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R&D COOPERATION IN EMERGING INDUSTRIES, ASYMMETRIC INNOVATIVE CAPABILITIES AND RATIONALE FOR TECHNOLOGY PARKS

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Abstract

Starting from the premise that firms are distinct in terms of their capacity to create innovations, the present paper explores the rationale for R&D cooperation and the choice between alliances that involve information sharing, cost sharing or both. Defining innovative capability as the probability of creating an innovation, it examines firm strategy in a duopoly market, where firms have to decide whether or not to cooperate to acquire a fixed cost R&D infrastructure that would endow each firm with a firm-specific innovative capability. Furthermore, since emerging industries are often characterized by high technological uncertainty and diverse firm focus that makes the exploitation of spillovers difficult, the paper focuses on a zero spillover context. It demonstrates that asymmetry has an impact on alliance choice and social welfare, as a function of ex-post market competition and fixed costs of R&D. With significant asymmetry no alliance may be formed, while with similar firms the cost sharing alliance is dominant. Finally it ascertains the settings under which the equilibrium outcome is distinct from that maximizing social welfare, thereby highlighting some conditions under which public investment in a technology park can be justified.

Keywords: R&D competition, R&D cooperation, technology parks.

JEL Classification: L1, L24, L5

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1. INTRODUCTION

While cooperation at the production and marketing stages between firms is nothing new, since the 1980's it is increasingly observed that firms competing in the same market are initiating alliances at the research and development (R&D) stage. This phenomenon is particularly significant in the knowledge-intensive sectors like telecommunications, microelectronics, new materials and biotechnology as well as in emerging ones using nanotechnology. Growing costs, increasing technological uncertainty and increasing complexity of commercialization of innovations are said to be fueling the phenomenon of R&D cooperation. Governments of developed and developing countries have also started investing in science and technology parks to support entrepreneurship, R&D cooperation and innovation creation. However, most of the literature examining R&D cooperation considers only symmetric firms. Clearly, the assumption of homogeneous firms is unrealistic, especially in emerging or fast evolving markets, which are shaped by innovation created by a variety of firms. Therefore, starting from the premise that firms are distinct in terms of their capacity to create innovations, the present paper attempts to explore how firms choose between different forms of R&D cooperation and their consequences for social welfare. It also identifies the conditions under which public investment in technology parks can be justified as a means to promote R&D cooperation in order to maximize social welfare.

Public investment in the creation of 'innovation intense environments' including science or technology parks, science cites or technopolises is driven by a desire to build national competitive advantage in the face of globalization by providing infrastructural facilities that encourage new product innovation, incubation of new technology based firms, knowledge spillovers and construction of inter-firm or public-private networks (see Phillimore and Richard (2003) for history and survey of technology parks). It is clear that if markets by themselves provide sufficient incentives for the formation of R&D alliances between a variety of firms, there is no need for public investment in technology parks. Indeed, public investment becomes necessary only if the social welfare generated by an R&D alliance is positive in a setting where the market fails to provide enough incentives for the formation of the R&D alliance in the first place. What does the existing industrial organization theory say about the conditions under which the above holds?

While there are no game theoretic articles that have examined the rationale for technology parks per-se, there is an extensive literature on the market conditions under which it is in the interests of firms to initiate R&D cooperation. However, this stream mainly treats the context of markets with symmetric firms. Stimulated by the seminal papers of Arrow (1962), Katz (1986), D'Aspremont and Jacquemin (1988) and Kamien, Muller and Zang (1992), there exists an extensive literature that examines the impact of knowledge spillovers between symmetric firms in a variety of contexts, such as with deterministic R&D, stochastic R&D, different degrees of market competition, different configurations of production costs, varying degrees of efficiency of R&D in the creation of product or process innovations (see Cabon-Dhersin and Ramani (2005) for survey). They yield two central results on symmetric markets. First, when spillovers are high, R&D cooperation is more beneficial than R&D competition for both firms and society. Second, when both information and costs of R&D are shared and coordinated, the alliance yields a higher payoff for both firms and society, than if only information or only costs are shared. Therefore, in symmetric markets whenever spillovers are high, private incentives are likely to be sufficient for the formation of technology parks and no public investment can be justified.

What about the more realistic context of asymmetric markets? There are two streams of literature that have attempted to explore this scenario[1]. The first examines how heterogeneity emerges ex-post, given homogeneous firms ex-ante, in the context of R&D investment. Mill and Smith (1996) relate non-convexity in technology choices to uncertainty about demand or costs; while Amir and Wooders (1999) show that one-way spillovers can lead to different R&D investments among firms as a function of R&D costs and degree of spillovers. Finally Van Long and Soubeyran (1999) demonstrate that if a mean preserving increase in the variance of the distribution of unit production costs can increase the profit of the group through differential R&D spreading, then asymmetry can also emerge. Kamien and Zang (2000) examine the case where firms choose their "absorptive capacity" to learn from spillover-pools and to contribute to spillover-pools. Again, R&D cooperation emerges as the attractive option whenever spillovers are high. Though these results are interesting in themselves, it is difficult to draw any definite conclusions on the rationale for public investment in technology parks from them.

A second stream examines the incentives for R&D alliances between asymmetric firms, but there is no consensus in the results. Some authors consider asymmetry to play a positive role in the formation of R&D alliances. Veugelers and Kesteloot (1996) consider firms engaged in cost reducing R&D, which could be asymmetric in terms of production costs, R&D investment and absorptive capacities but are symmetric in terms of opportunism. They find that asymmetries are important for successful joint ventures because when synergy yields are high, unequal bargaining shares compensate for incentives to cheat. Poyago-Theotoky (1997) studies an n-firm market with specialist and non-specialist firms, where the specialist firms can improve upon some of the characteristics of the good through R&D and she shows that depending on the extent of quality improvement R&D cooperation may or may not be socially desirable though it is always beneficial to firms.

In contrast to the first set of authors, some others find asymmetry between firms to be a constraint for the formation of R&D alliances. Petit and Tolwinski (1999) base their analysis on the assumption that a firm's potential for innovation depends not only on its current investment in R&D but also its accumulated R&D investment over time. Then different R&D investment trajectories lead to different production costs and R&D alliances are not formed if the firms are very heterogeneous. Chaudhuri (1999) considers asymmetry in terms of cost of making the R&D effort and shows that increase in a mean preserving spread of costs can increase the probability of success as the more efficient firms invest more to make up for the free-riding by the less efficient firms. However, since this leads to lower R&D investment than outright mergers, he concludes that R&D collaboration is unlikely to occur if firms are very dissimilar. Aloysius (2002) considers a cooperative game theoretic model and shows that asymmetries in terms of ability to fund, market power and technological capital can also bar R&D cooperation.Cabon-Dhersin and Ramani (2005) consider firm asymmetry in terms of propensity for opportunism. They show in a population with opportunist and non-opportunist firms, for any given level of spillover there is an upper limit to the number of opportunist firms beyond which R&D cooperation will not be initiated and this upper limit goes up with

[1] A third stream has studied the presence of asymmetric strategies within R&D alliances formed of symmetric firms in terms of opportunism, where firms do not respect their commitments in terms of R&D effort or do not truthfully reveal some information pertinent to the alliance. Some models resolve the problems of moral hazard and adverse selection by the formulation of revelatory mechanisms, complete optimal contracts or incentive schemes that render cooperation attractive (see Veugelers (1998); and Sena (2004) for surveys).

the degree of spillovers. Roller et al. (2007) extend the d'Aspremont and Jacquemin model of collaboration in cost reducing R&D to incorporate asymmetry in terms of different ex-ante marginal costs of production and they show that under both Cournot and Bertrand competition, significant asymmetry can lead to non-formation of alliances and cost-sharing is imperative to providing an incentive to collaborate.

