Are You the Right Partner ? RD Agreement as a Screening Device

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Are You the Right Partner ? R&D Agreement as a Screening Device[*]

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Abstract

This paper focusseses on the strategic use of firms' R&D agreements to overcome R&D inefficiencies in presence of asymmetric information and research spillovers. We introduce a duopoly game where initially one firm is not fully informed on its rival's R&D productivity. We show that, without R&D agreements, the usual underinvestment problem can be exacerbated by the presence of asymmetric information. However, by proposing a R&D agreement, the uninformed firm may not only gain from the internalization of R&D investment spillovers, but also use it strategically as a screening device to assess the true type of its rival. According to the model, firms are more likely to pursuit R&D agreements in presence of similar productivity and less when their productivity gap is high. This is consistent with the empirical findings highlighting the importance of firms' similarities for R&D collaborations.

Keywords: *Asymmetric Information, Screening, Duopoly, R&D investments, R&D Spillovers, R&D agreements.*

JEL classification: C72; D43; L11; L13; O30.

1   Introduction

As is well known, the presence of research spillovers may have a non negligible impact on the level of firms' R&D investments. In particular, since under high research spillovers part of the competitive advantage obtained from R&D efforts may go to the rivals, firms can refrain from investing in innovative activities. The presence of R&D spillovers was empirically verified by Jaffe (1986), who showed the extent to which firms can usually benefit from rivals' R&D activities. Later on, Ornaghi (2006) assessed the existence of a gap between private and social rate of R&D returns, concluding that an insufficient appropriability is likely to discourage this kind of investments. More recently, using data on Australian firms, Bakhtiari and Breunig (2017) has confirmed that the presence of spillovers may result in firms investing less in R&D than they would do otherwise. Focusing on innovation in wind power technologies, Grafström (2017) found evidence of knowledge spillovers across EU countries and advocated coordination at supranational level to avoid free-riding hindering the support to clean technologies.

Within the theoretical literature, the highly celebrated model by d'Aspremont and Jacquemin (1988) made clear how, in presence of high spillovers, two Cournot duopolists investing independently in R&D may lack to internalize the positive externality exerted on the rival and underinvest in R&D from an industry and social point of view. In this case, cooperation in R&D can increase their R&D spending, leading the investment level closer to the social optimum (see also Katz, 1986; Kamien *et al.*, 1992; Suzumura, 1992; Brocas, 2004). Empirical works confirm the positive effect of R&D cooperation on innovation (Simonen and McCann, 2008) and on firms' performance (Benfratello and Sembenelli, 2002).

Despite the beneficial effects of research coordination, firms' willingness to cooperate in R&D cannot be taken for granted. A wide empirical literature has shown that R&D cooperation among competing firms may seldom occur in practise. In particular, firms' asymmetries, typically having an impact on their size, are likely to affect the gains from cooperation and, hence, their decision to sign R&D agreements (Kogut and Zander, 1992; Röller *et al.*, 1998; Hernan *et al.*, 2003).[1]

However, quite surprisingly, the role of firms' asymmetries for investment decisions and the effect on their propensity to cooperate in R&D has, so far, received scarce attention from the theoretical literature. Baerenss (1999) and Petit and Tolwinski (1999) are among the few papers formally looking at these aspects. In their models firms' asymmetries stem from different initial marginal costs, and a simple comparison between R&D competition and R&D cooperation regimes

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[1]Kogut and Zander (1992) point out that firms may have different R&D absorptive capacities, due to several factors, such as their size and past experience, ultimately affecting their willingness to be part of R&D agreements. Röller *et al.* (1998), looking at the features of the firms involved in research joint ventures, show that size symmetry and product complementary enhance the likelihood of these agreements. In a similar vein, Hernan *et al.* (2003), analyzing the determinants of research agreements, conclude that firms' size positively affects their rate of success.

reveals that asymmetric firms typically possess different incentives to cooperate. However, even introducing firms' heterogeneity, these two papers assume away information asymmetries, and all firms' characteristics are fully observable by both firms. In contrast, in real markets, it may easily be the case that firms are not able to observe the rivals' characteristics, especially when the latter are new entrants in the market. Indeed, the role played by asymmetric information in R&D agreements is an additional facet of the problem, still scarcely explored. Incomplete information in the R&D literature has been mainly related to contract arrangements (d'Aspremont *et al.*,1998; Pastor and Sandonis, 2000; Brocas, 2004), knowledge disclosure (d'Aspremont *et al.*, 2000), relative position in patent race (Grishagin *et al.*, 2001; Kao, 2002) and new technology adoption (Zhu and Weyant, 2003). In addition, Cassiman (2000) assumes asymmetric information between firms and a regulator on R&D spillovers, while Cabon-Dhersin and Ramani (2004; 2007) use incomplete information to study the role of trust for R&D cooperation. More recently, Niedermayer and Wu (2013), focussed on the contracts regulating the research consortia, showing that a breakup clause can represent an effective screening device to make participation less attractive to non-committed types, i.e. the firms more inclined to reap private benefits from R&D agreements than contributing to their success.

Recently, the paper by Kabiraj and Chattopadhyay (2015) developed a duopoly model with stochastic R&D and incomplete information of every firm on the rival's success in innovation activity to focus on their incentives to cooperate in R&D. The authors show that, since under noncooperative R&D information incompletness decreases firms' expected payoffs, the incentive of firms to cooperate in R&D - where firms are assumed to unveiled all information - becomes higher. This implies that R&D agreements are more likely to occur under incomplete than under complete information. One missing piece in their framework, though, is that it does not take into account the incentives of firms to innovate since, by assumption, firms are assumed to exert a fixed amount of R&D effort. Accordingly, also the potential effects of R&D spillovers are excluded from the analysis.

In view of the above considerations, the main aim of our paper is to extend the original model by d'Aspremont and Jaquemin (1988) and look at the effect of asymmetric information on firms' R&D strategies and incentives to sign R&D agreements in presence of R&D spillovers. Specifically, we develop an asymmetric information framework in which firms can be both asymmetric as to their R&D productivity and asymmetrically informed about it. Differently from most of the existing models, we explicitly analyze the incentives of firms towards cooperation, by endogenizing the formation of R&D agreements.[2] In this way, our model allows to study: (i) how asymmetric

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[2] Some other studies analyzing the formation of cooperative agreements mostly focus on partner selection (Atallah, 2005b), coalition stability, (Goyal et al., 2001; Song and Vannetelbosch, 2007) and timing (Marini *et al.*, 2014)

information affects firms' investment decisions in R&D; (ii) how firms' asymmetries affect their incentive to cooperate; (iii) the mechanism through which, for the uninformed firm, proposing a R&D agreement may ultimately work as a *screening device* to assess the true type of its rival.

Our main findings are the following. When firms conduct noncooperatively their R&D activities, the uncertainty on the rival's R&D productivity generates additional adverse effects, other than those usually attributed to free-riding. In particular, asymmetric information can exacerbate the underinvestment problem by inducing the uninformed firm toward an (*ex post*) inefficient investment decision. However, the possibility to cooperate in R&D allows to overcome such an adverse outcome. In particular, when the gap in R&D productivity between the firms is sufficiently high, the unwillingness to cooperate of the less efficient one is responsible for the emergence of a *screening effect*: by proposing a R&D agreement and looking at the rival's response, the efficient firm can unveil the type of its rival, thus taking efficient investment decisions as a result. Therefore, when the rival is of the efficient type, the resulting equilibrium may entail more investment, higher profits and welfare than when R&D cooperation is not possible. Finally, with an inefficient rival, the R&D agreement will not be reached for most of parameters' values: as the gap between firms' productivity increases, the likelihood of cooperation tends to vanish. This is consistent with the empirical literature which emphasizes the role of firms' asymmetries in the failure of R&D collaborations.

The paper is organized as follows. Section 2 introduces the model, while Section 3 analyzes the equilibrium investment decisions when firms compete in R&D and show the effects of incomplete information on such equilibria. R&D agreements are introduced in Section 4. Section 5 discusses the model results and concludes.

2   The model

Following the well known literature on spillovers and R&D investment (e.g. d'Aspremont and Jaquemin, 1988; Kamien *et al.*, 1992; Suzumura, 1992), R&D investment decisions and R&D cooperation are modelled in a context of process innovation, using a multi-stage Cournot setting in which R&D expenditures result in cost reduction.

Let two firms (firm 1 and firm 2) compete in quantities facing an inverse demand for a homogeneous good given by $P(Q) = a - Q$, with $a > Q$ and $Q = q_1 + q_2$, where q_i stands for the quantity produced by firm $i = 1, 2$. Firms can decide whether to invest (or not) a fixed amount $K > 0$ in R&D in order to reduce their initial marginal cost c (assumed identical for both firms) by an amount $t_i > 0$. The extent of cost reduction coming from the R&D investment can be different for the two firms: in fact, firm 1 and firm 2 could be not equally efficient in R&D activity. As a result, firms can become asymmetric after the investment stage, if only one of them decides to

invest, or even if they both invest. Due to R&D spillovers, part of the competitive advantage that a firm obtains from R&D investment may go to the rival. Firm i's marginal cost can be written as:

$$c_i = c - t_i - \beta t_j \qquad (1)$$

with $i, j = 1, 2, i \neq j$ and $\beta \in (0, 1)$, where β represents the exogenous spillover through which the investment of firm j contributes to reduce the cost of firm i. If firm i does not invest, $t_i = 0$.

The model is characterized by asymmetric information: while firm 2 knows that the extent of cost reduction obtained by firm 1 investing in R&D is t $(t_1 = t)$, firm 1 has incomplete information on the level of R&D productivity of firm 2.[3] Let $\alpha \in (0, 1)$ denote the productivity of firm 2's R&D investment; therefore, firm 2 can be of two types, α_L or α_H, with the probability assigned to the efficient type defined as $Prob(\alpha = \alpha_H) = \mu$. Therefore, if firm 2 is of type α_L (low R&D productivity), the cost reduction generated by investing K is $t_2 = t\alpha$. If firm 2 is of type α_H (high R&D productivity), the cost reduction is $t_2 = t$; in this case firm 1 and firm 2 turn out to be symmetric.[4] The maximum cost reduction is obtained when the two firms are symmetric, both invest and the spillover is maximum.

Before facing investment decisions, firms have the possibility to create a R&D cooperation agreement (RDA) to coordinate their investment strategies and avoid the strategic interaction that characterizes the R&D competition. The agreement is modelled as a coordination device: in a RDA regime both firms commit to invest. Therefore, each firm is willing to cooperate in R&D if it thinks that the agreement leads to a higher profit than that attainable under R&D competition. As in most of the existing models, coordination in production is not allowed, even if firms cooperate in R&D.

