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Cooperative vs. Non-cooperative R&D under Uncertain Probability of Success

Abstract: R&D decision of a firm involves various sources of incomplete information. The present paper introduces incomplete information about the success probability of R&D in a model of two firms interacting in R&D and production and discusses the choice between cooperative and non-cooperative research. We consider research joint venture as the form of R&D cooperation. While the choice depends on the constellation of parameters, the following results are derived, in general. First, the high type firm always has a larger incentive for both cooperative and non-cooperative R&D compared to the low type firm. Second, if the low type firm goes for non-cooperative research, then the high type firm must go for the same, and if the high type firm prefers cooperative research, the low type firm must also prefer cooperative R&D. However, if the high type firm prefers non-cooperative R&D, the low type firm may go for either form of research depending on the parameters. The paper derives conditions, in particular, for the case when the high type firm prefers non-cooperative research whereas the low type firm prefers cooperative research.

Keywords: Cooperative research; Non-cooperative research; Probability of success; Incomplete information; Research joint venture.

JEL classifications: D43; D82; L13; O31.

1. Introduction

Importance of research and development (R&D) is well-recognized in the literature. But given the fact that R&D involves huge research expenditure and uncertain outcome, along with the possibility of imitation, spillovers and leaking out of knowledge, there is an underinvestment in R&D. Hence at the policy level it is encouraged that firms should go for cooperative research, and in particular, for research joint venture in which case the potential investors can share their R&D results as well as the research cost. Thereafter the choice between cooperative and non-cooperative R&D, hence the choice of R&D organization, has been an important arena of research.

The existing literature has already studied extensively the incentives of the competing firms for cooperative research, but this literature is mostly developed in the framework of complete information, that is, R&D firms not only know the size of the innovation but also the probability of success along with other associated information. The pioneering work in this field has been contributed by d'Aspremont and Jacquemin (1988), which provides the choice between cooperative and non-cooperative R&D in a framework of Cournot duopoly with homogeneous goods and spillovers. The work has been extended by Kamien et al. (1992) to the case of differentiated duopoly and by Suzumura (1992) to the case of oligopoly with the more general assumption regarding spillovers. Motta (1992) has studied the case of vertically differentiated products. The paper by Amir et al. (2003) has discussed the problem with endogenous spillovers. Grossman and Shapiro (1986) and Brodley (1990) have analyzed research cooperation in relation to antitrust laws. Kabiraj and Roy (2004) have studied the problem when R&D affects the quality of products, which in turn results in a shift of the market demand.

That uncertainty alone can be the source of R&D cooperation has been pointed out first by Marjit (1991). Then Combs (1992) has extended the model to the case of multiple research projects. Kabiraj (2007) has introduced patent protection and synergy in the analysis in the context of Marjit (1991) and Combs (1993). Mukherjee and Ray (2009) have discussed the choice in the presence of uncertainty in patent approvals. Further, Kabiraj (2006) has analyzed the choice when there are two conceivable products. On the other hand, Mukherjee and Marjit (2004) and Kabiraj and Kabiraj (2019a) have introduced technology transfer and research duplication to the choice of R&D organization. A brief survey of some works dealing with uncertainty in the same framework can be found in Kabiraj and Kabiraj (2019b). This helps to identify the factors which are more favorable to cooperative research. Then cooperation and non-cooperation in R&D in a three firm industry is studied by Kabiraj and Mukherjee (2000) and Kabiraj (2018). In particular, Kabiraj and Mukherjee (2000) have studied how cooperation in production may affect the choice between cooperative and non-cooperative R&D.

While the above literature gives a good insight to understand the choice problem between cooperative and non-cooperative research, but the decisions are taken under complete information about all the characteristics of the firms and innovations. The literature on the choice of R&D organization under incomplete information has started growing only recently. There are various sources of incomplete information to the problem. Incomplete information means that some firms or investors know more than some other firms or investors about one or other characteristic relevant for R&D decision, hence each firm holds private information.