Clearly, while the theoretical literature presents some justification for public investment in technology parks in order to promote R&D cooperation between asymmetric firms, it is silent on which modes of R&D cooperation are most likely to emerge between asymmetric firms and whether such equilibrium outcomes will be welfare-maximizing. In this context, the present paper makes a contribution to this third and last stream of literature with its consideration of three features (zero spillovers, bargaining over cost-sharing, asymmetric innovative capabilities) and its results on R&D cooperation between asymmetric firms.

Against the back-drop of the well known result that R&D cooperation is beneficial to symmetric firms when spillovers are high, the present paper explores if there is any incentive for R&D cooperation in the opposite extreme context of zero spillovers between asymmetric firms. Zero-spillovers are likely to hold in niches of emerging industries with high technological uncertainty and diverse firm technology focus. This could also occur if the adsorptive capabilities of firms do not match the spillovers present so that they cannot be integrated into the production process. This assumption also rings true in the case of innovations where knowledge spillovers are generated after commercialization rather than during the process of innovation creation.

Secondly, innovation creation is not considered as a deterministic process, but as a stochastic process, whereby at a given time period considered, firms are endowed with different innovative capabilities as a function of their historical trajectories.

However, stochastic innovation with asymmetric firms introduces some additional complexities. For instance, whenever the R&D cooperation chosen by the two firms involves cost-sharing, it brings into play a direct bargaining between the firms on how the share the R&D costs given asymmetric capabilities. This is in keeping with reality where firms negotiate on the terms of R&D cooperation before implementation.

To deal with the above, the present paper develops a model of a winner-takes-all R&D race in a duopoly setting. It considers two firms which are faced with the choice of investing a fixed sum in the creation or acquisition of an R&D infrastructure. Given exogenous factors such as the managerial vision and the historical trajectory of the firm, acquisition of the same R&D infrastructure gives rise to distinct firm-specific innovative capabilities. Since there are no spillovers, the innovative capabilities of the two firms are independently determined. If one of the firms succeeds then it becomes a monopolist and if both firms succeed, then the market remains a duopoly.

The R&D race is then modelled as a two stage game. In the first stage the firms decide whether to invest in the fixed-cost R&D infrastructure alone or in one of three possible alliances with the other firm or abandon the prospects of R&D altogether. Any alliance is initiated only if both firms find it in their interest to cooperate. The three standard modes of cooperation are: sharing of information only, sharing of the fixed costs only and sharing of both the fixed costs and information. Whenever the alliance chosen by the two firms involves cost sharing, the two firms enter into a second stage in which they bargain on the ratio in which the fixed cost is to be shared given their innovative capabilities.

The contribution of the results derived from the above model to the existing industrial organization literature on R&D collaboration between asymmetric firms can then be understood in terms of its five central results.

First, the model shows that firms which are close in terms of their innovative capability have a greater propensity to form an R&D alliance than asymmetric firms, thereby confirming an observation that has been repeatedly made in the empirical literature (Veugelers (1998); Miotti and Sachwald (2003); de Man and Duysters (2005); Lopez (2008)).

Second, the paper confirms another finding noted in several empirical analyses that the most frequently observed form of cooperation involves only cost sharing (Miotti and Sachwald, (2003); de Man and Duysters, (2005)). The model indicates that this could be the case because cost-sharing alliances tolerate a greater degree of asymmetry than other forms of cooperation.

Third, it proposes an explanation for the non-pervasiveness of R&D alliances. Theoretical models considering symmetric firms have shown that cooperation is beneficial to firms under many different situations, so that one is led to expect that cooperation at the R&D level will be a pervasive phenomenon. However this is not the case. Even in high tech sectors where R&D strategic alliances are more prevalent, cooperation at the R&D level is more the exception than the rule. We show that significant asymmetry in innovative capabilities could be a cause of the problem.

Four, the model provides a rationale for public investment in science and technology parks for the hi-tech sectors. A social welfare ranking of the R&D alliances according to our model confirms the standard result that a cost cum information sharing alliance is best for society. However, we also show that under certain conditions involving combinations of high asymmetry in firm capabilities as well as high innovation profit and fixed costs, no R&D alliance will be formed. Therefore, in the face of such contradictions between social choice and private choice, public investment promoting collaboration is called for.

Five, it also refines some standard theoretical results. For instance, an established result is that R&D competition yields highest payoffs to firms when spillovers are low. However, we show that in the context studied with zero spillovers, although R&D competition always dominates an information sharing alliances, with asymmetry there are parameter configurations where a cost sharing alliance and a cost cum information sharing cartel dominate R&D competition.

The rest of the paper is organized as follows. Section 2 presents the model. Then section 3 compares payoffs from R&D competition and the three R&D alliances, and this is followed by section 4, which examines firm preferences for R&D collaboration, social welfare ranking and implications for investment in technology parks. Section 5 concludes.

2. THE MODEL

Consider a duopoly market with two firms *i* and *j*. With a fixed investment of F the two firms *i* and *j* can create a product innovation with probabilities p_i and p_j respectively. The fixed investment of F could represent recruitment of new researchers, purchase of new machinery, purchase of licenses, installation of a new lab etc. Development of asymmetric innovative capabilities given symmetric R&D investments is justified by the hypothesis that while two firms may have the same cost of production ex-ante, they almost never have identical histories, knowledge portfolios or managerial vision. Therefore, the acquisition of the same infrastructural base can give rise to distinct firm specific dynamic innovative capabilities[2]. There are no spillovers or learning externalities in the market and hence the probabilities p_i and p_j are independent of one another. In this paper, for simplicity we consider $p_i \geq p_j$. Any firm that creates the innovation first becomes a monopolist earning π_m. If both firms manage to create the innovation simultaneously, then each earns the duopoly Cournot-Nash profit of π_d .

In the above context, suppose the two firms *i* and *j* play a two-stage game. In the first stage, each firm either chooses one of the following four organizational modes to undertake the R&D outlay *F* or the firm chooses not to undertake the R&D outlay at all.

i. *R&D competition*: The firms do not share the R&D costs *F* or the R&D findings.

ii. *Cost sharing alliance (CSA):* The two firms agree upon a sharing arrangement for the fixed costs *F*. Since knowledge can be replicated costlessly, the two firms exploit their knowledge input separately thereafter. Thus, in a cost sharing alliance, cost savings are achieved through non-duplication of the efforts required to produce the knowledge input at the pre-competitive stage.

iii. *Information sharing alliance (ISA)*: The firms invest in *F* separately but share their R&D findings so that the probability of creating the innovation is maximized.

iv. *Cost and information sharing alliance (CISA)*: The firms share both the cost *F* and the R&D findings so that there are cost economies and with their combined innovative capabilities the probability of creating an innovation is maximized.

