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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 hosting a contest. When designing an R&D contest, we find that the firm benefits from inviting as many suppliers as possible if the R&D participation barrier is low. Otherwise, the firm may prefer to offer entry subsidies or impose fees to purposefully manipulate the contest structure.

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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 [12], more than 83% of industry respondents in the US 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 [6,2]. R&D outsourcing is becoming a common practice in other industries such as medical devices and software developments. In 2012, the total R&D expenditure spent in the US was estimated to be $436 billion, of which about 7% is captured by outsourcing or external firms [13,14].

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 firms profit is often directly determined by the quality of innovation. We capture such innovation arrival by a Poisson process akin to the *search model* introduced in [10], where the optimal stopping policy for the search that maximizes the expected return is 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 and its variants have been often used in modeling technological discoveries [11,9,7]. The main trade-off 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 hosting an *R&D contest*, also referred to as *R&D tournament*, inviting multiple contributors or suppliers that compete against. In the contest, the uncertain innovation time and quality as well as 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 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 [5,15,3]. However, [16,1] recently show that the firm can benefit from increasing the participants when the degree of uncertainty in the problem is large enough due to extreme-value effect.

We contribute to this growing literature by studying a firm's sourcing decision and the design of R&D contest, taking into account the above mentioned trade-off and possible *entry interventions* (imposing entry fees or offering entry subsidies to the

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participating suppliers). We find that: when the barrier for R&D participation is low, the firm benefits from hosting a large-scale R&D contest (i.e., increasing the number of suppliers); otherwise, the firm may be better off by purposefully manipulating the contest structure with proper intervention means.

2. When to outsource?

Consider an innovation search process (i.e., R&D) of which arrivals follow a homogeneous Poisson process with rate λ if an effort rate λ for the search is exerted. Thus, the inter-arrival time of each innovation, denoted by $T(\lambda)$, is an exponential random variable with rate λ. Associated with each arrival, we assume that the random innovation quality $p \in [0, 1]$ is drawn in an i.i.d. fashion from a distribution with a density function $f(\cdot) > 0$ on $[0, 1]$; 0 otherwise. For simplicity, we assume innovation quality is independent of the effort rate λ. 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 [16]). To simplify the analysis, we consider the innovation searching cost is $c\lambda^2$ for effort rate λ. We denote the discount factor by r.

As shown in [10], the above optimal policy for the R&D process is given by a threshold policy: stop the 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 it by $\bar{p}$ and the probability of innovation exceeding the threshold $\bar{p}$, excess probability, by $\xi(\bar{p}) = \mathsf{P}(p > \bar{p})$. We assume $\bar{p} < 1$ to retain our attention to a nontrivial case. For brevity of notation, we suppress $\xi(\bar{p})$ by ξ 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 $\eta(\bar{p}) = \mathsf{E}[p-\bar{p}|p > \bar{p}]$. This is also suppressed to η 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 ξ. Hence, a profit-maximizing firm who determines the R&D exerting effort rate λ and the innovation threshold $\bar{p}$ solves the following problem:

$$\Pi = \max_{(\bar{p},\lambda)} \mathsf{E}\left[p e^{-rT(\lambda\xi)} - c\lambda^2 \int_0^{T(\lambda\xi)} e^{-rt} dt \,\middle|\, p > \bar{p} \right]$$
$$= \max_{(\bar{p},\lambda)} \left\{ (\eta + \bar{p}) \frac{\lambda\xi}{r + \lambda\xi} - \frac{c\lambda^2}{r + \lambda\xi} \right\}. \quad (1)$$

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:*

$$4cr\bar{p} = \mathsf{E}\Big[(p - \bar{p})^+\Big]^2. \quad (2)$$

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

The proof of this lemma can be found in the online supplement (see Appendix A). 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 τ^* (since the firm's expected revenue is $\mathsf{E}[p|p > \bar{p}] = \eta + \bar{p}$). From (2), we can infer how the optimal effort rate λ^* 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 λ^*; a decrease in c yields an increase in λ^*, whereas a decrease in r yields a decrease in λ^*. A similar trend is observed for the expected time to innovation as well. We note that this result can also be obtained in other papers in the literature albeit differences in model setting; e.g., [11].

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, δ; hence, the supplier participates in the contest only if the expected profit of each supplier is no less than δ. 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 subsection, we first assume that the number of suppliers n is exogenously given so as to understand the firm's sourcing decisions and do not take into account the participation threshold explicitly. Later in Section 3, we assume the firm *can* optimize the number of suppliers and consider the participation threshold more specifically as this acts as a factor determining the optimal size of the 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 λ to exert, which determines the arrival rate of the innovation. Let us denote the time to the first innovation exceeding $\bar{p}$ of the ith 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 $\min_{j=1,\ldots,n} T(\lambda^{(j)}\xi)$, where $\xi = \xi(\bar{p}) = \mathsf{P}(p > \bar{p})$ is the excess probability. Therefore, the firm's problem can be formulated as follows:

$$\Pi_n = \max_{(\bar{p},w)} \mathsf{E}\left[e^{-r \min_j T^{(j)}} (p - w) \,\middle|\, p > \bar{p} \right].$$

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 $\bar{p}$:

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

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

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