Two contributions available at hand in this context are by Kabiraj and Chattopadhyay (2015) and Chattopadhyay and Kabiraj (2015).[1] Kabiraj and Chattopadhyay (2015) have introduced incomplete information about the size of the innovation and derived the choice between cooperative and non-cooperative research. R&D success is stochastic and discretely

[1] Choi (1992) had introduced moral hazard problem in cooperative R&D investment and have shown that non-contractible inputs are under provided by the participants.

distributed, and each firm knows whether it has succeeded or not, but it is private information; therefore, given the information about its own success or failure (hence its innovation size), it knows only the conditional probability of success or failure of its rival. However, under cooperative research when both the firms share their R&D outcomes and expenditures, they have symmetric information about the success and failure of cooperative research. Thus under non-cooperative R&D at the stage of production each firm has private information about its own unit cost of production and only a probabilistic notion about its rival's unit cost. Under cooperative R&D, however, they have symmetric information about their costs of production. Therefore, they will cooperate in research if and only if ex ante the expected payoff from cooperation is strictly larger than that under non-cooperative research. Incomplete information benefits the firm to the extent it holds private information, and it hurts the firm because it does not exactly know the rivals type. '

Chattopadhyay and Kabiraj (2015), on the other hand, have considered the model when R&D outcome is stochastic but continuously distributed with a given mean and a constant variance. It is shown that the incentive for cooperative research is smaller the larger is the variance of the R&D outcome. The problem has been studied under both Cournot and Bertrand competition.

The present paper seeks to extend the model of incomplete information in another direction. In the previous two papers, the R&D outcome is stochastic but the success probability is completely known to the firms. But the success probability to a large extent depends on factors many of which are endogenous to the respective firm. So one firm has much better information about the success probability than its rival. This means, success probability itself is private information and probability of success of R&D for a particular firm constitutes its type. Thus in the present paper we consider Cournot duopoly with two outcomes of R&D, viz., success and failure, but the firm has private information about the probability of success in R&D. This means that there is incomplete information about the probability distribution of success in R&D. Ex ante when the firms decide whether to do R&D cooperatively or non-cooperatively, each firm knows its probability of success, but the rival's probability of success is unknown to the firm. We assume that under cooperative research each firm believes that R&D success is determined by the maximum of their success probabilities. Considering only two types of firms, viz., high type and low type (depending on the realization of nature's move), we have shown that whether a firm will go for cooperative or non-cooperative R&D depends on the constellation of parameters. In general, the high type firm has a larger incentive for both cooperative and non-cooperative R&D compared to the low type firm. We have further shown that if the low type firm has a larger incentive for non-cooperative research, then the high type firm must also have a higher incentive for non-cooperative research, and if the high type firm prefers cooperative research then the low type firm will also do the same. Finally, we have derived conditions, in particular, for the case when the high type firm has a larger incentive for non-cooperative research whereas the low type firm has a higher incentive for cooperative research. This is in fact the case when the R&D expenditure is neither too large nor too small and the probability of the probability of success belongs to an interval. The basic intuition of the result is that the low type firm attaches an average probability of success of the rival higher than its own success probability whereas the high type firm attaches a lower average probability of success for its rival.

The layout of the paper is the following. Section 2 provides the structure of the model. Section 3 discusses the choice between cooperative and non-cooperative research. Section 4 provides the summary of the paper.

2. Structure and Model

Consider two firms, A and B, which produce and sell a homogeneous good. The market demand function for the product is given by:

$$P = \max\{0, a - Q\} \tag{1}$$

where $Q = q_A + q_B$ is the aggregate industry output and q_i is the amount of goods produced by firm i, $a > 0$ is the demand parameter which represents market size, and P is the price of the product. Initially, each firm has a constant marginal cost of production, $c, 0 < c < a$. However, through R&D the unit cost of production can be reduced to $c - \varepsilon, 0 < \varepsilon < c$, if successful; then ε is considered to be the size of the innovation.

We consider two forms of R&D organization. Under non-cooperative R&D the firms will conduct research independently in their own research lab by investing an amount $R > 0$. Under cooperative research the firms do R&D jointly in a single lab by investing $R/2$ by each and agree to share the research results. So this is research joint venture (RJV) form of R&D cooperation. In either case, we assume that getting success in R&D is uncertain.