It is to be noted that in the existing literature the different forms of R&D cooperation have been called differently and therefore to avoid all confusion we distinguish the different forms of R&D cooperation in terms of what is being shared by the two firms[3].

If both firms choose the same mode of cooperation, then an R&D alliance is initiated. Furthermore, if the R&D alliance chosen involves cost-sharing, then the two firms enter into a second stage, where they bargain over the ratio in which to share the costs. Then the game ends. All parameters of the game are common knowledge.

Given these three possible options for R&D cooperation, in what follows, we examine the following questions. Under what conditions will an R&D alliance be initiated by the firms? For which innovative competency profiles will each kind of R&D alliance be initiated? What is the maximum degree of asymmetry between the competencies that can be tolerated under the three different kinds of R&D alliances? The answers in turn permit us to make inferences on the role of public policy to promote innovation through collaboration.

3. RESULTS ON R&D COMPETITION AND R&D ALLIANCES

We proceed in two steps. First, we identify the capability profiles under which firms will engage in R&D competition as a function of the given parameters. In other words, we highlight the parameter configurations under which abandoning R&D will be a dominated strategy for

[2] See Athreye, Kale and Ramani (2008) for examples of this phenomenon in the Indian pharmaceutical industry.
[3] For example, Kamien, Muller and Zang (1992) use 'RJV cartel' and 'R&D cartel' respectively to refer to CISA and CSA forms of collaboration.

either of the firms. Thereafter, restricting our attention solely to the set of capability profiles under which R&D competition occurs, we examine firm preferences between R&D competition and each form of R&D cooperation.

3.1 *R&D Competition*

In the absence of collaboration, the expected profit of any firm i from R&D investment is $\pi_i^{nc} = p_i(1-p_j)\pi_m + p_i p_j \pi_d - F$. Firm i can either be the only innovator and earn the monopoly profit π_m with a probability $p_i(1-p_j)$ or both firms can be successful and earn the duopoly profit π_d with a probability $p_i p_j$. Whenever firm j alone succeeds, firm i is left out of the market.

Clearly, a firm will undertake R&D investment in the first place only if it anticipates earning positive payoffs. Furthermore, it can be easily shown that when $p_i = p_j$, $\pi_i^{nc} = \pi_j^{nc}$ and when $p_i > p_j$, $\pi_i^{nc} > \pi_j^{nc}$. Therefore, to identify the condition under which R&D competition can occur, i.e. when both firms will invest in R&D, it is sufficient to check if the less capable firm j incurs R&D expenditure in each of the cases. If $\pi_j^{nc} > 0$ and firm j decides to incur the R&D expenditure, it must follow that firm i does likewise. This leads to our first proposition on the necessary conditions for R&D competition.

PROPOSITION 1: *Conditions for R&D competition as a function of the firm capabilities, R&D cost and market returns*

(i) *Whatever the technological capabilities of the firms if* $F \geq \frac{\pi_m^2}{4(\pi_m - \pi_d)} > \pi_d$, *there is no R&D competition.*

(ii) *If* $p_j < p_i = p$ *and* $\frac{\pi_m^2}{4(\pi_m - \pi_d)} > F > \pi_d$, *there exists capability levels* $\hat{p}, \hat{\hat{p}}$ *with* $\hat{p} < \frac{\pi_m}{2(\pi_m - \pi_d)} < \hat{\hat{p}}$, *such that for* $p_i = p \in (\hat{p}, \hat{\hat{p}})$ *and* $p_j \in (\frac{F}{(1-p)\pi_m + p\pi_d}, p)$ *there is R&D competition. Similarly, if* $p = p_i = p_j$ *there is R&D competition when* $p \in (\hat{p}, \hat{\hat{p}})$.

(iii) *If* $p_j < p_i = p$ *and* $\frac{\pi_m^2}{4(\pi_m - \pi_d)} > \pi_d \geq F$, *there exists a capability level* $\overline{p} < \frac{\pi_m}{2(\pi_m - \pi_d)}$, *such that for all* $p_i = p \in (\overline{p}, 1)$ *and* $p_j \in (\frac{F}{(1-p)\pi_m + p\pi_d}, p)$ *there is R&D competition. Similarly, if* $p = p_i = p_j$ *there is R&D competition when* $p \in (\overline{p}, 1)$.

(iv) *As F falls, the interval* $(\hat{p}, \hat{\hat{p}})$ *and the interval* $(\overline{p}, 1)$ *expand.*

Proof. The full details are given in the appendix. Here we give the intuition behind the proof. Part (i) is evident. Given any configuration of firm capabilities and innovation profit, R&D investment can be undertaken only if R&D outlay can be recuperated in the post-innovation period.

Coming to parts (ii)-(iv), it is clear from the outset that when the R&D expenditure is fixed and certain at *F*, but the returns from such investment are uncertain being dependent on firm capabilities, there is a trade off between the firm capability levels and the magnitude of R&D expenditure. There is R&D competition with both firms engaging in an R&D race only if the innovative capabilities of both the firms are sufficiently high as compared to the size of *F*. Thus proposition 1 reveals that as *F* increases, the minimum capabilities required to support the fixed costs while anticipating positive profit increases. In the case of symmetric firms, for example, R&D competition takes off at capability levels $p \in (\overline{p},1)$ when $F \leq \pi_d$ but when $\pi_d < F < \frac{\pi_m^2}{4(\pi_m - \pi_d)}$ the range of capability levels shrinks at the upper end to $p \in (\hat{p}, \hat{\hat{p}})$.

When capabilities are asymmetric, it can be observed from the definition of π_i^{nc} that an R&D investment yields either an expected monopoly profit of $p_i \pi_m$ or an expected loss of $p_i p_j (\pi_m - \pi_d)$. For higher capability levels of the rival, the expected loss increases while the expected gain remains the same. Therefore, it follows that for a higher value of *F*, a more capable rival will discourage a lower ability firm from undertaking the R&D investment as its expected loss will outweigh its expected gain. In other words, a lower ability firm will not invest in R&D unless its more efficient rival (having its capability level p) is not too efficient as compared to its own capability level i.e. $p_j \in (\frac{F}{(1-p)\pi_m + p\pi_d}, p)$.

In the remainder of the paper, in order to facilitate the comparison of payoffs under R&D competition and R&D cooperation, we restrict our attention to parameter configurations under which both firms engage in R&D competition anticipating payoffs of $\pi_i^{nc} > 0$ and $\pi_j^{nc} > 0$ respectively[4]. In particular, we make the following assumption for the rest of the paper[5]:

[4] In some forms of collaborations like the cost-sharing alliance and the CISA as the fixed cost of producing the knowledge input gets shared, some firms which do not participate in R&D competition may turn out to be willing to participate in the collaborations. Even if we consider them, their ranking over the alternative forms of collaboration would be the same as in the case considered in the paper and the basic results would remain unchanged.

[5] Similar arguments can be applied to the case where $\pi_d < F < \frac{\pi_m^2}{4(\pi_m - \pi_d)}$ and the nature of the results remain unchanged.

Assumption 1: The configuration of required R&D outlay F, market profits π_m, π_d, and firm capabilities p_i and p_j are such that R&D competition prevails with $F \leq \pi_d$, i.e. the conditions (iii) of proposition 1 hold.