2.1 Assumptions and Timing

As a first step, let us introduce the following assumptions on the model parameters:

A.1. $0 < t \leq \frac{c}{2}$ (non-negative costs);

A.2. $t \leq (a - c) \equiv \theta$ (non-negative quantities).

The model is a three-stage game. More specifically, the timing is as follows.

First stage: R&D agreement. Firm 1 can propose to firm 2 a cooperative agreement, aimed to coordinate R&D efforts. An agreement implies that both firms commit to invest a given level K in the following stage. Once an agreement is reached, investment is observable and no firm can

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[3]Here firm 1 can be thought as a firm renowned for its innovative activity, while firm 2 could be a firm just planning for the first time a new R&D activity.

[4]For completeness, we also developed the analysis for $\alpha > 1$, in which the informed firm 2 can be more efficient than firm 1. However, since the results obtained do not add much to the current analysis, we prefer to skip it to economize on space. They are, however, available upon request.

deviate from the decision to invest. The strategy profile at this stage is defined by $s = (s_1, s_2)$, with $s_2 = (s_{2L}, s_{2H})$ indicating the strategies of type α_L and α_H, respectively. The possible actions of firm 1 are denoted by "RDA", meaning that it is willing to form the R&D agreement, and "NRDA". If firm 1 has made the proposal, firm 2 can either accept or not. Its possible actions are, therefore, "Yes" and "No". Failing the agreement, firms end up in the R&D competition regime.

Second stage: Investment. In this stage firms can act under two different regimes, according to the choices made in the previous stage. Let define the strategy profile as $k = (k_1, k_2)$, with $k_2 = (k_{2L}, k_{2H})$. If no R&D agreement is signed, firms decide noncooperatively and simultaneously whether to invest or not in R&D: hence, each firm's action can be either 0 or K. If firms have joined the agreement, there is no strategic interaction at this stage, since they all agreed to invest $(k_1 = k_{2L} = k_{2H} = K)$.

Third stage: Cournot competition. Firms set noncooperatively their quantities to maximize their profits given the strategy of the rival.

At the beginning of each stage, firms observe the outcome of the previous stage and beliefs updating is possible. At the market stage (third stage), information is assumed to be complete: after the investment stage, firm 1 infers the type of its rival through the spillover.[5] The game is solved backward. The solution concept adopted for the equilibria of the game is the *perfect Bayesian equilibrium*. Moreover, when multiple equilibria arise, a unique equilibrium is selected using the *interim Pareto dominance* criterion,[6] whenever possible.

2.2 A comparison with some existing models

In this section we discuss some assumptions underlying our model that are different from those characterizing most of past R&D oligopoly models. A first difference is that, in our model, the investment choice is dichotomous (as in Arrow, 1962). Following the original framework by d'Aspremont and Jaquemin (1988), most of R&D oligopoly models usually adopt a continuous variable for the R&D effort and compare their equilibrium values under different regimes to assess which is the most suitable to foster innovation. The use of a dichotomous variable implies that our results have to be interpreted in terms of regions of parameters values, looking at the combinations of R&D costs and extent of firms asymmetry (K and α) that allow investment at equilibrium. If, under a certain regime, there exists a broader region for which an equilibrium with positive investment occurs, we can presume that in that regime the probability to observe investment is higher and there is more incentive to innovate.

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[5] Without this assumption we would have a situation in which at the last stage firm 1 produces being uncertain on its own cost. This is because, when both types invest and beliefs updating is not allowed, uncertainty on cost reduction of firm 2 would enter firm's 1 cost function through the R&D spillover.

[6] See Hölmstrom and Myerson (1983).

Another difference deals with the way in which R&D collaboration is modelled. In the past literature R&D cooperation (in most cases denoted *research joint venture*, or *RJV*) is described as a situation in which symmetric firms choose the level of R&D effort maximizing their joint profit. As a consequence, the spillover externality is internalized and the free-riding problem is eliminated, thanks to the (indirect) coordination effect. Usually, the solution to the maximization problem turns out to be symmetric (as in R&D competition), that is, the two firms choose the same strategy.[7] Although in these models the *RJV* formation process is not explicitly modelled, it can be easily seen that firms possess the same incentives towards cooperation, which is always profitable from the firms' point of view for high spillovers. In this paper, we depart from the "joint profit maximization hypothesis" when defining the RDA regime. When firms are asymmetric, joint profit maximization might require asymmetric R&D efforts and generate uneven profits for firms. So, without taking into account side payments (as we do in the current model), there is no reason why firms should maximize the joint profit. Moreover, under asymmetric information, the joint profit function will not be the same for the two firms, making the "joint profit maximization hypothesis" even more unreliable. Thus, here the R&D agreement is modelled as a coordination device, aiming at reducing the free riding and reaching a better outcome. This is consistent with the past literature and leads to equivalent results in the particular case of symmetric firms under complete information.[8]

Finally, the spillover is assumed exogenous: it is not a choice for the firms[9] and its value does not change when firms enter a R&D agreement.[10] We follow d'Aspremont and Jacquemin (1988) in keeping the spillover exogenous. This is not intended to underestimate the role of information disclosure for R&D cooperation; simply, we claim that a firm may be unwilling to share its knowledge with the rival if this reduces its final profit. Indeed, Poyago-Theotoky (1999) shows that, when firms maximize their own profit and are able to decide on the value of the spillover parameter as a measure of information disclosure, they set it at the minimum level, meaning that additional leakages of knowledge are not profitable to them.[11] While R&D expenditure is

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[7]In a model with symmetric firms, Salant and Shaffer (1998), identify a region of exogenous parameters for which asymmetric investment decisions lead to the largest joint profit. However, this region exists only for low spillovers, a case not analyzed in our paper (see Section 3).

[8]Limited to the case of complete information, we also solved the model under the alternative assumption of joint profit maximization in the RDA regime. Results showed that, for symmetric or asymmetric firms, the incentive to sign a R&D agreement in presence of high spillovers exists only in the regions of parameters for which the joint profit maximization requires investment by both firms.

[9]As in Poyago-Theotoky (1999) and Amir et al. (2003).

[10]In the works of Beath et al. (1998), Atallah (2005a), Kamien et al. (1992), Baerenss (1999), Petit and Towlinski (1999) and Lambertini and Rossini (2009), in a RJV regime, the spillover parameter takes a value of one since, in addition to the coordination of R&D efforts, firms fully share their information.

[11]When endogenously determined by the firms, the spillover parameter takes its maximal value if firms maximize their joint profit, under the assumption of symmetric R&D efforts. See also Amir *et al.* (2003) for an analogous result.

observable, information disclosure is not a contractible variable. For instance, the value of a partner's technological know-how may be hard to assess *a priori* (Veugelers, 1998). Hence, it is reasonable to assume that the extent of knowledge leakage is the same in both regimes.

3   Investment under R&D competition

We can start by looking at the equilibria arising at the second stage of the model, taken for granted the Cournot equilibrium occurring at the third stage, given that the game is solved backward. We will focus on the case of high spillovers ($\beta > 1/2$) that is the most interesting case, one for which the spillover externality is responsible for inefficient outcomes and, in particular, R&D underinvestment.[12] The obtained results also allow, through a straightforward comparison with the complete information case, to evaluate the consequences of one firm's uncertainty on its rval's productivity.

3.1   Equilibrium investment strategies

Given the unique Cournot equilibrium quantities obtained at the third stage, second stage firms' profits are:

$$\Pi_1(k_1, k_2) = \frac{1}{9} \left(\theta + t_1 \left(2 - \beta \right) + t_2 \left(2\beta - 1 \right) \right)^2 - k_1, \tag{2}$$

$$\Pi_2(k_1, k_2) = \frac{1}{9} \left(\theta + t_2 \left(2 - \beta \right) + t_1 \left(2\beta - 1 \right) \right)^2 - k_2. \tag{3}$$

The decisions of the firms on R&D investment determine the values of k_1 and k_2. The values of t_1 and t_2 depend, in turn, on the investment choices and on the type of firm 2. Let $k_1 \in \{0, K\}$ denote the discrete strategy of firm 1 at the investment stage and $k_2 = (k_{2L}, k_{2H})$ that of firm 2, where the first element identifies the strategy of the *inefficient* type α_L while, the second, that of the *efficient* type α_H. Let us assume that, similarly to firm 1, every type of firm 2 has a discrete investment choice between 0 and a fixed amount K, i.e. $k_{2j} \in \{0, K\}$, for $j = L, H$.

Firm 2 knows its type, so it will take the action leading to the highest profit, for any strategy of firm 1. Firm 1 cannot distinguish between the two types of firm 2 and will, therefore, maximize

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[12] We did all the computation for the case of low spillovers. However, in this case there are no regions of parameters for which the commitment to invest leads firms to higher profits than under R&D competition. Hence, the possibility to form a R&D agreement simply does not alter the analysis as compared to the case in which only R&D competition is allowed.

its expected profit given the strategy of firm 2, i.e. given the four possible combination of actions taken by the two types: $k_2 \in \{(0, 0), (0, K), (K, 0), (K, K)\}$. As in any standard Bayesian games the probability that firm 1 assigns to every type of firm 2 descends from prior probabilities according to the Bayes' rule, when applicable. When firm 1 has incomplete information at stage 2 (no beliefs updating), the probabilities assigned to each type are the same as prior beliefs, namely $P(\alpha = \alpha_H) = \mu$.[13]

Thus, there are eight possible investment strategy profiles

$$\mathbf{k} \equiv (k_1, (k_{2L}, k_{2H}))$$

to consider when assessing which ones can be part of an equilibrium in the continuation of the game.

The complete analysis of equilibria and their possible selection according to the criterion of *interim Pareto dominance* can be found in the Appendix. We show there that only three strategy profiles are sustainable as equilibria when firms compete in R&D under asymmetric information, depending on the level of the investment cost K. Let

$$h \equiv \frac{1}{9} t\alpha \left(2 - \beta\right) \left[2\theta + t\alpha \left(2 - \beta\right) + 2t \left(2\beta - 1\right)\right] \tag{4}$$

and

$$\gamma(\mu) \equiv \frac{t(2 - \beta)}{9} \left[2\theta + t(2 - \beta) + 2t\mu(2\beta - 1)\right] \tag{5}$$

denote the two relevant thresholds for the investment cost K characterizing the different equilibria occurring at the investment stage. These are described in the next proposition.