Although R&D can be cooperative or non-cooperative, but, we assume, in the product market the firms play a Cournot game, hence they choose quantities simultaneously and non-cooperatively. However, we assume that the post-innovation market structure will remain duopoly.[2]

Let us denote: $K := a - c$ and $\pi(x) := \left(\frac{K+x}{3}\right)^2$. Then, if α and β be the extent of cost saving of A and B after R&D, their payoffs will be given by:

$$\Pi_A(\alpha, \beta) = \pi(2\alpha - \beta) \text{ and } \Pi_B(\alpha, \beta) = \pi(2\beta - \alpha)$$

Hence given that the R&D outcome can be either ε or 0, the possible payoffs will be:

$$\Pi_A(\varepsilon, \varepsilon) = \pi(\varepsilon), \Pi_A(0, 0) = \pi(0), \Pi_A(\varepsilon, 0) = \pi(2\varepsilon), \Pi_A(0, \varepsilon) = \pi(-\varepsilon) \quad (2a)$$

$$\Pi_B(\varepsilon, \varepsilon) = \pi(\varepsilon), \Pi_B(0, 0) = \pi(0), \Pi_B(0, \varepsilon) = \pi(2\varepsilon), \Pi_B(\varepsilon, 0) = \pi(-\varepsilon) \quad (2b)$$

Note that $\pi(.)$ is increasing and convex. Hence,

$$\pi(2\varepsilon) > \pi(\varepsilon) > \pi(0) > \pi(-\varepsilon), \text{ and} \quad (3a)$$

$$\big(\pi(2\varepsilon) - \pi(\varepsilon)\big) - \big(\pi(0) - \pi(-\varepsilon)\big) > 0 \quad (3b)$$

We have already mentioned that R&D outcome (i.e. success or failure) is probabilistic. But in our paper firms have incomplete information about the probability of success. While each firm knows its type, but it does not know the type of the other firm with certainty. Let s_A and s_B be the probability of success in R&D by A and B respectively under non-cooperative research. Then these constitute the types of the firms, and these are private information. Assume only two types of firms, viz., high type and low type, hence

$$s_A, s_B \in \{s_L, s_H\}, \text{ where } s_H > s_L$$

However, nature decides whether a firm is high type or low type. Let the nature's probability distribution be:

$$s = \Pr(s_A = s_H) = \Pr(s_B = s_H) \text{ ; so } (1 - s) = \Pr(s_A = s_L) = \Pr(s_B = s_L); 0 < s < 1.$$

Finally, we assume that the probability of success in RJV is $\max\{s_A, s_B\}$. Therefore, if at least one firm is of high type, the probability of success under RJV will be high (s_H).

[2] This means, the size of the innovation must not be very large, hence we restrict that $\varepsilon < K = a - c$.

Conveniently, let us define

$$\hat{s} = ss_H + (1-s)s_L; \text{ so } (1-\hat{s}) = s(1-s_H) + (1-s)(1-s_L)$$

From this it further follows that

$$s_H > \hat{s} > s_L\,, (1-s_H) < (1-\hat{s}) < (1-s_L) \tag{4a}$$

$$\lim_{s\to 0}\hat{s} = s_L \text{ and } \lim_{s\to 1}\hat{s} = s_H. \tag{4b}$$

Finally, it is assumed that at the stage of production the firms know their technologies they have come up with through research, either independently or cooperatively, and this is common knowledge. Then the present paper focuses on the ex ante decision of the firms regarding their choice of R&D organization. Since both the firms are otherwise symmetric, so in the following analysis, we consider the decision of firm A only regarding the decision for cooperation and non-cooperation in R&D.