Given the above (proposition 1 and assumption 1) R&D competition becomes the default organizational mode whenever collaboration does not take off.

3.2 *The Cost Sharing Alliance*

The benefit of a cost sharing alliance is that the fixed cost F can be shared between the firms, say as αF for firm i, and $(1-\alpha)F$ for firm j, where $\alpha \in (0,1)$. Cost savings are achieved through non-duplication of efforts required to produce the knowledge input at the pre-competitive stage, but the probability of success at the development stage remains unchanged. Let us represent the payoff from a cost sharing alliance for the ith firm and the jth firm by the pair (π_i^c, π_j^c). Then by the above argument $\pi_i^c = p_i(1-p_j)\pi_m + p_i p_j \pi_d - \alpha F$ and $\pi_j^c = p_j(1-p_i)\pi_m + p_i p_j \pi_d - (1-\alpha)F$.

In a cost sharing alliance, the firms bargain over the cost sharing ratio α. Under the Nash-bargaining setting[6], the disagreement payoffs are evidently the R&D competition payoffs $\pi_i^{nc} > 0$ and $\pi_j^{nc} > 0$ (under conditions of assumption 1). Then the cost-sharing ratio that will prevail at equilibrium is given by the following proposition.

PROPOSITION 2: *(i) For all configurations of costs, payoff structure and innovative capabilities, at equilibrium each firm will bear 50% of the fixed costs F.*

(ii) Whenever R&D competition is possible, a cost sharing alliance will be preferred to R&D competition.

Proof. Applying the Nash-Bargaining solution to this context, the cost sharing ratio α emerges as the ratio that maximizes the product of the net gains from bargaining for the partner firms. In other words, maximizing $[(\pi_i^c - \pi_i^{nc})(\pi_j^c - \pi_j^{nc})]$ with respect to α yields the cost sharing ratio as $\alpha = \frac{1}{2}$ for all capability configurations of the two firms.

The interesting point to note in the above exercise is that usually varying the disagreement points changes the outcome of the bargaining process, because the gains from negotiation change as the disagreement points change. However, in our case, the gains from negotiation, in terms of cost savings are totally independent of the disagreement points. Hence, the 50% share is the only ratio that satisfies the Nash bargaining solution criteria of equal sharing of surplus generated by the cost sharing alliance. With this ratio, the equilibrium payoff of the firms in the cost-sharing collaboration becomes:

[6] A number of endogenously determined cost-sharing rules are possible. In the present context, given that it is a pure bargaining problem, the simple Nash bargaining solution has been considered.

$$\pi_i^c = p_i(1-p_j)\pi_m + p_i p_j \pi_d - \frac{1}{2}F \text{ and } \pi_j^c = p_j(1-p_i)\pi_m + p_i p_j \pi_d - \frac{1}{2}F .$$

Clearly, the two firms will participate in a cost sharing alliance only if they earn more than under R&D competition or the following participation constraints are satisfied:

$$\pi_i^c > \pi_i^{nc} . \quad (1)$$

$$\pi_j^c > \pi_j^{nc} . \quad (2)$$

From the definitions of $\pi_i^c, \pi_j^c, \pi_i^{nc}$ and π_j^{nc} it follows that inequalities (1) and (2) will hold if and only if the following inequalities hold:

$$(1-\alpha)F > 0. \quad (3)$$

$$\alpha F > 0. \quad (4)$$

It can be easily observed that at equilibrium, with $\alpha = \frac{1}{2}$, whatever the innovative capabilities of the firms, under the conditions of our assumption, the participation constraints given by inequalities (3) and (4) are satisfied for both firms.

3.3 *The Information Sharing Alliance*

In an information sharing alliance, R&D findings are shared, which means that if one of the firms discovers the new product, in no time the other firm can launch an almost identical product. Thus, the new product can be launched if either of the two firms makes the discovery. Sharing of information at the development stage reduces the probability of failure in R&D, as the innovative capability of the research joint venture becomes $1-(1-p_i)(1-p_j) = p_i(1-p_j) + p_i p_j + p_j(1-p_i)$, which is greater than either of the individual capabilities of the two firms p_i or p_j. However, if successful, both the firms will launch the innovation jointly in the market earning the duopoly profit, π_d. Thus, for any firm *i*, the expected profit from an information sharing alliance is $\pi_i^i = (1-(1-p_i)(1-p_j))\pi_d - F$. Again, an information sharing alliance will be formed only if both the firms can earn more than they could obtain under non-collaboration or R&D competition, i.e. if and only if the respective participation constraints given by $\pi_i^i > \pi_i^{nc}$ and $\pi_j^i > \pi_j^{nc}$ are satisfied as given below:

$$(p_i + p_j - 2p_i p_j)\pi_d > p_i(1-p_j)\pi_m . \quad (5)$$

$$(p_i + p_j - 2p_i p_j)\pi_d > p_j(1-p_i)\pi_m . \quad (6)$$

Under which capability configurations will the above two conditions be satisfied? This is revealed in the next proposition.

PROPOSITION 3: *Whatever the configuration of innovative capabilities of the two firms, an information sharing alliance will never be formed.*

Proof. With the full proof in the appendix, the intuition behind proposition 3 can be outlined as follows. Each firm considers the possibility of sharing information to insure itself against being thrown out of the market, in case its rival creates the innovation while it does not. However, there is a price for this option. By sharing information both firms reduce their chance of failure in the R&D competition, but by doing so they also completely forego the chance to capture the monopoly rent π_m. Information sharing leads to launching almost identical products at the market almost at the same time whereby each firm earns the duopoly profit π_d. From standard oligopoly theory we know $\pi_m > 2\pi_d > \pi_d$. Therefore, if the firms are symmetric i.e. no one has advantage over the other in R&D, it can be shown that for individual firms the opportunity cost of missing out on monopoly rent is greater than the expected profit from participation in the alliance even though the probability of failure reduces with the alliance. Hence, the alliance is not formed.

When the firms are asymmetric, the non-formation of an information alliance can be explained similarly. The more capable firm is dissuaded from entering into an alliance because its probability to succeed is higher and it sees no point in foregoing the monopoly rent by forming an alliance that could lower its profit drastically. The inefficient firm in this situation facing the odds against its success in the R&D competition, may be willing to participate in the alliance as it provides an insurance against exclusion from the monopoly rent which is imminent, but its proposal is declined by the more capable firm. Therefore, in this case also, the information sharing alliance is not formed.

3.4 *Cost and information sharing alliance or CISA*

Let the expected payoffs from a CISA, representing cooperation on all aspects of R&D, be given by π_i^r and π_j^r respectively such that:

$$\pi_i^r = (1-(1-p_i).(1-p_j))\,\pi_d - \alpha F \text{ and } \pi_j^r = (1-(1-p_i).(1-p_j))\,\pi_d - (1-\alpha)F .$$

Furthermore, in the bargaining on cost sharing, given the disagreement payoffs $\pi_i^{nc} > 0$, $\pi_j^{nc} > 0$ the Nash Bargaining solution[7] α^* emerges as :

$$\alpha^* = Max\left\{0, \frac{1}{2} - \frac{\pi_m(p_i - p_j)}{2F}\right\} . \tag{7}$$

The CISA will be preferred over R&D competition, if and only if at α^*, the participation constraint of the *i*th firm, $\pi_i^r > \pi_i^{nc}$, and that of the *j*th firm, $\pi_j^r > \pi_j^{nc}$, are satisfied. In other words, a CISA is formed if and only if the following inequality holds:

$$F > (p_i + p_j - 2\,p_i\,p_j)(\,\pi_m - 2\pi_d\,). \tag{8}$$

[7] When $\frac{1}{2} - \frac{\pi_m(p_i - p_j)}{2F}$ is negative then the R&D outlay will be entirely borne by the less efficient firm *j*.