Proposition 1 *According to the value taken by the investment cost K, the following strategy profiles can be sustained as equilibria of the investment stage:*

$$\mathbf{k} \equiv (k_1, (k_{2L}, k_{2H})) = \begin{cases} (K, (K, K)) \text{ for } K \leq h; \\ (K, (0, K)) \text{ for } h < K \leq \gamma(\mu); \\ (0, (0, 0)) \text{ for } K > \max\{\gamma(\mu), h\} \end{cases}$$

Proof. See the Appendix. ∎

Figure 1 illustrates the different equilibria obtained at the second stage by plotting the two thresholds for the investment cost K (4)-(5) as a function of the R&D productivity parameter $\alpha \in (0, 1)$, for selected parameters' values.[14] Changing the parameters values does not modify qualitatively

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[13]Firm's 1 posterior probabilities differ from its prior probabilities only when, at the first stage, it proposes a RDA to firm 2 and the two types of firm 2 provide different answers.

[14]More precisely $\theta = 2$, $t = 1$, $\beta = 0.7$, $\mu = 0.5$.

the equilibrium outcomes and, therefore, the figure is illustrative of the nature of the equilibria occurring at the investment stage under asymmetric information. It can be seen that, when $K \leq h$, namely for relatively small values of the R&D investment cost K, both firms and both types of firm 2 invest. For any given value of $\alpha \in (0, 1)$, if the cost of the investment K exceeds the threshold h, the less efficient type (α_L) finds no longer profitable to invest, and it prefers to free-ride by enjoying the spillover of its efficient rival without engaging in R&D activity. In contrast, firm 1 continues to invest until the investment cost reaches the level of $\gamma(\mu)$; moreover, as long as firm 1 invests, the efficient type of firm 2 will also invest. Above this level, no firms will find profitable to invest. It should be noticed that the threshold h is increasing in α. This means that, as the gap in R&D productivity between the two firms decreases, the less efficient type of firm 2 is willing to invest even for larger values of K. Note also that two equally efficient firms by definition always make symmetric investment choices. In addition, the only possible asymmetric equilibrium entails investment only for the most efficient firm. Such an asymmetric equilibrium does not arise for α very close to 1, namely when the productivity differences between the firms tend to vanish, and the firms' investment strategies return to the usual symmetric equilibrium.

[**Figure 1 approximately here**]

3.2   The effect of incomplete information

The results obtained above can be used to illustrate the main effects of asymmetric information. As depicted in Figure 1, the level of investment cost $K = \max\{\gamma(\mu), h\}$ represents the threshold which separates the region where efficient firms invest from the one in which they do not. In particular, the threshold $\gamma(\mu)$ is a function of firm 1's beliefs. For $\mu = 1$, it collapses to the maximum threshold for which two equally efficient firms invest in R&D when information is complete. Alternatively, for $\mu = 0$, $\gamma(\mu)$ is equal to the maximum threshold for which, without uncertainty on the rival's characteristics, an efficient firm is willing to invest even when the less efficient rival would not (see the Appendix). In Figure 2, $\gamma(0)$ and $\gamma(1)$ are added to the thresholds characterizing the equilibrium investment strategies under incomplete information already displayed in Figure 1.[15]

The hatched area shows the effects of incomplete information when firms can only compete in R&D with no possibility of cooperation. In particular, the "X area" indicates the region of parameters where incomplete information prevents R&D investment by the efficient firms. The "+ area", instead, indicates the region of parameters in which firm 1's investment is *ex post* suboptimal when the rival is inefficient. This will be illustrated in Proposition 2 and 3, respectively.

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[15]Parameters' values are set as in Figure 1.

Proposition 2 *It does always exist a range of investment cost K, defined by $\max\{h, \gamma(\mu)\} < K \leq \gamma(1)$, for which the presence of incomplete information prevents both efficient firms, namely firm 1 and the efficient type of firm 2, from investing in R&D.*

Proof. See the Appendix. ∎

The threshold $\gamma(1)$ is higher than $\gamma(\mu)$, meaning that incomplete information shrinks the region of parameters for which the efficient firms invest. Inside the region defined in Proposition 2, under asymmetric information firm 1 does not invest when it considers the possibility that its rival is of the less efficient type, since in this case the latter would not invest and the level of K is not small enough to make a unilateral investment profitable for firm 1. Given the choice of firm 1, the best reply of the efficient type of firm 2 is to adopt a symmetric investment choice.[16] So, the presence of asymmetric information increases the probability of *ex post* suboptimal investment decisions. If informational asymmetry could be eliminated, the symmetric firms would always invest in the region under consideration, thus obtaining higher profits.

When, instead, firms are asymmetric, incomplete information is likely to make only the most efficient firm worse off than under complete information. Note that, irrespectively of the information setting, when firms are sufficiently asymmetric (i.e. for α not too close to 1), there is a region where only the efficient firm invests while the less efficient one prefers to save in investment costs exploiting the benefit of cost reduction through the spillover effect. This region becomes larger under incomplete information. Indeed, as stated above, $\gamma(0)$ represents the maximum investment cost that firm 1 is willing to sustain when, under complete information, the less efficient rival does not invest. The corresponding threshold under incomplete information ($\gamma(\mu)$) is higher. Whenever asymmetric information generates outcomes which are different from those obtained under complete information, the most efficient firm, namely firm 1, is worse off. This is illustrated by the next proposition:

Proposition 3 *When firms are asymmetric, and $\max\{\gamma(0), h\} < K \leq \gamma(\mu)$, incomplete information leads firm 1 to an ex post suboptimal investment choice.*

Proof. See the Appendix. ∎

In particular, inside such region of the parameters, firm 1 invests because of the positive probability to compete with an efficient firm (that would invest), and, if this does not occur, firm 1 would be *ex post* better off by not investing. In contrast, in the same region of parameters,

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[16]With symmetric firms only symmetric equilibria exists: either both firms invest or none invests, whatever the information structure. This is due to the strategic complementary of the investment game.

under incomplete information the inefficient type of firm 2 is always better off as compared to the complete information case.

To conclude, asymmetric information on the rival's R&D productivity reduces the profit gained *ex post* by the efficient firms (firm 1 and type α_H of firm 2), while, for the some parameters' values, it makes more likely for the inefficient firm to free ride on the rival's R&D investment.

4   R&D cooperation

At the first stage of the game firms are allowed to decide whether to form or not a R&D agreement to coordinate their R&D efforts. The first stage is assumed to possess a sequential structure: firm 1 moves first by either proposing a R&D agreement to firm 2 (RDA) or not ($NRDA$). Let us denote firm 1's strategy set at stage one as $S_1 = \{RDA, NRDA\}$ and its strategy profile $s_1 \in S_1$. If firm 1 selects "$NRDA$", the firms play the investment stage as in a standard R&D competition game, with outcomes defined as in Section 3. If firm 1 plays "RDA", firm 2 can either decide "Yes", giving rise to a R&D agreement, or "No", thus remaining in a R&D competition regime. Let us denote firm 2's first stage strategy set as

$$S_2 = \{(Yes, Yes), (Yes, No), (No, Yes), (No, No)\},$$

and its strategy profile as $s_2 = (s_{2L}, s_{2H}) \in S_2$. At stage one a complete strategy profile can, thus, be simply denoted as $\mathbf{s} = (s_1, s_2)$. The procedure used here to find the first stage equilibrium strategy profile is the following: firstly, we define both types of firm 2's best replies to firm 1's RDA proposal;[17] secondly, we evaluate firm 1's incentive to propose a R&D agreement when anticipating firm 2's best response. We analyze the incentives of firms to cooperate by just comparing the payoffs that they expect under R&D competition with those generated under a R&D agreement. In addition, firms' payoffs have to be evaluated at both *separating* and *pooling* strategies of firm 2.

In what follows we concentrate only on the regions of parameters where the possibility to propose a R&D agreement can generate outcomes which differ from those arising when only the R&D competition regime is feasible. This implies that we can limit our analysis to the regions of parameters for which $h < K \leq z$, with h defined as in (4) and

$$z \equiv \frac{t}{9}[t(2 - \beta) + t(2\beta - 1)][2\theta + t(2 - \beta) + t(2\beta - 1)]. \tag{6}$$

Indeed, for $K \leq h$, the equilibrium under R&D competition is such that all firms and all types invest, whatever their beliefs. Hence, for this range of the investment cost, a R&D agreement

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[17]If firm 1 plays $NRDA$, the game moves to the R&D competition regime, whatever the strategy of firm 2.

would always lead to the same outcome as with R&D competition (see the Appendix and Section 3). By contrast, for $K > z$, it can be easily shown that, irrespective of the existing beliefs and the rival's strategies, no firm and no type would increase their profits by investing in R&D. Indeed, the maximum value of the investment cost K making the investment feasible is just the level of K which makes the two symmetric (efficient) firms indifferent between the joint investment and no investment at all. Such threshold is determined by the following equality,

$$\frac{1}{9}[\theta + t(2 - \beta) + t(2\beta - 1)]^2 - K = \frac{1}{9}\theta^2,$$

which implies $K = z$. Hence, for $K > z$ a R&D agreement will never take place, since in this case the R&D investment is unprofitable for every firm. Also, on the basis of the above considerations, we analyze exclusively the equilibria at which at least one of the two types of firm 2 finds profitable to accept the agreement.

Lemma 1. *For $h < K \leq z$, a perfect Bayesian equilibrium with, at the first stage, a strategy profile $s_2 = (Yes, No)$ for firm 2 never exists.*

Proof. See the Appendix. ∎

Moreover, let us denote

$$\phi \equiv \frac{t}{9}[\alpha t(2 - \beta) + t(2\beta - 1)][2\theta + \alpha t(2 - \beta) + t(2\beta - 1)] \tag{7}$$

the maximum value of K for which the inefficient type always prefers a mutual R&D investment to no investment at all.

Lemma 2. *For any $\alpha \in (0, 1)$ and $\max\{\phi, \gamma(0)\} \leq K \leq z$, an equilibrium in which firm 1 proposes a R&D agreement at the first stage and firm 2 plays a separating strategy, such that $\mathbf{s} = (RDA, (No, Yes))$, always arises.*

Proof. See the Appendix. ∎

Now, let us define the following value for α:

$$\alpha^* = 1 - \frac{2\beta - 1}{2 - \beta}, \tag{8}$$

which will be used in the following Lemma.

Lemma 3. *For $\alpha > \alpha^*$ and $\max\{h, \gamma(0)\} < K \leq \phi$, an equilibrium in which firm 1 proposes a R&D agreement and firm's 2 plays a pooling strategy, such that: $\mathbf{s} = (RDA, (Yes, Yes))$, always occurs.*

Proof. See the Appendix. ∎

Figure 3 below illustrates the first stage equilibrium strategies as stated in Lemma 2 and 3.[18]

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[18]In Figure 3 the parameters' values are set as in Figure 1 and 2.

Region 1 represents the *separating equilibrium* described in Lemma 2, where firm 1 proposes the agreement, type α_L of firm 2 refuses it, while type α_H accepts it. Hence, the R&D agreement can occur only between two equally efficient firms. However, for some parameters' values, a R&D agreement takes place also between asymmetric firms, provided that the efficiency gap between the two firms is not too large.