2.1 Non-Cooperative R&D

Consider firm A. Then under non-cooperative research its expected payoff will be given by:

$$\begin{aligned}\mathrm{E}\Pi_A^{NC} &= s_A\big[s\big(s_H\pi(\varepsilon) + (1-s_H)\pi(2\varepsilon)\big) + (1-s)\big(s_L\pi(\varepsilon) + (1-s_L)\pi(2\varepsilon)\big)\big] + \\ &\quad (1-s_A)\big[s\big(s_H\pi(-\varepsilon) + (1-s_H)\pi(0)\big) + (1-s)\big(s_L\pi(-\varepsilon) + (1-s_L)\pi(-\varepsilon)\big)\big] \\ &\quad - R\end{aligned}$$

$$= s_A[\hat{s}\,\pi(\varepsilon) + (1-\hat{s})\pi(2\varepsilon)] + (1-s_A)[\hat{s}\,\pi(-\varepsilon) + (1-\hat{s})\pi(0)] - R$$

$$= \hat{s}[s_A\,\pi(\varepsilon) + (1-s_A)\pi(-\varepsilon)] + (1-\hat{s})[s_A\,\pi(2\varepsilon) + (1-s_A)\pi(0)] - R$$

Then, when $s_A = s_H$,

$$E\Pi_A^{NC}(s_H) = s_H[\hat{s}\,\pi(\varepsilon) + (1-\hat{s})\pi(2\varepsilon)] + (1-s_H)[\hat{s}\,\pi(-\varepsilon) + (1-\hat{s})\pi(0)] - R$$

$$= \hat{s}[s_H\pi(\varepsilon) + (1-s_H)\pi(-\varepsilon)] + (1-\hat{s})[s_H\pi(2\varepsilon) + (1-s_H)\pi(0)] - R$$

Similarly, when $s_A = s_L$

$$E\Pi_A^{NC}(s_L) = s_L[\hat{s}\,\pi(\varepsilon) + (1-\hat{s})\pi(2\varepsilon)] + (1-s_L)[\hat{s}\,\pi(-\varepsilon) + (1-\hat{s})\pi(0)] - R$$

$$= \hat{s}[s_L\,\pi(\varepsilon) + (1-s_L)\pi(-\varepsilon)] + (1-\hat{s})[s_L\,\pi(2\varepsilon) + (1-s_L)\pi(0)] - R$$

We can then easily check that:

$$E\Pi_A^{NC}(s_H) > E\Pi_A^{NC}(s_L) \quad (5)$$

2.2 Cooperative R&D

Consider the expected payoff of firm A under cooperative research (C). When $s_A = s_H$, the firm knows that the probability of success will certainly be s_H, Hence its expected payoff under cooperation will be:

$$E\Pi_A^C(s_H) = s_H\,\pi(\varepsilon) + (1 - s_H)\pi(0) - \frac{R}{2}$$

When $s_A = s_L$, the firm knows its own type (low), but the other firm can be either low type or high type. Hence firm A's expected payoff from cooperative research is:

$$E\Pi_A^C(s_L) = s[s_H\,\pi(\varepsilon) + (1 - s_H)\pi(0)] + (1 - s)[s_L\,\pi(\varepsilon) + (1 - s_L)\pi(0)] - \frac{R}{2}$$

$$= \hat{s}\,\pi(\varepsilon) + (1 - \hat{s})\pi(0) - \frac{R}{2}$$

Since $s_H > \hat{s}$ and $\pi(\varepsilon) > \pi(0)$, therefore,

$$E\Pi_A^C(s_H) > E\Pi_A^C(s_L) \quad (6)$$

3. Cooperative vs. Non-cooperative R&D

Since we shall be comparing incentives of firms for cooperative and non-cooperative R&D, so we restrict to the assumption that, given the parameters, each type firm has positive incentive for both cooperative and non-cooperative research, that is, $E\Pi_A^C(.) > 0$ and $E\Pi_A^{NC}(.) > 0$.[3]

Now, from the inequality (5) and (6) in the last section, we can write the following proposition.

Proposition 1: *The high type firm has always a larger incentive for both cooperative and non-cooperative R&D compared to that of the low type firm.*

The intuition of the result is very simple. Since success in R&D for high type firm occurs with a higher probability, the incentive for non-cooperative research is higher. Under cooperative

[3] Based on the parameters, however, either one or both of these expressions can be negative.

research the high type firm attaches higher probability with the successful outcome whereas the low type firm attaches an average probability of success, hence the result.

