_n (\eta_n^2 + \bar{p}_n^*) = 1$. Since $\lim_n \Pi_n = 1$, we obtain the desired result.

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Part (b): We first observe that \( V^*_n \leq \max(\bar{p}, w) \) \( V_n(\bar{p}, w) =: \bar{\bar{V}}_n \) for any \( n \). It is obvious that \( V_n(\bar{p}, w) \leq V_n(\bar{p}, 1) = 1 - 2c_1\lambda_n(\bar{p}, 1)/\xi_n \). Let us denote the function \( 2c_1\lambda_n(\bar{p}, 1)/\xi_n \) by \( y(x) \) with \( x = 2c_1r/\xi_n^2 \). Then, it is straightforward to check that
\[
y_n(x) = \frac{2x}{\sqrt{(x+n-1)^2 + 2x + x - (n-1)}}, \quad 2c_1r \leq x < \infty.
\]
One can also check that \( y_n(x) \) is strictly increasing in \( x \), which in turn implies that \( V_n(\bar{p}, 1) \) is maximized at \( \bar{p} = 0 \). Since it is readily verified that \( \lim_{n} y_n(2c_1r) = 1 \), we conclude that \( 0 \leq \lim_{n} V^*_n \leq \lim_{n} \bar{\bar{V}}_n = 0 \). Therefore, for a given \( \delta > 0 \), the constraint \( V^*_n \geq \delta \) becomes violated for all large \( n \). Therefore, we can set \( n_\delta \) as the largest number \( k \) such that the \( k \) supplier R&D contest is feasible.

On the other hand, we note that \( D_{n+1} \subset D_n \) where \( D_n := \{ (p, w) | w - 2c_1\lambda_n \xi_n \geq \delta \} \). This is because we showed in the proof of Lemma 3 that \( \lambda_n \) is increasing in \( n \) for each fixed \( (\bar{p}, w) \). Therefore, the \( n \) supplier R&D contest is feasible for any \( n \leq n_\delta \). Consequently, the optimal \( n \) is chosen among integers \( \{ 1, 2, \ldots, n_\delta \} \).

From Proposition 2, we find that the optimal number of suppliers to invite in the R&D contest depends on the suppliers’ participation threshold. When \( \delta = 0 \), we find that it is optimal to invite as many suppliers as possible. In fact, the asymptotic behavior of the innovation threshold increases in \( n \) while the expected time to innovation decreases in \( n \); that is, an increase in the number of suppliers improves the innovation outcome in both time and quality. In contrast to the increasing firm’s profit in the number of suppliers, suppliers’ effort rate and their expected profit decrease as a result of a stiffer competition. Consequently, as \( n \to \infty \), the firm not only extracts all the supply chain surplus leaving no rent to the suppliers, its expected profit is also maximized (\( \lim_{n} \bar{\bar{V}}_n = 1 \)). This reveals that, for the type of R&D task which the participation threshold is relatively small, the increased likelihood of obtaining an extreme-valued innovation dominates the diminishing effort rates and that the firm benefits from hosting a large-scale R&D contest, crowdsourcing. The Netflix open innovation contest, a competition for the best movie recommendation algorithm for a prize of $1 million [Forbes, 2009], or the Millennium Prize Problems, seven mathematics problems with a prize of $1 million each [Clay Mathematics Institute, 2000], are examples of such crowdsourcing. We note that this result forms a stark contrast with a popular result in the R&D contest literature that the firm may benefit from limiting the number of R&D participants (e.g., Fullerton and McAfee [1999], Taylor [1995], Che and Gale [2003]). This result is due to capturing the innovation timing and discounting explicitly.

Although the firm benefits from increasing the number of suppliers, the participation constraint may prohibit such a possibility if \( \delta \) is non-negligible. Under such condition, we find that there exists an upper bound on the number of suppliers to invite in Proposition 2(b). This leads us to the question of whether the firm should offer entry subsidies to the suppliers to encourage competition and exploit the extreme-value effect.