Region 2 shows the *pooling equilibrium* characterized in Lemma 3, where a R&D agreement occurs irrespective of the type of firm 2. The higher the value of α with respect to α^*, namely the smaller the efficiency gap between the asymmetric firms, the higher is the R&D investment cost K compatible with a R&D effort coordination between two asymmetric firms. Note also that α^* is decreasing in β. This means that when the spillover is large, the R&D agreement may occur also when the efficiency gap is large. Indeed, the higher the spillover, the larger is the benefit that the inefficient type can obtain from the R&D activity of the efficient firm. This creates an incentive to accept a R&D agreement proposal, since otherwise the efficient firm would not invest in the R&D competition regime. Using Lemma 2 and Lemma 3, we can derive the following result.

Proposition 4. *(i) It does always exist a region of parameters for which a R&D agreement between symmetric (efficient) firms takes place, leading to more investment than without agreement. (ii) When the firms are highly asymmetric, namely when the R&D productivity of the inefficient type is significantly lower than that of the efficient type, a R&D agreement is unlikely to occur.*

Figure 4 below divides the regions with R&D agreement in four areas, each one characterized by a different effect generated by the possibility for firms to sign a R&D agreement.

Firstly, in regions **A** and **B** the game leads to an equilibrium with R&D agreement only between efficient firms. Without the possibility to coordinate R&D efforts, in region **A** we would see an equilibrium with no investment (i.e. as $\mathbf{k} = (0, (0, 0))$ in Figure 1). In this case, for $\alpha = \alpha_H$, the R&D agreement, leading to R&D investment and generating higher profits, is welfare improving. In particular, for $K \leq \gamma(1)$ the possibility to sign a R&D agreement restores complete information between firms and allows to overcome the inefficiency generated by incomplete information, that prevents the investment when firms plan strategically their R&D efforts. For $K > \gamma(1)$, instead, the R&D investment is caused by the effect of *coordination device* of the agreement: under R&D competition both firms would be better off by investing, but this outcome is not attainable in equilibrium because of the incentive to free-ride. In contrast, for $\alpha = \alpha_L$, an agreement does not

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take place and no firm invest: this is the same outcome occurring in R&D competition both under complete and incomplete information.

In region **B**, the outcome in absence of R&D cooperation would entail investment by firm 1 and the efficient type of firm 2, while the inefficient type would not invest: $\mathbf{k} = (K, (0, K))$. Firm 1 invests without knowing the type of the rival because of the positive probability of facing an efficient type; however, when the information is revealed and $\alpha = \alpha_L$, evaluated *ex post,* this choice is not optimal. Indeed, under complete information, firm 1 would not invest when facing an inefficient firm, while, under incomplete information, the inefficient type can exploit the spillover of firm 1's without investing. Thus, the possibility to propose a R&D agreement and the separating strategy of firm 2 allow beliefs updating. Firm 1, after observing firm 2's refusal to its proposal, does not invest and its choice turns into an *ex post* optimal one.

Finally, in region **C** and **D** the game leads to an equilibrium with R&D agreement, whatever the type of firm 2. In particular, in region **C**, the R&D agreement equilibrium is always welfare improving, leading to both higher investment and profits (the outcome would be $\mathbf{k} = (0, (0, 0))$ without R&D agreement). This is due to the coordination effect.

In region **D**, instead, the difference of outcomes with respect to a situation in which only R&D competition is feasible is the commitment to invest of type α_L of firm 2.[19] This outcome arises because the R&D agreement proposal by firm 1 make unavailable to type α_L the possibility to benefit from firm 1's R&D without investing. Indeed, if firm 1 observes the rejection of firm 2, it assigns probability 1 to type α_L of firm 2, given that for the efficient type is never convenient to refuse the agreement. Accordingly, under R&D competition (out of the equilibrium path) firm 1 would not invest if the rival is inefficient. Therefore, if the asymmetry between the two firms is not too large, for type α_L is more profitable if both firms invest than if none invests and, hence, the inefficient type will accept to sign a R&D agreement. The different outcome arising in region **D** with respect to region **B** - where type α_L does not accept the agreement - is explained by the higher value of α: the smaller the efficiency gap, the higher the probability that type α_L finds profitable to invest when also its rival invests. Moroever, region **D** is characterized by a higher level of total investment than under R&D competition, although only firm 1 is better off.

Overall, a large number of the results illustrated above are driven by the *screening effect* generated by the possibility, for the uninformed firm, to propose a R&D agreement. Looking at firm 2's response, firm 1 can infer the type of its rival and, accordingly, proceed with efficient investment choices. This occurs in region **A**, in particular for $\gamma(\mu) < K \leq \gamma(1)$, and in region **B**, where the RDA proposal allows firm 1 to distinguish between the two types and, thus, to avoid inefficient investment choices generated by the lack of information on the rival. Moreover,

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[19]The R&D competition equilibrium in this parameters region is, in fact, $\mathbf{k} = (K, (0, K))$.

in region **D**, although firm 2 plays a pooling strategy, the RDA proposal compels the inefficient type to agree on join investment, given that a refusal would unveil its type, hence preventing it to free ride on firm 1' investment.

As a last comment, it has to be noticed that the possibility to propose a R&D agreement is *always beneficial* for the uniformed firm. In addition, whenever the agreement increases the level of investment of the efficient firms (region **A** and **C**), it is also *welfare improving*. However, the analysis of the equilibria also shows that, for most of the parameters values, R&D agreements are seldom signed when firms are strongly asymmetric. This is due to the asymmetric equilibrium arising at the R&D investment stage: in the region of parameters for which such equilibrium occurs and the productivity gap between firms is not too small, the inefficient type may well prefer to exploit the benefit that comes by just free-riding on its rival's investment.

5   Concluding Remarks

In this paper we have developed a three-stage duopoly model to analyze the incentives of firms to enter a cooperative agreement with the purpose of coordinating their investments in R&D in a framework with asymmetric information on R&D productivity. The innovation enhancing effects of R&D cooperation are confirmed, at least for the case in which firms are equally efficient. Coordination of R&D efforts allows to internalize the externality generated by spillovers and overcome the free-riding problem.

In addition, a new beneficial effect of R&D cooperation has been identified: for given values of the investment cost, the possibility to propose a R&D agreement allows the efficient (uninformed) firm to discriminate between efficient and inefficient partners, thus increasing the level of investment and welfare. Our model shows that when both firms are efficient and compete in R&D, the presence of incomplete information makes an equilibrium with R&D investment less likely to arise, thus exacerbating the problem of R&D under-investment. The possibility to sign a R&D agreement helps to solve such inefficiency, by revealing information. The model highlights the existence of a role for R&D agreements to function as a screening device by helping the uninformed (efficient) firm to avoid *ex post* sub-optimal investment choices when facing a less productive rival. This mainly occurs for intermediate values of the investment costs, simply because outside this range either no firm invests (when the investment cost is too high) or every firm invests (when this cost is very low). Finally, the model shows that for most of the parameters values a R&D agreement is never signed between asymmetric firms and, therefore, the alleged coordination effect does not actually arise. This result contributes to explain the existing empirical evidence on the shortage of R&D cooperation agreements between asymmetric firms competing in the same market (Kogut and Zander, 1992; Röller *et al.*, 1998; Hernan *et al.*, 2003) and is in line with

the previous theoretical works, though offering an alternative explanation of the reasons behind firms' behavior in R&D cooperation. In particular, the works by Baerenss (1999) and Petit and Tolwinski (1999) suggest that asymmetric firms may not have the same incentives towards cooperation, thus hampering the formation of R&D agreements. In their models, where the asymmetry concerns initial marginal costs and there is full information sharing under cooperation, it is the less efficient firm that gains from cooperation, while the more efficient firm has less incentive to cooperate. This is because cooperation tends to make the market more symmetric, reducing cost asymmetries. In our model, where the asymmetry concerns R&D productivity and arises after R&D investments take place, firms' incentives are reversed: the inefficient firm is unwilling to cooperate just because under R&D competition may benefit from its rival's investment through the spillover effect without bearing the investment cost, whereas in a R&D agreement would be committed to invest.

6 Appendix

Proposition 1. *According to the value taken by the investment cost K, the following strategy profiles can be sustained as equilibria of the investment stage*:

$$\mathbf{k} \equiv (k_1, (k_{2L}, k_{2H})) = \begin{cases} (K, (K, K)) \text{ for } K \leq h; \\ (K, (0, K)) \text{ for } h < K \leq \gamma(\mu); \\ (0, (0, 0)) \text{ for } K > \max\{\gamma(\mu), h\} \end{cases}$$

Proof. The proof is split in two parts: (a) firstly, we derive all possible second stage equilibrium strategies; (b) secondly, for every region of parameter K in which multiple equilibria arise, we select a unique equilibrium according to the *interim Pareto dominance* criterion, leading to the three regions described in Proposition 1.

(a) *Equilibrium strategies in R&D competition.* Let us start by showing that no equilibrium exists with $k_2 = (K, 0)$, i.e. such that the inefficient type of firm 2 invests while the efficient type does not. First, $k_2 = (K, 0)$ is never a best reply to $k_1 = K$. When firm 1 invests, type α_L of firm 2 has no incentive to deviate from $k_{2L} = K$ only if $(\Pi_{2L}|k_1 = K, k_{2L} = K) \geq (\Pi_{2L}|k_1 = K, k_{2L} = 0)$, namely for $\frac{[\theta+t(2\beta-1)+\alpha t(2-\beta)]^2}{9} - K \geq \frac{[\theta+t(2\beta-1)]^2}{9}$, or $\frac{\alpha t(2-\beta)[2\theta+\alpha t(2-\beta)+2t(2\beta-1)]}{9} \geq K$. Similarly, type α_H has no incentive to deviate from $k_{2H} = 0$ only if $(\Pi_{2H}|k_1 = K, k_{2H} = 0) \geq (\Pi_{2H}|k_1 = K, k_{2H} = K)$, i.e. for $K \geq \frac{t(2-\beta)[2\theta+t(2-\beta)+2t(2\beta-1)]}{9}$. Thus, using the fact that

$$\frac{t(2-\beta)[2\theta+t(2-\beta)+2t(2\beta-1)]}{9} > \frac{\alpha t(2-\beta)[2\theta+\alpha t(2-\beta)+2t(2\beta-1)]}{9},$$

there is no region of K where the two types have no incentive to deviate from $k_2 = (K, 0)$ when $k_1 = K$. Moreover, $k_2 = (K, 0)$ is never a best reply also to $k_1 = 0$. In fact, the two required

conditions $\frac{\alpha t(2-\beta)[2\theta+\alpha t(2-\beta)]}{9} \geq K$ and $K \geq \frac{t(2-\beta)[2\theta+t(2-\beta)]}{9}$ can never be both satisfied at the same time. Consider now $k_2 = (0, K)$. This strategy can be a best reply to $k_1 = K$ only if

$$\frac{\alpha t(2-\beta)[2\theta+\alpha t(2-\beta)+2t(2\beta-1)]}{9} \leq K \leq \frac{t(2-\beta)[2\theta+t(2-\beta)+2t(2\beta-1)]}{9}.$$

We first need to check if in this region $k_1 = K$ can be a best reply to $\mathbf{k_2} = (0, K)$, which occurs for $E(\Pi_1|k_1 = K, k_{2L} = 0, k_{2H} = K) \geq E(\Pi_1|k_1 = 0, k_{2L} = 0, k_{2H} = K)$. This is satisfied for

$$(1-\mu)(\frac{(\theta+t(2-\beta))^2}{9} - K) + \mu(\frac{(\theta+t(2-\beta)+t(2\beta-1))^2}{9} - K) \geq (1-\mu)\frac{\theta^2}{9} + \mu(\frac{(\theta+t(2\beta-1))^2}{9}),$$

or $K \leq \frac{t(2-\beta)[2\theta+t(2-\beta)+2t\mu(2\beta-1)]}{9}$. Note that this threshold is always smaller than $\frac{t(2-\beta)[2\theta+t(2-\beta)+2t(2\beta-1)]}{9}$ for $0 < \mu < 1$.