Now consider incentive of a firm under cooperative research over non-cooperative research. We define that a firm, A, has higher incentives for cooperative research over non-cooperative research if and only if $E\Pi_A^C(s_A) - E\Pi_A^{NC}(s_A) > 0$, given the type of the firm, i.e., $s_A = s_H \; or \; s_L$. We can derive the following:

$$E\Pi_A^{NC}(s_H) - E\Pi_A^C(s_H)$$

$$= (1-\hat{s})s_H[\pi(2\varepsilon) - \pi(\varepsilon)] - (1-s_H)\hat{s}[\pi(0) - \pi(-\varepsilon)] - \frac{R}{2}$$

$$= s_H[\pi(2\varepsilon) - \pi(\varepsilon)] - \hat{s}[\pi(0) - \pi(-\varepsilon)] - s_H\hat{s}[\pi(2\varepsilon) - \pi(\varepsilon) - \pi(0) + \pi(-\varepsilon)] - \frac{R}{2}$$

and

$$E\Pi_A^{NC}(s_L) - E\Pi_A^C(s_L)$$

$$= (1-\hat{s})s_L[\pi(2\varepsilon) - \pi(0)] - (1-s_L)\hat{s}[\pi(\varepsilon) - \pi(-\varepsilon)] - \frac{R}{2}$$

$$= s_L[\pi(2\varepsilon) - \pi(0)] - \hat{s}[\pi(\varepsilon) - \pi(-\varepsilon)] - s_L\hat{s}[\pi(2\varepsilon) - \pi(\varepsilon) - \pi(0) + \pi(-\varepsilon)] - \frac{R}{2}$$

Therefore,

$$[E\Pi_A^{NC}(s_H) - E\Pi_A^C(s_H)] - [E\Pi_A^{NC}(s_L) - E\Pi_A^C(s_L)]$$

$$= s_H[\pi(2\varepsilon) - \pi(\varepsilon)] - s_L[\pi(2\varepsilon) - \pi(0)] + \hat{s}[\pi(\varepsilon) - \pi(0)]$$

$$-(s_H - s_L)\,\hat{s}[\pi(2\varepsilon) - \pi(\varepsilon) - \pi(0) + \pi(-\varepsilon)]$$

$$> s_H[\pi(2\varepsilon) - \pi(\varepsilon)] - s_L[\pi(2\varepsilon) - \pi(\varepsilon)] - (s_H - s_L)\,\hat{s}[\pi(2\varepsilon) - \pi(\varepsilon) - \pi(0) + \pi(-\varepsilon)]$$

$$= (s_H - s_L)\,[(1-\hat{s})\{\pi(2\varepsilon) - \pi(\varepsilon)\} + \hat{s}\{\pi(0) - \pi(-\varepsilon)\}] > 0$$

Hence we must have,

$$[E\Pi_A^{NC}(s_H) - E\Pi_A^C(s_H)] > [E\Pi_A^{NC}(s_L) - E\Pi_A^C(s_L)] \qquad (7a)$$

0r, $$[E\Pi_A^C(s_L) - E\Pi_A^{NC}(s_L)] > [E\Pi_A^C(s_H) - E\Pi_A^{NC}(s_H)] \qquad (7b)$$

This has following implications.

(i) If $[E\Pi_A^{NC}(s_L) - E\Pi_A^C(s_L)] \geq 0$, then $[E\Pi_A^{NC}(s_H) - E\Pi_A^C(s_H)] > 0$.

(ii) If $[E\Pi_A^{NC}(s_H) - E\Pi_A^{C}(s_H)] < 0$, then $[E\Pi_A^{NC}(s_H) - E\Pi_A^{C}(s_H)] < 0$.

This leads to the following proposition;

Proposition 2:

(a) When the low type firm prefers non-cooperative R&D, the high type firm will also prefer non-cooperative R&D.

(b) When the high type firm prefers RJV, the low type firm will also prefer RJV.