Since $\pi_m > 2\pi_d$, and $p_i + p_j - 2\, p_i\, p_j = [p_i\,(1-p_j) + p_j\,(1-p_i)] > 0$, the right hand side of inequality (8) is positive, which means that a CISA will be initiated only if the fixed costs of R&D investment are sufficiently high. Here, the question that can be raised is: does the degree of technological asymmetry play any role in initiating a CISA? The answer is provided in the next proposition.

PROPOSITION 4: *(i) A CISA will always be preferred to R&D competition if the R&D outlay, F, is greater than* $\left(\pi_m - 2\pi_d \big/ 2\right)$*, whatever the degree of asymmetry.*

(ii) When $F < \left(\pi_m - 2\pi_d \big/ 2\right)$ *a CISA will be initiated always if firms have very high innovative capabilities and limited asymmetry. However, for very small F, a CISA may also be formed if firms have low innovative capabilities with limited asymmetry.*

Proof. The appendix contains the formal presentation of the proposition and the proof. The insight behind the first part of the above proposition is as follows. If the fixed cost of R&D is high and the monopoly profit to be earned from the development of the new product is low, the opportunity cost of forfeiting the monopoly profit is low, while the benefit from sharing of the fixed cost of the knowledge input is high. Hence, a CISA is more attractive. However, for higher monopoly profit, the cost of information sharing may outweigh the benefit of cost sharing, and therefore, participation in the CISA may turn out to be an unattractive option depending on the configuration of firm capabilities. For instance, if firm capabilities are not high, by sharing information, they do not lose much, as the probability of new discovery on their own is fairly low, and furthermore if the fixed cost of R&D is high, the benefit of cost sharing is also high. Therefore, low capability firms will prefer a CISA under these conditions. On the other hand, if the firms are highly capable (i.e. p is in the neighbourhood of 1), in the absence of information sharing, an individual firm fears market exclusion as its rival could succeed with a high probability. Here participation in the CISA provides insurance against possible market exclusion, and benefits from cost sharing exceed the lowering of innovation rent due to information sharing, leading firms to initiate a CISA.

The second part of the proposition indicates that if the innovative capability of the relatively efficient firm itself is low and the asymmetry is limited, then the firms will form a CISA. Other than the cost sharing advantage, a CISA permits the relatively inefficient firm to increase its chances of success by collaborating with the more efficient firm. On the other hand, the more capable firm, not being too efficient itself does not lose much by sharing its R&D findings with the partner firm as this is compensated by gains from the cost sharing. Again, if both firms are very capable, then they initiate a CISA to avoid market exclusion in the post-innovation period.

In contrast to this, as asymmetry increases, the less capable firm is always willing to join the CISA as it benefits from sharing information (and is otherwise likely to lose out in R&D competition), but the more capable firm may not agree so easily. The more capable firm knows that even if it does not join the CISA and does not share the information, it will not lose much since the probability of its rival discovering the product is low and consequently its risk of market exclusion is also low. Therefore, a CISA is not formed.

The intuition described above is also illustrated in the following simulations.

TABLE 1: Profit under non-cooperation and CISA

F	p_i	p_j	c_i	c_j	π_i^{nc}	π_j^{nc}	π_i^r	π_j^r
50	0.9	0.9	25	25	58	58	74	74
50	0.9	0.8	10	40	76	46	88	58
50	0.9	0.5	0	50	130	10	95	45
50	0.9*	0.3*			166	-14		
50	0.3	0.25	17.5	32.5	25	10	30	15
50	0.3*	0.2*			28	-2		
50	0.55	0.3	0	50	82	7	68.5	18.5
50	0.5	0.5	50	50	25	25	50	50

$\pi^m = 300$; $\pi^d = 100$; *cases where R&D competition is not possible;

c_i and c_j are the costs borne by the firms *i* and *j* in the CISA.

Table 1 presents simulations corresponding to a context where $F < \pi_m - 2\pi_d$. As can be seen, for high and low capability profiles of both firms, as long as asymmetry is limited, a CISA dominates non-cooperation. However, there are capability profiles (e.g. p_i=0.55 and p_j=0.3) when a CISA cannot be formed because the more capable firm prefers to compete alone. It can also be noticed that for low capabilities, the *j*th firm cannot engage in R&D competition and therefore such cases are not considered for comparison.

4. PRIVATE VS PUBLIC CHOICE AND RATIONALE FOR TECHNOLOGY PARKS

In the preceding sections we compared the returns from each of the three forms of R&D cooperation with R&D competition and identified the conditions under cooperation will be preferred to competition. Now, we turn to the first stage of the game where the two firms come together to choose between R&D competition and one of the three forms of R&D cooperation (non-investment being a dominated strategy given assumption 1). We first examine the equilibrium choice of the firms, and then we rank the choices according to social welfare in order to explore the rationale for public investment in technology parks.

4.1 *Firm choice among the R&D alliances*

From propositions 1-4, we know that the choice will lie essentially between a CISA and a cost sharing alliance. In fact, whenever the CISA is possible, the cost sharing alliance is also possible, though the converse need not be true. This leads us to the question: If both a

CISA and a cost sharing alliance are possible for a firm, which would be preferred? We answer this question in the next proposition.

PROPOSITION 5: *Given the choice between the formation of the CISA and the cost sharing alliance, if the firms are not too asymmetric in terms of their innovative capability, the cost sharing alliance will be preferred to the CISA. If the firms are very asymmetric, and the monopoly profit is high, then the less capable firm may prefer the CISA to the cost sharing alliance, while the more capable firm will prefer the opposite. In this case no alliance will be formed.*

Proof. Whenever the technological competencies are not too asymmetric so that α lies strictly between 0 and 1 in a CISA, then it is easy to show that for firm *i*:

$$\pi_i^c \geq \pi_i^r \Leftrightarrow (p_j + p_i - 2p_i p_j)(\pi_m - 2\pi_d) > 0. \tag{9}$$

Since $(\pi_m - 2\pi_d) > 0$ and $(p_i + p_j - 2p_i p_j) > 0$, equation (9) always holds. The argument can be derived similarly for firm *j*. Hence, both firms will always prefer the cost sharing cartel when technological asymmetries are not too great.