Let define

$$\frac{\alpha t(2-\beta)[2\theta + \alpha t(2-\beta) + 2t(2\beta-1)]}{9} \equiv h$$

and

$$\frac{t(2-\beta)[2\theta + t(2-\beta) + 2t\mu(2\beta-1)]}{9} \equiv \gamma(\mu)$$

The threshold $\gamma(\mu)$ depends on firm 1's beliefs and is increasing in μ. It is straightforward to show that $\gamma(1)$ represents the threshold under which efficient firms invest under complete information, provided that the rival invest, while $\gamma(0)$ is the threshold under which an efficient firm invests when the rival does not invest. Under complete information, symmetric firms' R&D choices at equilibrium are always symmetric; on the contrary, when firms are not equally efficient in R&D activity, it can exist an equilibrium in which only the efficient firm invests. This choice is optimal as long as $K \leq \gamma(0)$. Moving back to the incomplete information setting, some simple algebra shows that the threshold $\gamma(\mu)$ is larger than h for most of the parameters' values, more specifically when the parameter α is not very close to 1. In this case, $\mathbf{k} = (K, (0, K))$ is sustainable as equilibrium in this part of the game for $h \leq K \leq \gamma(\mu)$. When $K > \gamma(\mu)$, instead, $k_1 = 0$ is the best reply to $k_2 = (0, K)$. However, when firm 1 does not invest, the efficient type of firm 2 invests only if $(\Pi_{2H}|k_1 = 0, k_{2H} = K) \geq (\Pi_{2H}|k_1 = 0, k_{2H} = 0)$, that is if $K \leq \frac{t(2-\beta)[2\theta+t(2-\beta)]}{9} \equiv \gamma(0)$. Hence, since $\gamma(0) < \gamma(\mu)$, the strategy $\mathbf{k} = (0, (0, K))$ can never be part of an equilibrium.

Let us now move to analyze the possible equilibria in which the two types of firm 2 choose the same investment strategy. When $k_2 = (K, K)$, firm 1's best reply is $k_1 = K$ only if $E(\Pi_1|k_1 = K, k_{2L} = K, k_{2H} = K) \geq E(\Pi_1|k_1 = 0, k_{2L} = K, k_{2H} = K)$, that is for

$$K \leq \frac{t}{9}(2-\beta)\left[(2\theta + t(2-\beta) + 2t(2\beta-1)(\mu + (1-\mu)\alpha)\right].$$

As shown before, when firm 1 invests, type α_L has no incentive to deviate from $k_{2L} = K$ if $K \leq h$, while type α_H has no incentive to deviate from $k_{2H} = K$ if $K \leq \frac{t(2-\beta)[2\theta+t(2-\beta)+2t(2\beta-1)]}{9} \equiv \gamma(1)$.

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Given that the binding threshold is the one of the inefficient type, $\mathbf{k} = (K, (K, K))$ can be sustained as an equilibrium investment strategy for $K \leq h$. The strategy profile $\mathbf{k} = (0, (K, K))$, instead, can never be part of an equilibrium. Indeed, $k_1 = 0$ is the best reply to $k_2 = (K, K)$ when $K \geq \frac{t}{9}(2 - \beta)\left[(2\theta + t(2 - \beta) + 2t(2\beta - 1)(\mu + (1 - \mu)\alpha)\right]$, but in this region type α_H will not invest if $k_1 = 0$. Finally, we need to check possible equilibria in which the two types of firm 2 do not invest. The strategy $k_1 = 0$ is a best reply to $k_2 = (0, 0)$ when $K \geq \gamma(0)$. This threshold also define the region for which $k_{2H} = 0$ is a best reply to $k_1 = 0$. As for the inefficient type, $k_{2L} = 0$ is a best reply to $k_1 = 0$ when $K \geq \frac{\alpha t(2-\beta)[2\theta + \alpha t(2-\beta)]}{9}$, which is lower than $\gamma(0)$. In this case the binding threshold is the highest one, so $\mathbf{k} = (0, (0, 0))$ can be part of an equilibrium for $K \geq \gamma(0)$. On the contrary, $\mathbf{k} = (K, (0, 0))$ cannot be an equilibrium, given that firm 1 has no incentive to deviate for $K \leq \gamma(0)$, the efficient type has no incentive to deviate for $K \geq \gamma(1)$, and $\gamma(0) < \gamma(1)$.

To sum up, the equilibrium combinations of investment strategies in R&D competition are: (i) $\mathbf{k} = (K, (0, K))$ for $h \leq K \leq \gamma(\mu)$, (ii) $\mathbf{k} = (K, (K, K))$ for $K \leq h$, (iii) $\mathbf{k} = (0, (0, 0))$ for $K \geq \gamma(0)$.

The threshold $\gamma(0)$ and $\gamma(\mu)$ do not depend on α, while h is increasing in α and exceed $\gamma(0)$ and $\gamma(\mu)$ as α comes close to 1. Considering the possible order of the thresholds, it turns out that in some regions of parameters there are multiple equilibria. In particular, for the values of α such that $\gamma(\mu) > h$, when $\max\{\gamma(0), h\} \leq K \leq \gamma(\mu)$ both $\mathbf{k} = (K, (0, K))$ and $\mathbf{k} = (0, (0, 0))$ are possible equilibria. Let define this region as "I". Moreover, for α such that $\gamma(0) < h$, when $\gamma(0) \leq K \leq h$, $\mathbf{k} = (K, (K, K))$ and $\mathbf{k} = (0, (0, 0))$ coexist. Let define this region as "II". In these regions, we can select a single equilibrium using the *interim Pareto dominance* criterion.

(*b*) *Equilibrium selection*

Definition (Interim Pareto Dominance). *Let s be a generic combination of strategies at some point of the game. An equilibrium entailing a strategy profile s$'$interim Pareto dominates an equilibrium entailing s$''$ if, given the available information at the time in which s$'$ and s$''$ are chosen, the payoffs stemming from s$'$ are such that no player is worse off and at least one player is better off, with respect to the payoffs stemming from s$''$.*

Consider first region "I". It is easy to show that:

(i) for type α_L, $(\Pi_{2L}|\mathbf{k} = (K, (0, K))) = \frac{[\theta + t(2\beta - 1)]^2}{9} > \frac{\theta^2}{9} = (\Pi_{2L}|\mathbf{k} = (0, (0, 0)))$;

(ii) for type α_H, $(\Pi_{2H}|\mathbf{k} = (K, (0, K)) \geq (\Pi_{2H}|\mathbf{k} = (0, (0, 0))$, given that

$$\frac{[\theta + t(2-\beta) + t(2\beta - 1)]^2}{9} - K \geq \frac{\theta^2}{9}$$

occurs for

$$K \leq \frac{(t(2-\beta) + t(2\beta-1))(2\theta + t(2-\beta) + t(2\beta-1))}{9} = \gamma(\mu) + \frac{t(2\beta-1)[2\theta + 2t(2-\beta)(1-\mu) + t(2\beta-1)]}{9}$$

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;

(iii) for firm 1 $E(\Pi_1|\mathbf{k} = (K, (0, K))) \geq E(\Pi_1|\mathbf{k} = (0, (0, 0)))$, given that

$$\mu \left\{ \frac{(\theta + t(2-\beta) + t(2\beta-1))^2}{9} - K \right\} + (1 - \mu) \left\{ \frac{(\theta + t(2-\beta))^2}{9} - K \right\} \geq \mu \frac{\theta^2}{9} + (1 - \mu) \frac{\theta^2}{9}$$

holds for

$$\begin{aligned} K &\leq \mu \left\{ \frac{(t(2-\beta) + t(2\beta-1))(2\theta + t(2-\beta) + t(2\beta-1))}{9} \right\} + (1 - \mu) \left\{ \frac{t(2-\beta)(2\theta + t(2-\beta))}{9} \right\} = \\ &= \gamma(\mu) + \frac{t\mu(2\beta-1)[2\theta + t(2\beta-1)]}{9}. \end{aligned}$$

Then, in region "I", an equilibrium with $\mathbf{k} = (K, (0, K))$ at second stage *interim Pareto dominates* an equilibrium with $\mathbf{k} = (0, (0, 0))$.

Similarly, given that,

(i) $(\Pi_{2L}|\mathbf{k} = (K, (K, K))) \geq (\Pi_{2L}|\mathbf{k} = (0, (0, 0)))$ when

$$K \leq \frac{[\alpha t(2 - \beta) + t(2\beta - 1)][2\theta + \alpha t(2 - \beta) + t(2\beta - 1)]}{9} \equiv \phi;$$

(ii) $(\Pi_{2H}|\mathbf{k} = (K, (K, K))) \geq (\Pi_{2H}|\mathbf{k} = (0, (0, 0)))$ when

$$K \leq \frac{[t(2 - \beta) + t(2\beta - 1)][2\theta + t(2 - \beta) + t(2\beta - 1)]}{9} \equiv z;$$

(iii) $E(\Pi_1|\mathbf{k} = (K, (K, K)) \geq E(\Pi_1|\mathbf{k} = (0, (0, 0)))$ when

$$K \leq \mu \left\{ \frac{[t(2-\beta) + t(2\beta-1)][2\theta + t(2-\beta) + t(2\beta-1)]}{9} \right\} + (1 - \mu) \left\{ \frac{[t(2-\beta) + \alpha t(2\beta-1)][2\theta + t(2-\beta) + \alpha t(2\beta-1]}{9} \right\} =$$

$$= \mu z + (1 - \mu) \left\{ \frac{[t(2-\beta) + \alpha t(2\beta-1)][2\theta + t(2-\beta) + \alpha t(2\beta-1]}{9} \right\};$$

(iv) $h < \phi < \mu z + (1 - \mu) \left\{ \frac{[t(2-\beta) + \alpha t(2\beta-1)][2\theta + t(2-\beta) + \alpha t(2\beta-1]}{9} \right\} < z;$

we can say that in region "II" an equilibrium $\mathbf{k} = (K, (K, K))$ *interim Pareto dominates* an equilibrium with $\mathbf{k} = (0, (0, 0))$.