R&D Contest Design with Entry Subsidies. In the presence of non-negligible participation threshold, the firm may offer an entry subsidy (a fraction of \( \delta \)) and increase the number of participating suppliers to the extent that the increased revenue (via extreme-value effect) offsets the aggregate entry subsidies. Suppose that the firm invites \( n \) suppliers with \( V_n \geq \delta \) for fixed \( (\bar{p}, w) \). Then our question is whether there exists an integer \( m > n \) and some entry subsidy \( \Delta > 0 \) such that
\[
h_m(\bar{p}, w) - m\Delta \geq h_n(\bar{p}, w) \quad \text{such that} \quad V_m + \Delta \geq \delta \quad (6)
\]
Proposition 2(a). The last statement then follows immediately from

\[ h(\text{optimum max}) \text{ is subsidized by some amount} \Delta \] \[ \text{[U.S. Department of Defense, 2001], is an example. With relatively high setup and opportunity costs in} \]

fighter aircraft hosted by the U.S. Department of Defense in 1996 (won by Lockheed-Martin defeating Bowa-

cr; however, the contest would yield a negative profit if

\[ m \text{ profit} \text{ such that} \] \[ V(\text{some initial cost (offering subsidies) but can enlarge the feasible region of} \] \[ \text{participation threshold. In essence, the benefit of offering subsidies lies in the trade-off that the firm bears} \]

\[ \Delta \text{ is the optimal firm value under the constraint} \] \[ V \] \[ \text{satisfies this inequality, it is profitable to have the contest with} \] \[ m \text{ suppliers.}\]

\[ \text{Lemma 4. Consider the} n \text{ supplier R&D contest with} (\bar{p}, w) \text{. Then, there exists a nonempty region for} \]

\[ (\bar{p}, w, r, c) \text{ in which it is profitable for the firm to subsidize the participating suppliers.} \]

Proof. The inequality in (6) is equivalent to

\[ (\eta + \bar{p} - w) \left( \frac{r}{r + n\lambda_n \xi} - \frac{r}{r + m\lambda_m \xi} \right) \geq m \Delta. \]

\[ \text{From the proof of Lemma 3, we know that} \lambda_m > \lambda_n. \text{ Also, the smallest subsidy that makes the contest with} m \text{ suppliers feasible is} \Delta = \delta - V_m \text{ which is less than or equal to} V_n - V_m. \text{ Hence, the following inequality is a}

\[ (\eta + \bar{p} - w) \frac{mr \xi (\lambda_m - \lambda_n)}{(r + n\lambda_n \xi)(r + m\lambda_m \xi)} \geq m (V_n - V_m) = \frac{2mc_s}{\xi} (\lambda_m - \lambda_n), \]

which is in turn re-written as

\[ (\eta + \bar{p} - w) \frac{r \xi^2}{2c_s} \geq (r + n\lambda_n \xi)(r + m\lambda_m \xi). \]

As long as \((\bar{p}, w, r, c)\) satisfies this inequality, it is profitable to have the contest with \(m\) suppliers, each of which

\[ \text{is subsidized by some amount} \Delta \text{ between} \delta - V_m \text{ and} V_n - V_m. \text{ Such a region for} (\bar{p}, w, r, c) \text{ is not empty. For}

instance, it holds if \((\eta + \bar{p}) \xi^2 \gg 2rc_s\) and \(w\) is small. \)

In the following, we consider an R&D contest with entry subsidies.

Proposition 3. Consider the R&D contest in which it is optimal for the firm to invite \(n\) suppliers. Then, the firm

\[ \text{should offer entry subsidies to increase the number of participating suppliers to} m (> n) \text{ if} h_m(\bar{p}, w) \geq \Pi_n + m \delta \]

\[ \text{for some} (\bar{p}, w). \text{ However, such} m \text{ cannot exceed} (1 - \Pi_n) / \delta. \]

Proof. The condition that guarantees the profitability of a subsidy is equivalent to \(\Pi^\delta_m - \Pi_n \geq m \Delta\) where \(\Pi^\delta_m\) is

the optimal firm value under the constraint \(V_m(\bar{p}, w) \geq \delta - \Delta\) with subsidy \(\Delta\). One extreme choice of subsidy

\[ \text{is} \Delta = \delta, \text{ that is, to remove the participation threshold. In such case,} \Pi^\delta_m \text{ is nothing but the unconstrained}

\[ \text{optimum} \max(\bar{p}, w) h_m(\bar{p}, w) \text{ because we know that the} m \text{ supplier contest is feasible for any} (\bar{p}, w) \text{ thanks to}

Proposition 2(a). The last statement then follows immediately from \(h_m(\bar{p}, w) \leq 1. \)