Now consider the situation when technological asymmetries and π_m are so great such that the cost of R&D is entirely borne by firm *j*, i.e. $\alpha = 0$. Then, firm *i* will prefer a cost sharing cartel if:

$$\pi_i^c = \left[p_i(1-p_j)\pi_m + p_i p_j \pi_d - \frac{F}{2} \right] \geq \pi_i^r = (p_i + p_j - p_i p_j)\pi_d$$

$$\Leftrightarrow p_i(1-p_j)\pi_m - \frac{F}{2} > (p_i + p_j - 2p_i p_j)\pi_d$$

Firm *j* will prefer a CISA if :

$$\pi_j^c = \left[p_j(1-p_i)\pi_m + p_i p_j \pi_d - \frac{F}{2} \right] \geq \pi_j^r = (p_i + p_j - p_i p_j)\pi_d - F$$

$$\Leftrightarrow p_j(1-p_i)\pi_m + \frac{F}{2} < (p_i + p_j - 2p_i p_j)\pi_d$$

It is easy to show that when both these conditions hold then $(p_i - p_j)\pi_m \geq F$, which indicates that there is a contradiction of preferences only when monopoly profit is very high and the technological asymmetries are also very high.

The proposition is also illustrated by the simulations given in table 2.

TABLE 2: Profit under R&D competition and different forms of R&D cooperation

p_i	p_j	π_i^{nc}	π_j^{nc}	c_i	c_j	α	π_i^i	π_j^i	π_i^c	π_j^c	π_i^r	π_j^r
0.90	0.90	58.00	58.00	25.00	25.00	0.50	49.00	49.00	83.00	83.00	74.00	74.00
0.90	0.50	130.00	10.00	0.00	50.00	0.00	45.00	45.00	155.00	35.00	95.00	45.00
0.90*	0.30*	166.00	-14.00									

$\pi^m = 300$; $\pi^d = 100$; $F = 50$; *case where R&D competition is not possible;

c_i and c_j are the costs borne by the firms *i* and *j* in the CISA.

It can be noted from table 2, that for the given configuration, when both the firms are equally highly capable, they prefer to initiate a cost sharing alliance. However, when there is significant asymmetry the more capable firm gains more from a cost sharing alliance, while the less capable firm prefers a CISA. If both firms have equal bargaining powers, in this case, no alliance is likely to be initiated.

4.2 *Ranking according to Social Welfare*

There is a widespread acceptance that the State should encourage innovation through promoting cooperation between firms at the R&D level. In this case, which kind of R&D alliance should be promoted? In other words, can we rank the alternative R&D collaborations that private firms can form between themselves, in terms of the social welfare generated? How do the social benefits from the initiation of the three R&D alliances compare with that from R&D competition? In this section we try to answer these questions.

Suppose, the social surplus (defined as the sum of the consumer and the firms' surplus) is given by s_m if a monopoly is created in the market for the new product. Similarly, the social surplus is given by s_d, if a duopoly is created. From standard oligopoly theory we know that it is always the case that $s_d > s_m$. Then the expected social surplus of the society from the R&D competition is given by

$$S_{nc} = p_i(1-p_j)s_m + p_j(1-p_i)s_m + p_i p_j s_d - 2F .$$

Similarly, the social surplus from the cost sharing alliance, the information sharing alliance and the CISA are respectively given by:

$$S_c = p_i(1-p_j)s_m + p_j(1-p_i)s_m + p_i p_j s_d - F ;$$

$$S_i = p_i(1-p_j)s_d + p_j(1-p_i)s_d + p_i p_j s_d - 2F \text{ ; and:}$$

$$S_r = p_i(1-p_j)s_d + p_j(1-p_i)s_d + p_i p_j s_d - F .$$

PROPOSITION 6: *From the social welfare point of view, the CISA is preferable to both the cost sharing alliance and the information sharing alliance. Furthermore, having any form of R&D alliance is better than R&D competition.*

Proof. It follows clearly from the definitions that $S_r > S_i$. Therefore, society prefers the CISA to the information sharing alliance.

Comparing S_r and S_c it can be shown that:

$$S_r - S_c = [p_i(1-p_j) + p_j(1-p_i)](S_d - S_m) \quad (10)$$

Since $S_d > S_m$ and $p_i(1-p_j) + p_j(1-p_i) > 0$, from equation (10) it follows that $S_r > S_c$. Therefore, the statement in the first part of the proposition follows.

On the other hand, it can be seen from the definitions that since $S_d > S_m$, S_{nc} is smaller than either of S_c, S_i or S_r. Therefore, the statement of the second part of the proposition follows.

In other words, any of the three types of R&D alliances yields greater social welfare than R&D competition for either one or both of the following reasons: unlike in R&D competition, an R&D alliance eliminates duplication of fixed costs to acquire the knowledge input and any form of R&D cooperation creates a duopoly market for the innovation with a higher probability.

Furthermore, from the social welfare point of view, the CISA is preferable to the information sharing alliance because it prevents the duplication of the fixed cost of acquiring the knowledge input while yielding the same benefits (or costs) from information sharing. Similarly, even though the cost sharing rule is different in the cost sharing alliance and the CISA, the nature of the cost sharing benefits generated by the two alliances is the same and in addition, in the CISA, firms and society benefit from the sharing of R&D findings. Therefore, the CISA is preferred to either of the two alternative forms of alliances.

4.3 *Rationale for public investment in technology parks*

As may be recalled there is much in the theoretical literature that affirms the result that when spillovers are high R&D cooperation with both information and cost sharing is in the interest of both firms and society. Such findings support competition policy that permits cooperation at the R&D level, but they do not provide an explicit rationale for public investment in technology parks or R&D cooperation when spillovers are low. Technology parks are thus mainly viewed as a geo-political phenomenon, as public investment to build national competitiveness through promotion of innovation creation.

In contrast to the above, the results of section 4 indicate that public investment in technology parks may be worthwhile, especially in emerging industries, where innovation profit is high and creation of the innovation requires cooperation between different kinds of firms.

Proposition 5 indicates that when asymmetry between firms is high no R&D alliance might be formed because the CISA comes with a price tag of information sharing, especially for the firm which is more capable. In contrast, participation in the cost sharing alliance involves only benefit to both firms. Therefore, the more capable firm will prefer the cost sharing alliance to a CISA. However, the less capable firm will prefer the CISA to the cost sharing alliance because it benefits from both information sharing and cost sharing. Hence, no alliance will be formed and the two firms will continue to compete with each other as they were doing in the first place. Here a technology park might ease the constraints for R&D cooperation by providing other kinds of benefits either to the more capable or the less capable firm so that they cooperate.

Another policy inference is that according to proposition 3 among the different types of R&D alliances, pure information sharing alliances are least likely to be initiated on their own. Therefore, for life threatening problems like medicines for HIV/AIDS or strategic ones like energy, to speed up innovation, pure information research consortiums can also be promoted in technology parks in the name of corporate social responsibility or through publicly supported programs that require firms to cooperate by sharing information.

Proposition 2 suggests that firms always have an incentive to form a cost-sharing alliance, but we know that in reality strategic risks associated with any form of cooperation rules out even this form of cooperation from being omnipresent. Moreover proposition 6 demonstrates that any form of cooperation is better than R&D competition. Therefore, technology parks can be used to bring together firms by proposing policies like tax benefits or access to infrastructural facilities for members.