Hence, using the above equilibrium selection, we can partition the domain of K in regions with a unique equilibrium as follows: (i) $\mathbf{k} = (K, (K, K))$ for $K \leq h$; (ii) $\mathbf{k} = (K, (0, K))$ for $h < K \leq \gamma(\mu)$; (iii) $\mathbf{k} = (0, (0, 0))$ for $K > \max\{\gamma(\mu), h\}$. ∎

Proposition 2. *It does always exist a range of investment cost K, defined by $\max\{h, \gamma(\mu)\} < K \leq \gamma(1)$, for which the presence of incomplete information prevents both efficient firms, namely firm 1 and the efficient type of firm 2, from investing in R&D.*

Proof. As shown in Proposition 1, when $K > \max\{\gamma(\mu), h\}$, the equilibrium investment strategy under incomplete information is $\mathbf{k} = (0, (0,0))$, that is no firm invests. For lower levels of K, instead, the two efficient firms, namely firm 1 and type α_H, invest. Under complete information, if the firms are equally efficient, an equilibrium with investment by part of both firms is sustainable as long as $K \leq \gamma(1)$. Indeed, $k_{2H} = K$ is a best reply to $k_1 = K$ if $(\Pi_{2H}|k_1 = K, k_{2H} = K) \geq (\Pi_{2H}|k_1 = K, k_{2H} = 0)$, that is if

$$\frac{[\theta + t(2\beta - 1) + t(2 - \beta)]^2}{9} - K \geq \frac{[\theta + t(2\beta - 1)]^2}{9},$$

or

$$K \leq \frac{t(2 - \beta)[2\theta + t(2 - \beta) + 2t(2\beta - 1)]}{9} \equiv \gamma(1).$$

Symmetrically, $k_1 = K$ is a best reply to $k_{2H} = K$ if $K \leq \gamma(1)$. Since $\gamma(1) > \gamma(\mu)$, we can define $K \in (\max\{\gamma(\mu), h\}, \gamma(1)]$ as the region in which incomplete information equilibria differ from those arising under complete information. Specifically, there is investment only if information is complete. Also, firms' profits are higher when they choose to invest in R&D. ∎

Proposition 3. *When firms are asymmetric, and $\max\{\gamma(0), h\} < K \leq \gamma(\mu)$, incomplete information leads firm 1 to an ex post suboptimal investment choice.*

Proof. We start by showing that in the region characterized by $\max\{\gamma(0), h\} < K \leq \gamma(\mu)$, if information is complete and firms are asymmetric, the investment strategy at equilibrium is such that none of the two firms invest. Indeed, given that:

(i) $k_{2L} = K$ is a best reply to $k_1 = 0$ if $\frac{[\theta + \alpha t(2 - \beta)]^2}{9} - K \geq \frac{\theta^2}{9}$, or

$$K \leq \frac{1}{9}\alpha t(2 - \beta)[2\theta + \alpha t(2 - \beta)];$$

(ii) $k_{2L} = K$ is a best reply to $k_1 = K$ if $\frac{[\theta + \alpha t(2 - \beta) + t(2\beta - 1)]^2}{9} - K \geq \frac{[\theta + t(2\beta - 1)]}{9}$, or

$$K \leq \frac{1}{9}\alpha t(2 - \beta)[2\theta + t\alpha(2 - \beta) + 2t(2\beta - 1)] \equiv h;$$

(iii)

$$\frac{1}{9}\alpha t(2 - \beta)[2\theta + \alpha t(2 - \beta)] \leq \frac{1}{9}\alpha t(2 - \beta)[2\theta + t\alpha(2 - \beta) + 2t(2\beta - 1)],$$

the threshold h represents the maximum value of K making the inefficient firm willing to invest. Hence, when $K > h$, the inefficient firm will never invest and $k_1 = K$ is a best reply to $k_{2L} = 0$ if $\frac{(\theta + t(2 - \beta))^2}{9} - K \geq \frac{\theta^2}{9}$, or $K \leq \frac{1}{9}t(2 - \beta)[2\theta + t(2 - \beta)] \equiv \gamma(0)$. As long as the parameter α is not very close to 1, that is if the gap in R&D productivity is sufficiently high, the order of the threshold is such that $h < \gamma(0)$. If this is the case, for $K > \gamma(0)$ there is no investment, that is $(k_1, k_{2L}) = (0, 0)$. The same outcome arises for $K > h$, when α is close to 1

and $h > \gamma(0)$. In this case, since firms are almost equally efficient, an asymmetric equilibrium such that $(k_1, k_{2L}) = (K, 0)$ simply does not exist and we have only symmetric equilibria: $(k_1, k_{2L}) = (K, K)$ for $K \leq h$ and $K = (k_1, k_{2L}) = (0, 0)$ for $K \geq \gamma(0)$. Simple algebra shows that in the region $\gamma(0) \leq K \leq h$ the equilibrium strategy $K = (k_1, k_{2L}) = (K, K)$ *interim Pareto dominates* $K = (k_1, k_{2L}) = (0, 0)$. Hence we consider the following unique equilibria: $(k_1, k_{2L}) = (K, K)$ for $K \leq h$ and $K = (k_1, k_{2L}) = (0, 0)$ for $K > h$. We have thus shown that, under complete information, two asymmetric firms do not invest when $K > \max\{\gamma(0), h\}$. Under incomplete information, instead, firm 1 invests until $K \leq \gamma(\mu)$, simply because of the positive probability to face an efficient firm that would invest. However, once all information is unveiled and the rival turns out to be the inefficient type, when $\max\{\gamma(0), h\} < K \leq \gamma(\mu)$, for firm 1 the optimal choice would be not invest, given $k_{2L} = 0$. ∎

Lemma 1. *For $h < K \leq z$, a perfect Bayesian equilibrium with, at the first stage, a strategy profile $s_2 = (Yes, No)$ for firm 2 never exists.*

Proof. We need to demonstrate that the separating strategy $s_2 = (Yes, No)$ following firm 1's RDA proposal cannot be part of a PBE in the regions of parameters we are interested in. Let us start by considering type α_L's payoffs. Following the strategy, the inefficient type commits to invest and obtains $(\Pi_{2L}|k_1 = K, k_{2L} = K) = \frac{1}{9}(\theta + \alpha t(2 - \beta) + t(2\beta - 1))^2 - K$. If it deviates, in R&D competition $\mu = 1$, hence firm 1 invests until $K \leq \frac{t(2-\beta)[2\theta+3t\beta]}{9} \equiv \gamma(1)$. Remember that we are considering only the regions for which $h < K \leq z$ and that over the threshold h, when firm 1 invests, type α_L is better off not investing and simply exploiting the spillover. Hence, for $h < K \leq \gamma(1)$, $s_2 = (Yes, No)$ cannot be part of an equilibrium strategy since type α_L has incentive to deviate. For the remaining part of the region we are considering, namely $\gamma(1) < K \leq z$, we show that type α_H has incentive to deviate from $s_{2H} = No$. In fact, in R&D competition, the equilibrium strategy at the second stage entails no investment by both firms, while type α_H's profit under RDA would be higher:

$$(\Pi_{2H}|K_1 = K, K_{2H} = K) = \frac{1}{9}(\theta + t(2 - \beta) + t(2\beta - 1))^2 - K \geq$$

$$> \frac{\theta^2}{9} = (\Pi_{2H}|K_1 = 0, K_{2H} = 0)$$

for

$$K \leq \frac{(t(2 - \beta) + t(2\beta - 1))(2\theta + t(2 - \beta) + t(2\beta - 1))}{9} \equiv z.$$

∎

Lemma 2. *For any $\alpha \in (0, 1)$ and $\max\{\phi, \gamma(0)\} \leq K \leq z$, an equilibrium in which firm 1 proposes a R&D agreement at the first stage and firm 2 plays a separating strategy, such that $\mathbf{s} = (RDA, (No, Yes))$ always arises.*

Proof. Let us start by defining the region in which $s_2 = (No, Yes)$ can be a best reply to firm 1's RDA proposal. First of all, note that type α_H has never incentive to deviate from accepting firm 1's proposal in the region of parameters we are considering when analyzing R&D agreements, namely $h < K \leq z$. If it follows the strategy it can obtain

$$(\Pi_{2H}|K_1 = K, \ K_{2H} = K) = \frac{1}{9} \left(\theta + t(2 - \beta) + t(2\beta - 1) \right)^2 - K.$$

If it deviates playing "No", in R&D competition $\mu = 0$, that is firm 1 thinks to compete with a less efficient rival and invests until $K \leq \gamma(0)$ (see Proof of Proposition 3). Type α_H's best replies are symmetric with respect to firm 1's actions, hence by deviating type α_H would obtain:

(i) $(\Pi_{2H}|k_1 = K, \ k_{2H} = K) = \frac{1}{9} [\theta + t(2 - \beta) + t(2\beta - 1)]^2 - K$ when $K \leq \gamma(0)$ and

(ii) $(\Pi_{2H}|k_1 = 0, \ k_{2H} = 0) = \frac{1}{9} \theta^2$ when $K > \gamma(0)$.

Hence, in case (i) type α_H has no incentive to deviate simply because deviation would lead to the same payoff. In case (ii) type α_H has no incentive to deviate since

$$(\Pi_{2H}|k_1 = K, \ k_{2H} = K) \geq (\Pi_{2H}|k_1 = 0, \ k_{2H} = 0)$$

when $K \leq z$ (see Proof of Lemma 1).