It also follows that if the high type firm prefers cooperative R&D, the low type firm prefers non-cooperative R&D. On the other hand, when the high type firm prefers non-cooperative research, the choice of the low type firm can be either non-cooperative or cooperative research depending on the constellation of the parameters, given inequality (7). We are, in particular, interested to see under what condition(s) the high type firm prefers non-cooperative R&D and the low type firm prefers cooperative R&D.

To make the analysis simple, let us define

$$E(s|s_H) = E\Pi_A^{NC}(s_H) - E\Pi_A^{C}(s_H) + \frac{R}{2} \tag{8a}$$

$$E(s|s_L) = E\Pi_A^{NC}(s_L) - E\Pi_A^{C}(s_L) + \frac{R}{2} \tag{8b}$$

Hence,

$$E(s|s_H) - E(s|s_L) = [E\Pi_A^{NC}(s_H) - E\Pi_A^{C}(s_H)] - [E\Pi_A^{NC}(s_L) - E\Pi_A^{C}(s_L)]$$

Here

$$E(s|s_H) = (1-\hat{s})s_H[\pi(2\varepsilon) - \pi(\varepsilon)] - (1-s_H)\hat{s}[\pi(0) - \pi(-\varepsilon)]$$

$$E(s|s_L) = (1-\hat{s})s_L[\pi(2\varepsilon) - \pi(0)] - (1-s_L)\hat{s}[\pi(\varepsilon) - \pi(-\varepsilon)]$$

Note that both $E(s|s_H)$ and $E(s|s_L)$ are strictly falling in s. So both are maximized at $s = 0$ (i.e., $\hat{s} = s_L$) and minimized at $s = 1$ (i.e., $\hat{s} = s_H$). Hence,

$$\max_s E(s|s_H) = (1-s_L)s_H[\pi(2\varepsilon) - \pi(\varepsilon)] - (1-s_H)s_L[\pi(0) - \pi(-\varepsilon)]$$

$$\min_s E(s|s_H) = (1-s_H)s_H[\pi(2\varepsilon) - \pi(\varepsilon) - \pi(0) + \pi(-\varepsilon)]$$

$$\max_s E(s|s_L) = (1-s_L)s_L[\pi(2\varepsilon) - \pi(\varepsilon) - \pi(0) + \pi(-\varepsilon)]$$

$$\min_s E(s|s_L) = (1 - s_H)s_L[\pi(2\varepsilon) - \pi(0)] - (1 - s_L)s_H[\pi(\varepsilon) - \pi(-\varepsilon)]$$

We can easily check that:

$$\max_s E(s|s_H) > \max_s E(s|s_L) \text{ and } \min_s E(s|s_H) > \min_s E(s|s_L) \quad (9)$$

But,

$$\max_s E(s|s_L) \gtrless \min_s E(s|s_H) \Leftrightarrow (1 - s_L)s_L \gtrless (1 - s_H)s_H, \text{ i.e., } s_H + s_L \gtrless 1 \quad (10)$$

Therefore, when $s_H + s_L > 1$, we have

$$\max_s E(s|s_H) > \max_s E(s|s_L) > \min_s E(s|s_H) > \min_s E(s|s_L) \quad (11)$$

And when $s_H + s_L < 1$, we have

$$\max_s E(s|s_H) > \min_s E(s|s_H) > \max_s E(s|s_L) > \min_s E(s|s_L) \quad (12)$$

Now, given R, hence $\frac{R}{2}$, one can characterize all possible cases of when the low type or the high type will have a larger incentive for cooperative or non-cooperative research. Below we shall consider the interesting case, viz., the high type firm will have a larger incentive for non-cooperative research but the low type firm will have a larger incentive for cooperative research.

First suppose $s_H + s_L < 1$ and consider R such that $\max_s E(s|s_L) \leq \frac{R}{2} \leq \min_s E(s|s_H)$. Then for all $s \in (0,1)$the high type firm prefers non-cooperative R&D and the low type firm prefers cooperative R&D.