4. CONCLUSIONS

In a comprehensive survey of R&D collaboration, Veugelers (1998) insists that incentives for cooperation among asymmetric firms must be studied more because "Although the empirical analysis provides massive evidence of asymmetries between partners, the theoretical work has mostly concentrated on alliances between symmetric firms". In particular, firms are assumed to have the same innovative capabilities, which eliminates the need to examine one of the fundamental problems of R&D cooperation, namely that of "appropriate partner selection". Thus, in an attempt to contribute to a better understanding of R&D cooperation between asymmetric firms, this paper considered duopolistic firms of non-identical innovative competencies and examined the incentives for the formation of different kinds of R&D alliances. Firms had the option of either engaging in R&D competition or initiating an information sharing alliance, a cost sharing alliance or a CISA. Their choice was shown to depend on three factors: the degree of asymmetry of innovative capabilities between alliance partners, ex-post market competition and the magnitude of the fixed costs of R&D.

As has been noted in the introduction, though the theoretical literature extols the virtues of information cum cost sharing, the empirical literature finds much less cooperation at the R&D level than the theoretical literature would lead us to expect and that too mainly in terms of cost sharing. Our model confirms this result by showing that cost sharing may be more prevalent because it is beneficial to firms of any capability profile, while a CISA requires specific conditions for initiation (propositions 2 and 4). It also proposes that under significant asymmetry in innovative capabilities no alliance may be formed, especially if the monopoly profit is also significant (proposition 5). However, in terms of social welfare, any alliance is preferable to R&D competition and a cost cum information sharing alliance is the best (proposition 6). Thus, there is a rationale for public investment in technology parks to promote R&D cooperation especially when the competing firms are very asymmetric and the monopoly profit is high.

The present paper also provides two testable hypotheses that can be explored in future empirical studies. It indicates that outside of technology parks, R&D alliances are more likely to be initiated among firms of similar innovative capabilities; and secondly, among the different forms of R&D cooperation, the most prevalent will involve cost-sharing alone, followed by cost and information sharing and rarely pure information sharing.

The limitations of the paper must not be forgotten. Indeed these provide the ground for future theoretical extensions of the paper. We had considered the case of zero-spillovers as a point of departure because according to conventional theory R&D alliances are unlikely to be initiated then. The robustness of our results can be tested permitting for spillovers. We had made the simplifying assumption of fixed costs, which can be dropped also. Innovation profit can then be considered as a function of R&D effort and made endogenous to the game. Another possibility is to adapt the model to include other agents besides just competing firms. For instance, R&D cooperation in the high-tech sectors often involves public organizations as well as firms and cooperation can also be initiated between firms occupying different positions in the vertical product value chain (Belderbos et al. 2004a, 2004b). Finally, other types of bargaining solutions with different embedded bargaining powers may also be considered.

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APPENDIX

Proof of proposition 1.

Suppose, $p = p_i > p_j$, then $\pi_i^{nc} > \pi_j^{nc}$. Therefore, both firms enter into R&D competition if and only if $\pi_j^{nc} > 0$. From the definition of π_j^{nc}, it follows that this occurs if and only if :

$$p_j \in \left(\frac{F}{(1-p)\pi_m + p\pi_d}, p\right). \tag{A.1}$$

Furthermore, the given interval is non-empty only if $\frac{F}{(1-p)\pi_m + p\pi_d} < p$, which in turn implies:

$$f(p) = p^2 - \left(\frac{\pi_m}{\pi_m - \pi_d}\right)p + \frac{F}{\pi_m - \pi_d} < 0. \tag{A.2}$$

Observe that $f(p)$ is a continuous function over $p \in (0, 1)$. As $p \to 0$, $f(p) \to f(0) = \frac{F}{\pi_m - \pi_d}$ and as $p \to 1$, $f(p) \to f(1) = \frac{F - \pi_d}{\pi_m - \pi_d}$. Since $\pi_m > \pi_d$, $\frac{F}{\pi_m - \pi_d} > 0$ and $\frac{F - \pi_d}{\pi_m - \pi_d} >=< 0$ if and only if $F >=< \pi_d$.

The function $f(p)$ attains its minimum at $p_{\min} = \frac{\pi_m}{2(\pi_m - \pi_d)}$ and $f(p_{\min}) = \frac{4F(\pi_m - \pi_d) - \pi_m^2}{4(\pi_m - \pi_d)^2}$. Clearly, $f(p_{\min}) >=< 0$ if and only if $F >=< \frac{\pi_m^2}{4(\pi_m - \pi_d)}$.

Again, since $\pi_m > \pi_d$, it can be easily shown that $\frac{\pi_m^2}{4(\pi_m - \pi_d)} > \pi_d$.

Now we can check for R&D competition in three possible cases of R&D investment and profit configurations.

(i): $F \geq \dfrac{\pi_m^{\,2}}{4(\pi_m - \pi_d)} > \pi_d$. Here $f(p_{\min}) \geq 0$ and *f(1)> 0.* Furthermore, since *f(0)>0* always, the condition (A.2) is never satisfied for any technological capability $p \in (0, 1)$.

(ii): $\dfrac{\pi_m^{\,2}}{4(\pi_m - \pi_d)} > F > \pi_d$. Here *f(0)>0,* $f(p_{\min}) < 0$ and $f(1) > 0$. Since *f(p)* is a continuous function over $p \in (0, 1)$, there exists two capability values, $\hat{p}$ and $\hat{\hat{p}}$ in the interval (0,1) such that $\hat{p} < p_{\min} \leq \hat{\hat{p}}$ and for all $p \in (\hat{p}, \hat{\hat{p}})$ the condition (A.2) holds. Furthermore, if condition (A.1) holds, i.e. firm *j* is also competent enough to undertake R&D investment given the presence of firm *i*, there is R&D competition.

(iii): $\dfrac{\pi_m^{\,2}}{4(\pi_m - \pi_d)} > \pi_d \geq F$. Here *f(0)>0,* $f(p_{\min}) < 0$ and $f(1) \leq 0$. Again, since *f(p)* is a continuous function over $p \in (0, 1)$, there exists a value, $\overline{p}$ such that $p_{\min} < \overline{p} \leq 1$ and for all $p \in (\overline{p}, 1)$ the condition (A.2) holds. Furthermore, if condition (A.1) holds also there is R&D competition.

If $p = p_i = p_j$, then $\pi_i^{nc} = \pi_j^{nc} = \pi$ and the firms engage in R&D competition if and only if $\pi > 0$ or $f(p) < 0$. The derivation of the conditions under which $f(p) < 0$ are exactly the same as that in the proof above and the statement of the second part of the proposition follows.

Proof of proposition 3. Suppose, $p_i(1-p_j)(\pi_m-\pi_d)-p_j(1-p_i)\pi_d = \overline{\pi}$. Then the participation constraints given by inequalities (5) and (6) can be written as:

$$\overline{\pi} < 0 \tag{A.3}$$

$$\overline{\pi} + p_j(1-p_i)\,\pi_m\left[1 - \frac{p_i(1-p_j)}{p_j(1-p_i)}\right] < 0 \tag{A.4}$$

When the firms are symmetric, i.e. $p_i = p_j = p$, the two inequalities (A.3) and (A.4) are identical following $\frac{p_i(1-p_j)}{p_j(1-p_i)} = 1$. Moreover from standard oligopoly theory we know that $\pi_m > 2\pi_d$ and hence $\overline{\pi} = p(1-p)(\pi_m - 2\pi_d) > 0$. Therefore, the inequality (A.3) can never hold.