Consider now type α_L. If it follows the strategy and refuses the agreement it ends up in R&D competition under complete information. In this case there are two possible outcomes for $K \in (h, z]$: only firm 1 invests when $h < K \leq \gamma(0)$, while no firm invests when $K > \gamma(0)$. By deviating and accepting the RDA, type α_L would obtain

$$(\Pi_{2L}|k_1 = K, \ k_{2L} = K) = \frac{1}{9} \left(\theta + \alpha t(2 - \beta) + t(2\beta - 1) \right)^2 - K.$$

In the region of parameters such that $h < K \leq \gamma(0)$, type α_L has no incentive to deviate since

$$(\Pi_{2L}|k_1 = K, \ k_{2L} = 0) > (\Pi_{2L}|k_1 = K, \ k_{2L} = K)$$

when $K > h$. For $K > \gamma(0)$, type α_L has no incentive to deviate if

$$(\Pi_{2L}|k_1 = 0, \ k_{2L} = 0) \geq (\Pi_{2L}|k_1 = K, \ k_{2L} = K),$$

that is if

$$K \geq \frac{(\alpha t(2 - \beta) + t(2\beta - 1)) (2\theta + \alpha t(2 - \beta) + t(2\beta - 1))}{9} \equiv \phi,$$

with $\phi < z$.

Note that, in the region where $K \leq \gamma(0)$, $s_2 = (No, Yes)$ can be sustainable as part of a perfect Bayesian equilibrium, however this strategy would lead to the same outcome arising in R&D competition. Since we are focusing on the cases in which the RDA can affect the R&D competition equilibria, in the following we disregard this region. Hence we analyze firm 1's incentives to propose

the RDA when $\max\{\gamma(0), \phi\} < K \leq z$. Let define this region as "L". Since firm 1 anticipates firm 2's reaction, it knows that after the RDA proposal the efficient type will accept while the inefficient type will not. In absence of RDA proposal, the game will continue in R&D competition regime with $Pr(\alpha = \alpha_H) = \mu$.

Firm 1 will propose the RDA if

$$E(\Pi_1 | RDA, (No, Yes)) \geq E(\Pi_1 | NRDA, (No, Yes)).$$

The payoffs characterizing both the l.h.s and the r.h.s. depend on the value of K, hence we need to analyze firm 1' incentives according to different ranges for the parameter K inside region "L". In absence of agreement, as long as $K \leq \gamma(\mu)$, the equilibrium strategy at the second stage in R&D competition under incomplete information is $\mathbf{k} = (K, (0, K))$ (see Proof of Proposition 1). If firm 1 propose the RDA, at the second stage information will be complete given firm 2' separating strategy: when $\alpha = \alpha_L$ the RDA is not reached and there is no investment in R&D competition (see Proof of Proposition 3), while when $\alpha = \alpha_H$ the RDA is formed and both firms invest. Then, firm 1 will play $s_1 = RDA$ since

$$\mu \left\{ \frac{1}{9} [\theta + t(2 - \beta) + t(2\beta - 1)]^2 - K \right\} + (1 - \mu) \left\{ \frac{1}{9} \theta^2 \right\} \geq$$

$$\geq \mu \left\{ \frac{1}{9} [\theta + t(2 - \beta) + t(2\beta - 1)]^2 - K \right\} + (1 - \mu) \left\{ \frac{1}{9} [\theta + t(2 - \beta)]^2 - K \right\},$$

for $K \geq \gamma(0)$.

When instead, in region "L", $K > \gamma(\mu)$, the equilibrium strategy at the second stage in R&D competition under incomplete information is $\mathbf{k} = (0, (0, 0))$. The l.h.s. of the inequality is the same as above. Then, firm 1 will play $s_1 = RDA$ since

$$\mu \frac{1}{9} ([\theta + t(2 - \beta) + t(2\beta - 1)]^2 - K) + (1 - \mu) \frac{\theta^2}{9} \geq \mu \frac{\theta^2}{9} + (1 - \mu) \frac{\theta^2}{9}$$

for $K \leq z$. Hence, we can conclude that $\mathbf{s} = (RDA, (No, Yes))$ at the first stage can be part of a separating PBE for $\max\{\gamma(0), \phi\} < K \leq z$. ∎

Lemma 3. *For $\alpha > \alpha^*$ and $\max\{h, \gamma(0)\} < K \leq \phi$, an equilibrium in which firm 1 proposes a R&D agreement and firm's 2 plays a pooling strategy such that: $\mathbf{s} = (RDA, (Yes, Yes))$ always occurs.*

Proof. As before, we start by looking for the regions of parameters in which $s_2 = (Yes, Yes)$ can be a best reply to the proposal of a RDA. Type α_H has never incentive to deviate from $s_{2H} = Yes$ since, as long as $K \leq z$, the profit resulting from investment by part of both the efficient firms is the highest attainable. Hence, we assume that firm 1 will set $\mu = 0$ after observing a refusal (out of equilibrium path) and, once in R&D competition, will invest only if

$K \le \gamma(0)$.[20] Below this threshold, type α_L has incentive to deviate from $s_{2L} = Yes$ since the profit obtained in R&D competition regime ($\Pi_{2L}|k_1 = K$, $k_{2L} = 0$) is higher than that resulting from joint investment ($\Pi_{2L}|k_1 = K$, $k_{2L} = K$) for every $K > h$. When $K > \gamma(0)$, type α_L compares ($\Pi_{2L}|k_1 = K$, $k_{2L} = K$) with ($\Pi_{2L}|k_1 = 0$, $k_{2L} = 0$) and, accordingly, will follow the strategy $s_{2L} = Yes$ only if $K \le \phi$ (see Proof of Proposition 1). It follows that $s_2 = (Yes, Yes)$ can be part of a PBE only if $\phi > \gamma(0)$, that is if

$$\frac{[\alpha t(2 - \beta) + t(2\beta - 1)][2\theta + \alpha t(2 - \beta) + t(2\beta - 1)]}{9} > \frac{t(2 - \beta)[2\theta + t(2 - \beta)]}{9}.$$

Solving for α, the above inequality is satisfied for

$$\alpha > 1 - \frac{2\beta - 1}{2 - \beta} \equiv \alpha^*$$

Hence, $s_2 = (Yes, Yes)$ can be a best reply to firm 1's proposal when $\alpha \ge \alpha^*$ and $\max\{\gamma(0), h\} < K \le \phi$.

It is easy to show that proposing the RDA is an optimal strategy for firm 1 in this region. Indeed, in this region, the equilibria arising under R&D competition regime are such that (i) no firm invests when $K > \gamma(\mu)$ while (ii) only efficient firms invest when $K \le \gamma(\mu)$ (remember that $\gamma(\mu) > \gamma(0)$). In case (i)

$$E(\Pi_1 | RDA, (Yes, Yes)) \ge E(\Pi_1 | NRDA, (Yes, Yes))$$

since

$$\mu \left\{ \frac{1}{9} [\theta + t(2 - \beta) + t(2\beta - 1)]^2 - K \right\} +$$

$$+ (1 - \mu) \left\{ \frac{1}{9} [\theta + t(2 - \beta) + \alpha t(2\beta - 1)]^2 - K \right\}$$

$$\ge \mu \left\{ \frac{1}{9} \theta^2 \right\} + (1 - \mu) \left\{ \frac{1}{9} \theta^2 \right\}$$

when

$$K \le \mu z + (1 - \mu) \frac{1}{9} [t(2 - \beta) + \alpha t(2\beta - 1)][2\theta + t(2 - \beta) + \alpha t(2\beta - 1)]$$

and

$$\mu z + (1 - \mu) \frac{1}{9} [t(2 - \beta) + \alpha t(2\beta - 1)][2\theta + t(2 - \beta) + \alpha t(2\beta - 1)]$$

is a convex combination between two elements larger than ϕ.

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[20] Since in the analysis of first stage equilibrium strategies we do not take into account the region for which $K \le h$, here we do not consider the case in which α is close to one and both asymmetric firms invest below the threshold h.

In case (ii),
$$E(\Pi_1|RDA, (Yes, Yes)) \geq E(\Pi_1|NRDA, (Yes, Yes)),$$

since

$$\mu\left\{\frac{1}{9}\left[\theta + t(2-\beta) + t(2\beta-1)\right]^2 - K\right\} + (1-\mu)\left\{\frac{1}{9}\left[\theta + t(2-\beta) + \alpha t(2\beta-1)\right]^2 - K\right\} \geq$$

$$\geq \mu\left\{\frac{1}{9}\left[\theta + t(2-\beta) + t(2\beta-1)\right]^2 - K\right\} + (1-\mu)\left\{\frac{1}{9}\left[\theta + t(2-\beta)\right]^2 - K\right\}.$$

Hence, we can conclude that $\mathbf{s} = (RDA, (Yes, Yes))$ is an equilibrium strategy at the first stage for $\max\{\gamma(0), h\} < K \leq \phi$. $\blacksquare$