Consider now the more interesting case $s_H + s_L > 1$ and assume $\min_s E(s|s_H) < \frac{R}{2} < \max_s E(s|s_L)$. Given that both $E(s|s_H)$ and $E(s|s_L)$ are falling in s, let the $\frac{R}{2}$ line intersect the function $E(s|s_L)$ at $s = \underline{s}(R)$ and the function $E(s|s_H)$ at $s = \bar{s}(R)$ (see *Figure 1*). This means for all $s \in (\underline{s}, \bar{s})$, we have $E\Pi_A^{NC}(s_H) - E\Pi_A^C(s_H) > 0$ and $E\Pi_A^{NC}(s_L) - E\Pi_A^C(s_L) < 0$. Thus, given $\frac{R}{2}$ and $s \in (\underline{s}, \bar{s})$, the high type firm will prefer non-cooperative research while the low type firm will prefer cooperative research. Further note that as R falls (increases), both $\underline{s}$ and $\bar{s}$ increase (fall). Hence we can write the following proposition.

Proposition 3: *Consider* $s_H + s_L > 1$ *and assume* $\min_s E(s|s_H) < \frac{R}{2} < \max_s E(s|s_L)$. *Then* $\forall s \in (\underline{s}, \bar{s})$ *the high type firm will prefer non-cooperative research whereas the low type firm will prefer cooperative research.*

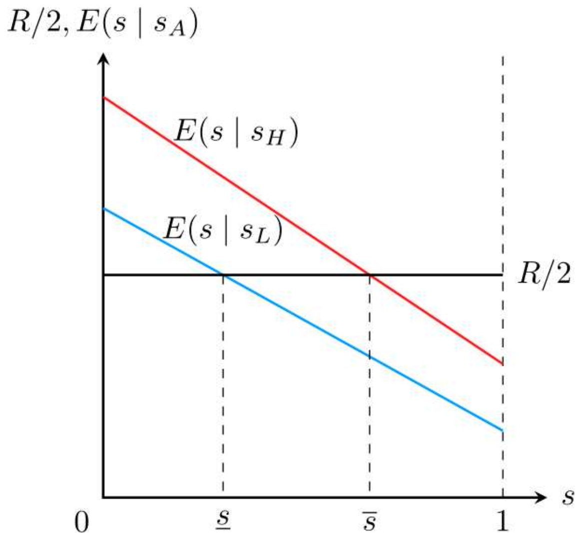

Figure 1: Choice of R&D organization for any given s.

In general, given s (and other parameters), the underlying result of the above proposition will hold when $E(s|s_L) < \frac{R}{2} < E(s|s_H)$, or equivalently,

$$E\Pi_A^{NC}(s_L) - E\Pi_A^{C}(s_L) < 0 < E\Pi_A^{NC}(s_H) - E\Pi_A^{C}(s_H) \tag{13}$$

Then (13) can be reduced to

$$[s_L(1-\hat{s})\varepsilon - (\hat{s} - s_L)K] < \frac{9R}{8\varepsilon} < [(s_H - \hat{s})\frac{K}{2} + (s_H(1-\hat{s}) - \frac{(s_H - \hat{s})}{4})\varepsilon] \tag{14}$$

See *Appendix* 1 for the derivation. Hence we can write the final proposition of the paper.

Proposition 4: *The necessary and sufficient condition for the low type firm to prefer RJV while the high type firm to prefer non-cooperative R&D is given by:*

$$[s_L(1-\hat{s})\varepsilon - (\hat{s} - s_L)K] < \frac{9R}{8\varepsilon} < [(s_H - \hat{s})\frac{K}{2} + (s_H(1-\hat{s}) - \frac{(s_H - \hat{s})}{4})\varepsilon]$$

Intuition of the result is the following. If the R&D cost, R, increases and becomes large, each firm will prefer to share the R&D cost rather than going independently, keeping all other parameters unchanged. Similarly, as R will fall incentives for RJV will fall. On the other hand, given R, if s (hence $\hat{s}$) increases, that is, the probability that the rival firm is of high type increases, the incentive for doing RJV will also go up. Below we shall give an example of our results

Example: Let $a = 120, c = 60, \varepsilon = 40, s = 0.2, s_H = 0.8, s_L = 0.6$. Not that here $s_H + s_L > 1$ holds. We can calculate the following:

$E(s|s_H) = \frac{1}{9}(2688 - 1664s) = 261.689$, $E(s|s_L) = \frac{1}{3}(512 - 896s) = 110.934$. Further $\max_s E(s|s_H) = 298.67, \min_s E(s|s_H) = 113.78, \max_s E(s|s_L) = 170.67, \min_s E(s|s_L) = -128$. Then we have the following results:

- For all $\frac{R}{2} \geq 261.689$, both the high type and the low type firms will prefer cooperative R&D.
- For all $\frac{R}{2} \leq 110.934$, both the high type and the low type firms will prefer non-cooperative R&D.
- So if $110.934 \leq \frac{R}{2} \leq 261.689$, the high type firm will prefer non-cooperative R&D and the low type firm will prefer cooperative R&D.

4. Summary

When a firm invests in R&D, it does not know, with certainty, whether success will come out or not. This means, success is uncertain or probabilistic. But the probability of success, to a large, extent depends on the factors endogenous to the firm. Therefore, it has incomplete information about the probability of success of its rival, hence it is private information. The present paper discusses the choice of R&D organization, that is, whether they will conduct research independently or cooperatively under incomplete information about the success probability. We have shown that: a high type firm has a larger incentive for both cooperative and non-cooperative R&D than the low type firm; if the low type firm has a larger incentive for non-cooperative R&D, then the high type firm must have a larger incentive for non-cooperative R&D; and if the high type firm prefers cooperative R&D, then the low type firm must prefer cooperative R&D. On the other hand, if the high type firm prefers non-cooperative R&D, whether the low type firm will prefer cooperative or non-cooperative R&D depends on the constellation of the parameters like R&D cost, the probability distribution of nature and the probability of success of each type firm. The paper has derived the conditions when the high type firm prefers non-cooperative R&D and the low type firm prefers cooperative R&D.

APPENDIX

Appendix 1

For the low type firm

$$E\Pi_A^{NC}(s_L) - E\Pi_A^C(s_L) < 0$$

$$\Leftrightarrow (1-\hat{s})s_L\big(\pi(2\varepsilon) - \pi(0)\big) - (1-s_L)\hat{s}\big(\pi(\varepsilon) - \pi(-\varepsilon)\big) < \frac{R}{2}$$

$$\Leftrightarrow (1-\hat{s})s_L\frac{(K+\varepsilon)4\varepsilon}{9} - (1-s_L)\hat{s}\frac{4K\varepsilon}{9} < \frac{R}{2}$$

$$\Leftrightarrow (1-\hat{s})s_L(K+\varepsilon) - (1-s_L)\hat{s}K < \frac{9R}{8\varepsilon}$$

$$\Leftrightarrow (1-\hat{s})s_L\varepsilon - (\hat{s} - s_L)K < \frac{9R}{8\varepsilon}$$

For the high type firm

$$E\Pi_A^{NC}(s_H) - E\Pi_A^C(s_H) > 0$$

$$\Leftrightarrow (1-\hat{s})s_H\big(\pi(2\varepsilon) - \pi(\varepsilon)\big) - (1-s_H)\hat{s}\big(\pi(0) - \pi(-\varepsilon)\big) > \frac{R}{2}$$

$$\Leftrightarrow (1-\hat{s})s_H\frac{(2K+3\varepsilon)\varepsilon}{9} - (1-s_H)\hat{s}\frac{(2K-\varepsilon)\varepsilon}{9} > \frac{R}{2}$$

$$\Leftrightarrow (1-\hat{s})s_H\,(2K+3\varepsilon) - (1-s_H)\hat{s}(2K-\varepsilon) > \frac{9R}{2\varepsilon}$$

$$\Leftrightarrow (s_H - \hat{s})2K + (3s_H + \hat{s} - 4s_H\hat{s})\varepsilon > \frac{9R}{2\varepsilon}$$

$$\Leftrightarrow (s_H - \hat{s})\frac{K}{2} + (s_H(1-\hat{s}) - \frac{(s_H - \hat{s})}{4})\varepsilon > \frac{9R}{8\varepsilon}$$

Combining the above we get the result.

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