When the firms are asymmetric with $p_j < p_i = p$ we have $\frac{p_i(1-p_j)}{p_j(1-p_i)} > 1$ (refer to footnote 3). This means that $\overline{\pi}$ can be written alternatively as:

$$\overline{\pi} = p_j(1-p_i)\left[\frac{p_i(1-p_j)}{p_j(1-p_i)}(\pi_m-\pi_d) - \pi_d\right]. \tag{A.5}$$

Again given that $\pi_m > 2\pi_d$ and $\frac{p_i(1-p_j)}{p_j(1-p_i)} > 1$ we have $\bar{\pi} > 0$ and in this case also inequality (A.3) can never hold. Therefore, the statement of the proposition follows.

Proof of proposition 4.

Recall that when firms are symmetric with $p_i = p_j = p$, there exists a minimum capability level, say $\bar{p}$, such that $f(\bar{p}) = 0$ and for all $p \in (\bar{p},1)$, $f(p) < 0$ making R&D competition possible.

In this interval $(\bar{p},1)$ are there any capability levels under which a CISA will be preferred ? To answer this question, we start by noting that a CISA dominates R&D competition whenever inequality (8) is satisfied along with assumption 1. Then, we simplify inequality (8) by assuming $F = \beta\pi_d$ where $\beta \in (0, 1]$ and rewrite the participation constraint as $\beta\pi_d > (p_i + p_j - 2p_i p_j)(\pi_m - 2\pi_d)$. When $p_i = p_j = p$, the preceding inequality is transformed into:

$$p^2 - p + \frac{\beta\pi_d}{2(\pi_m - 2\pi_d)} > 0. \tag{A.6}$$

Defining $\phi(p) = p^2 - p + \frac{\beta\pi_d}{2(\pi_m - 2\pi_d)}$, the condition for participation in the CISA in inequality (9) can then be rewritten as:

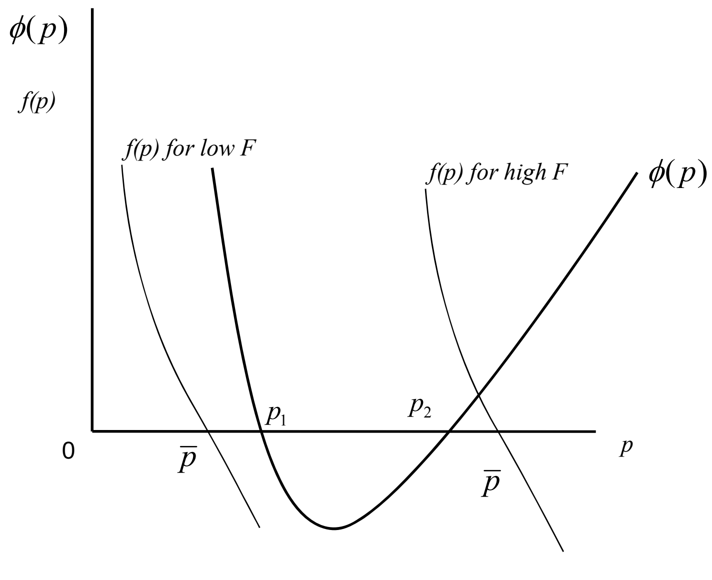
$$\phi(p) > 0. \tag{A.7}$$

The function $\phi(p)$ is continuous over $p \in (\bar{p},1)$ and reaches its minimum at $p = \frac{1}{2}$ with $\phi\left(\frac{1}{2}\right) = -\frac{1}{4} + \frac{\beta\pi_d}{2(\pi_m - 2\pi_d)}$. Furthermore it can be easily noted that , $\phi\left(\frac{1}{2}\right) > = < 0$ if and only if $2\pi_d(1 + \beta) > = < \pi_m$ or $2F > = < \pi_m - 2\pi_d$. We will now examine the case of high costs and low costs seperately.

Case 1: When $2F \geq \pi_m - 2\pi_d$, or β is high, then $\phi\left(\frac{1}{2}\right) \geq 0$. Second, since $\phi(0) > 0$, $\phi(1) > 0$ and $\phi(p)$ is a continuous function, it implies that $\phi(p) > 0$ for all p. Consequently, for any given configuration F, π_m and π_d, there exists a minimum capability level, $\bar{p}$ such that in the symmetric case, R&D competition is viable for all capabilities p, such that $p \in (\bar{p},1)$ and in the asymmetric case, R&D competition is viable for all $p_i = p \in (\bar{p},1)$ and $p_j \in (\frac{F}{(1-p)\pi_m + p\pi_d}, p)$. Finally, since $\phi(p) > 0$ for all $p \in (0,1)$, it is also the case that $\phi(p) > 0$ over the corresponding domains where R&D competition is possible in the symmetric and asymmetric cases. Hence, whenever R&D competition is viable it will be rejected in favour of a CISA.

Case 2: When $2F < \pi_m - 2\pi_d$ or β is low, then $\phi\left(\frac{1}{2}\right)$ *<0*. This is because the position of the $\phi(p)$ function in the $(p, \phi(p))$ space depends on the value of β and as the value of β decreases, the function shifts down. Furthermore, since $\phi(p)$ is a quadratic function, it will cut the X-axis at two points say p_1 and p_2 with $p_1 < \frac{1}{2} < p_2$ as shown in figure 1. Similarly the function *f(p)* depends on the value of the R&D outlay *F*, and as *F* decreases, the function *f(p)* shifts down. This means for higher values of *F*, the function *f(p)* will intersect the function $\phi(p)$ but for lower values of *F*, the function *f(p)* will be entirely to the left of the function $\phi(p)$. In the former case $\bar{p} > p_1$ and in the latter case $\bar{p} < p_1$ as shown in figure 1.

FIGURE 1 : Functions $\phi(p)$ and *f(p)*



When $\bar{p} > p_1$, it means that for all *p*, such that $1 \geq p \geq \max\{\bar{p}, p_2\}$, $f(p) \leq 0$ and $\phi(p) \geq 0$. In other words in this region of high technological capabilities, in the neighbourhood of 1, R&D competition will be possible but a CISA will be even better.

When $\bar{p} < p_1$, there will be two neighbourhoods in which $f(p) \leq 0$ and $\phi(p) \geq 0$. First, there will be a neighbourhood around $\bar{p}$, containing lower capabilities *p* such that $\bar{p} \leq p \leq p_1$ in which a CISA will dominate R&D competition. Second, there is a neighbourhood of high capabilities *p*, such that $1 \geq p \geq \max\{\bar{p}, p_2\}$, where again both the required conditions will be satisfied.

This completes the symmetric case.

Coming to asymmetric capabilities, recall that for R&D competition we must have for all $p_j < p_i$, $p_i = p \in (\overline{p},1)$ and $p_j \in \left(\frac{\beta\pi_d}{(1-p)\pi_m + p\pi_d}, p \right)$. Again recall that a CISA will be preferred to R&D competition, if inequality (9) is satisfied. Now when $p_j = p_i$, inequality (9) is the same as condition (A.7). Therefore, by continuity of all functions concerned, and by the arguments described above for the symmetric case, there exists an open neighbourhood around $p_j = p_i = 1$ where a CISA will dominate R&D competition and in the case of low values of *F*, an open neighourhood around $p_j = p_i = \overline{p}$ where a CISA will dominate R&D competition.

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