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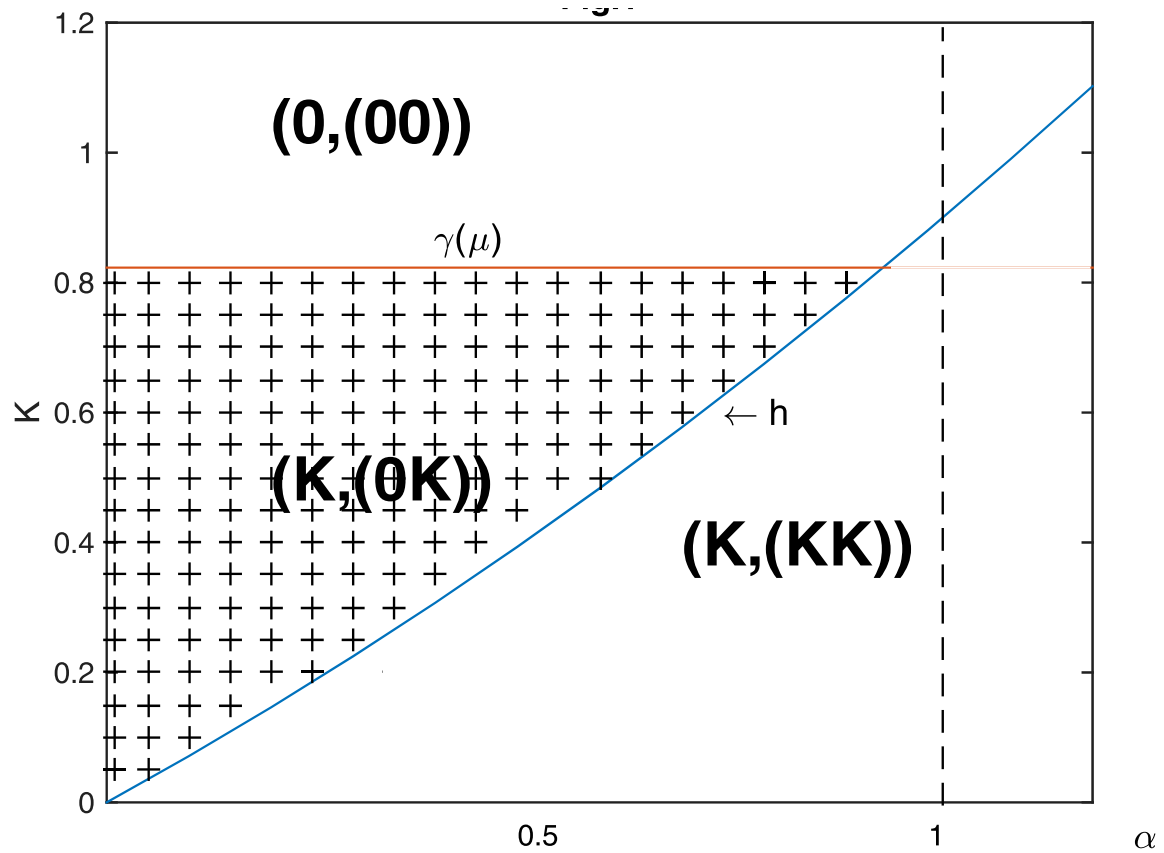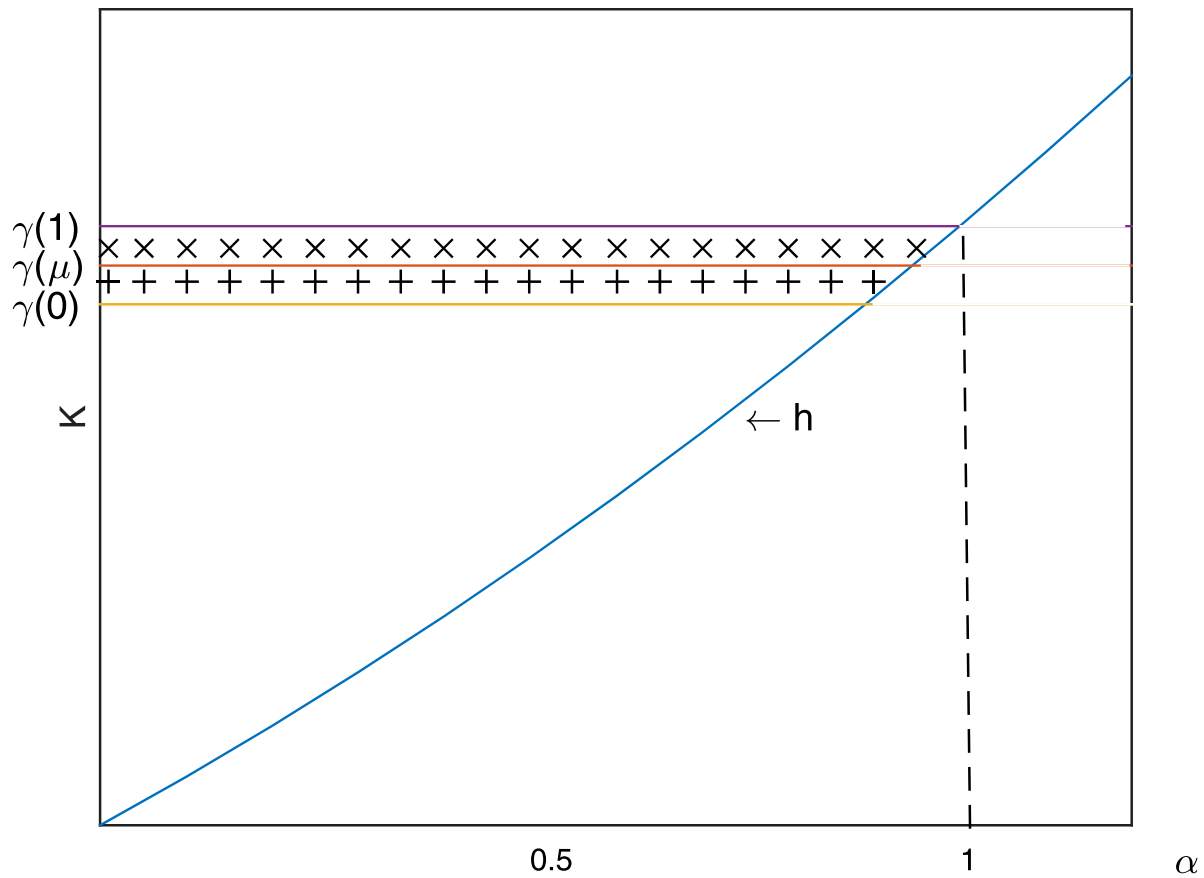
Figure 1: R&D competition Investment decisions

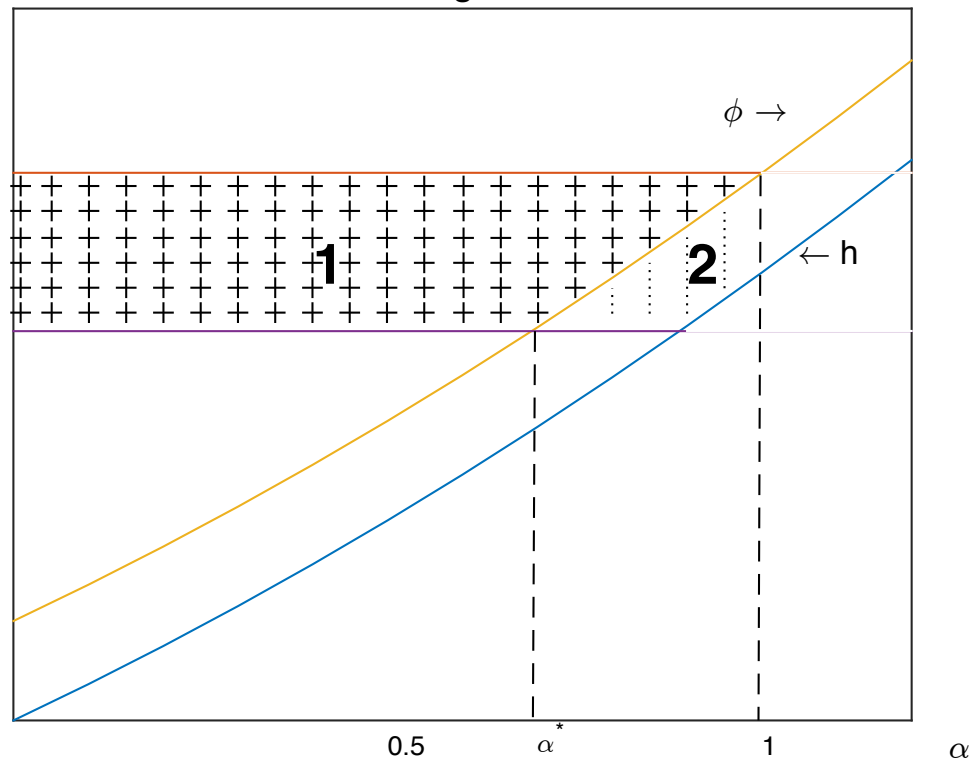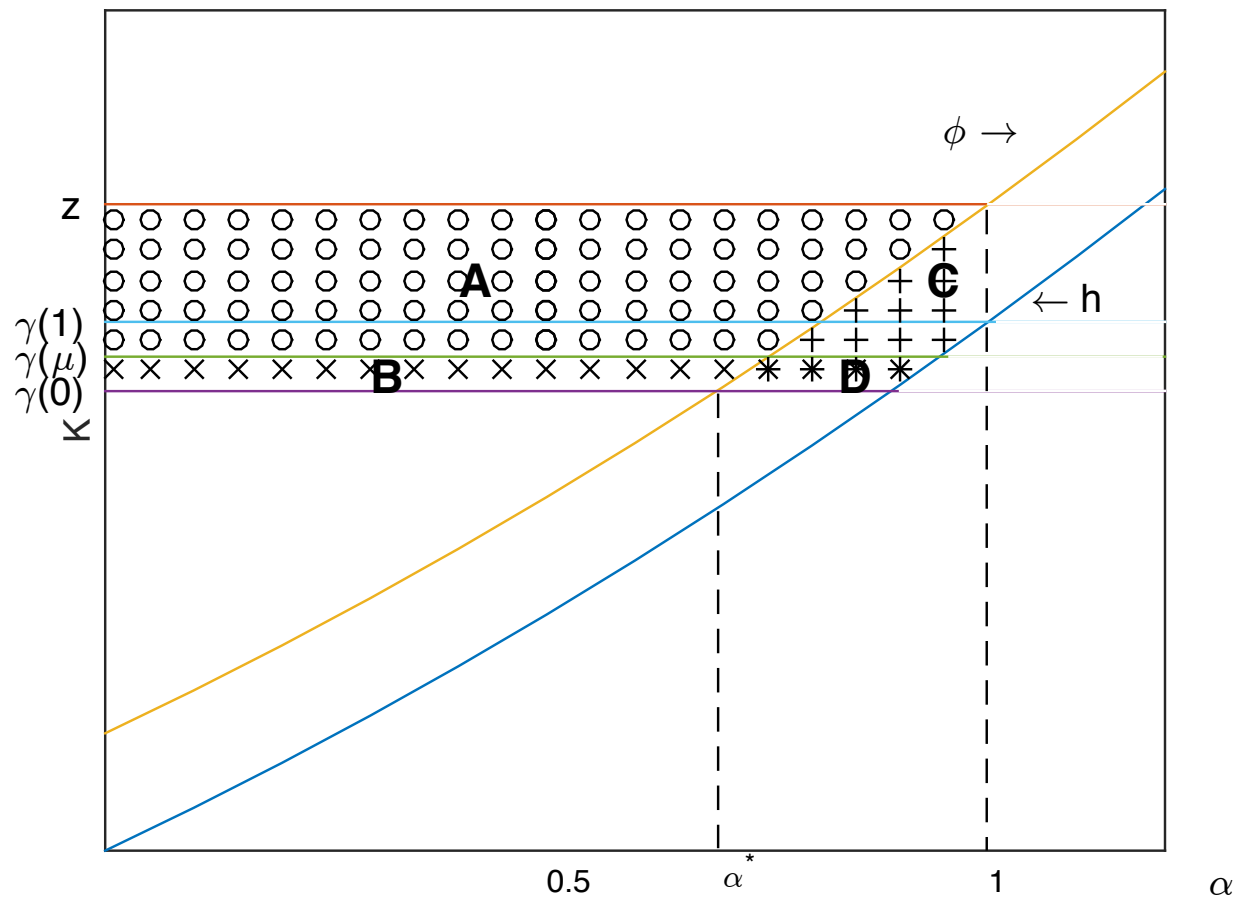**Figure 2: R&D competition - Effects of incomplete information**

Figure 3: RDA agreements - Equilibria

Figure 4: RDA agreements - Screening effects