Proposition 3 characterizes a condition for offering the entry subsidies in the presence of non-negligible

participation threshold. In essence, the benefit of offering subsidies lies in the trade-off that the firm bears

some initial cost (offering subsidies) but can enlarge the feasible region of \((m, \bar{p}, w)\) (improving its expected profit) such that

\[ V_m(\bar{p}, w) \geq \delta - \Delta. \] \[ \text{For example, in the special case of} \Delta = \delta, \text{ the more the firm invites, the}

better; however, the contest would yield a negative profit if \(m\) is too large. This sort of R&D contests are often

observed in military research; the Joint Strike Fighter project, developing the prototype of a future generation

fighter aircraft hosted by the U.S. Department of Defense in 1996 (won by Lockheed-Martin defeating Bowing) [U.S. Department of Defense, 2001], is an example. With relatively high setup and opportunity costs in
developing the demonstrator fighter models, each participating companies were given $750 million each as a seed research grant. We also note that the idea of offering entry subsidy is also documented in Lichtenberg [1988], where they empirically observe that the federal agencies often heavily subsidize shortlisted firms to participate in its R&D competitions.

**Numerical Illustration.** To better understand the implications of participation threshold in the R&D contest, we consider two numerical cases. In the first case, we examine the impact of the number of suppliers in the R&D contest. We assume the innovation distribution such that the resulting excess distribution is uniform, defined as $\xi(\bar{p}) = (1 - \bar{p})$. Figure 1(a) illustrates the firm’s optimal profit as functions of participation threshold $\delta$ with $c_s = 0.1$ and $r = 0.03$. While the firm’s optimal profit increases with $n$, we observe that it tails off earlier as the $\delta$ increases due to the participation constraint. Hence, the suppliers’ participation threshold acts as a major factor in determining the maximum number of participants in the R&D contest.

Figure 1(b) illustrates the firm’s optimal sourcing decision while varying the firm’s R&D cost coefficient $c$ for a given number of participating suppliers $n$ for the contest. All parameters remain the same as in the above example with $\delta = 0.01$. As shown in Proposition 1, there exists a set of thresholds $(\bar{c}_n, \bar{c}_n)$ for the optimal sourcing decision. When the firm’s R&D cost is low enough ($c \leq \bar{c}_n$), it prefers in-sourcing. While the firm may still prefer in-sourcing when its R&D cost is moderately high ($\bar{c}_n \leq c \leq \bar{c}_n$), the suppliers may pay the entry fee to the firm to make the outsourcing a more lucrative option, as shown in Corollary 1. When the firm’s R&D cost is sufficiently large ($c > \bar{c}_n$), it prefers R&D outsourcing and may even be willing to offer entry subsidies to the suppliers to increase the participation, as shown in Proposition 3. For example, considering the subsidy of 50% of the participation threshold, i.e., $\Delta = 0.005$, we find that the firm’s profit improves when inviting between 39 to 47 suppliers. However, the firm cannot arbitrarily increase the number of suppliers in the contest, as shown in Proposition 2(b); in this example, inviting $n \geq 48$ suppliers leads to a contest that is infeasible or feasible but with negative profit for the firm. Although exploring the optimal values of entry fee and subsidy are interesting topics to investigate, we leave those as a future research direction and limit the current work as a visualization step toward the optimal R&D contest design.

![Figure 1: (a) Firm’s optimal profit with respect to suppliers’ participation threshold. (b) Firm’s optimal sourcing decision with respect to its R&D cost.](image-url)
4. Conclusion

Although R&D outsourcing is becoming a common practice in many innovation-driven industries, the optimal sourcing strategy involving an innovation process is not well-established in the literature. In this paper, we investigate the optimal R&D sourcing decision for a profit-maximizing firm by comparing the option of keeping the R&D in-house to hosting an R&D contest to third-party suppliers. We find the thresholds in the firm’s R&D cost above which it prefers to outsource its R&D via a contest and that the suppliers may want to pay the entry fee for participating the contest to decrease that threshold. When the barrier for R&D participation is low, we find that the firm benefits from hosting a large-scale R&D contest by inviting as many suppliers as possible (crowdsourcing). When R&D participation threshold is non-negligible, we find that the firm may prefer to offer entry subsidies to the suppliers to increase the number of participation.

There are several possible extensions of this work that we have not covered. First, most R&D processes in reality are complex and may consist of multiple-stages, each involving different types of innovation. Of course, outsourcing decisions do not have to be all-or-nothing, thus deciding which stage to outsource (or in-source) is a very important issue to study. Under such multiple-stage R&D processes, coordination across each R&D stage should also be considered. Second, when faced with a set of suppliers with different characteristics (e.g., difference in terms of R&D cost structures, technology levels, time value of money), selecting the right type of a supplier (or a set of suppliers) is also an interesting question to investigate. Our current model does not capture these features, although it certainly provides a basis for such extensions. We leave these promising research directions as future work.

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