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Public-Private R&D Partnerships: A Solution to Increase Knowledge Sharing in R&D Cooperation*

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Abstract

Knowledge sharing is crucial for the success of most R&D cooperations. This paper investigates the best conditions for fostering knowledge sharing in R&D cooperation and looks at how the establishment of Public-Private R&D Partnerships (PPP in R&D) could be a useful tool for this purpose. In this end, it proposes a theoretical model, related to the R&D cooperation literature, that takes into consideration the impacts of firms outside R&D cooperation and the presence of two kinds of spillover: a technology spillover and a product rivalry effect. The model shows that both spillovers can affect knowledge sharing negatively, and that PPP in R&D can be useful to promote knowledge sharing. First, public authorities can choose partners that will facilitate efficient knowledge sharing. Second, to avoid the negative impacts of spillovers on behavior in terms of knowledge sharing, public laboratories should be used as intermediaries for the prior and strategic knowledge of firms. Public labs can use the prior knowledge of firms to innovate, and then spread this innovation among the partners of the PPP, without spreading the prior knowledge of the firms.

Keywords: Public-Private R&D Partnership, R&D cooperation, Knowledge Sharing, Spillovers.
JEL Codes: L13, L24, O30, O38.

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1 Introduction

The development of high-tech requires a large amount of knowledge and/or data. For example, in biotechnologies, plant variety creation needs knowledge on genes and enabling technologies that are partially protected by intellectual property rights or kept secret. Similarly, the progress in artificial intelligence is built on a huge amount of data, but these data are held privately by several firms. This closed knowledge is crucial for the development of new technologies in several high-tech sectors. Firms and public authorities have different strategies that act as incentives to share their knowledge. One of them, studied in this paper, is R&D cooperation between firms and public authorities (through public research institutes and universities). Indeed, Public-Private R&D Partnerships (PPP in R&D) are widely spread in developed countries, owing to public policies such as the H2020 policy in Europe or CRADAs in the US. Some examples of PPP in R&D have been studied by Stiglitz and Wallsten (1999), Sperling (2001), Taubman (2004), Kang and Park (2012), Fuglie and Toole (2014), Audretsch et al. (2019) among others. However, the main focus in the economic literature is on the economic rationale for public funding when there is private under-investments due to spillover effects. PPP in R&D are also used to disseminate the public fundamental research with pre-competitive consortium (e.g. Williamson, 2000).

One current example of PPP in R&D where closed knowledge is crucial for the success of the cooperation is the *Amaizing* consortium[1]. This PPP in R&D incorporates public laboratories and eight firms in biotechnology (originating in France, Germany and the Swiss Confederation), essentially firms specialized in plant variety innovation. This PPP in R&D has one main goal: to provide a process innovation of use to firms. This innovation will allow firms to create new varieties of maize that will withstand low temperatures and consume less water and chemical nitrogen. To this end, firms should not just share their R&D costs but also their genetic resources, which are highly strategic,[2] and the results of different experiments. The more they share their knowledge, the more significant will be the innovation spawned by the cooperation since this innovation is mainly based on shared genetic resources.[3]

As Samaddar and Kadiyala (2006) pointed out, the failure of R&D cooperation is frequently due to a lack of knowledge sharing, specifically on the prior knowledge developed before the cooperation. Actually, firms inside R&D cooperation are often rivals in the product market if they supply substitutable products. Moreover, the knowledge sharing required for the success of a R&D cooperation could increase spillover effects. Therefore, if a firm shares its knowledge it takes the risk that its competitors will develop new, more competitive products thanks to its technology. There is thus potentially a tradeoff between the value of the innovation obtained by the cooperation and the intensity of competition in the product market. One approach for fostering knowledge sharing could be to promote cooperation only between some firms, giving them a technology advantage against other firms in the market. This technology advantage could be provided by innovation from

[1]This PPP in R&D is funded partially by the French national research agency (ANR). Similar consortia exist for other species such as Breedwheat, Rapsodyn, Sunrise or Peamust among others.

[2]The parent varieties of commercialized maize varieties are mostly kept secret in Europe unlike the US where many of them are patented (it is not possible to directly patent a plant variety in Europe).

[3]The main innovation that should be created in the consortium will be a prediction equation. In order to obtain a useful prediction equation, it is necessary for firms to share their secret parent varieties used currently for the development of new varieties.

within public laboratories inside a PPP in R&D. A case in point is *Amaizing* where the first and the second firms in terms of market share are outside the consortium (Monsanto owned by Bayer and Pioneer Hi-Bred owned by DowDupont). Therefore, the research questions focus on cooperative behavior in terms of knowledge sharing inside R&D cooperation, and on what the impact of introducing public authorities through PPP in R&D might be. First, the following study allows us to analyze the impacts of different aspects of R&D cooperation on knowledge sharing behaviors. We analyze specifically the intensity of competition between partners within the cooperation and the spillovers emerging from the knowledge sharing. We also study the effects of firms outside the R&D cooperation. Second, these results provide various clues in terms of policy to establish an adequate PPP in R&D for fostering firms' knowledge sharing.

To address the highlighted problematics, a theoretical model is developed here, mainly based on the literature on R&D cooperation (d'Aspremont and Jacquemin, 1988; Kamien et al., 1992). In the model, two firms engage in a R&D cooperation. A third firm is outside the cooperation. In the first stage, both firms inside the cooperation have to choose whether they share their knowledge, which is a discrete choice.[4] In the second stage, they compete in a Cournot oligopoly with the third firm. The intensity of competition between these firms is represented through a horizontal differentiation where the products supplied by the firms are not perfectly substitutable. Obtaining a useful innovation requires that firms share their knowledge within the R&D cooperation. The innovation obtained thanks to the R&D cooperation will increase the quality of the supplied products in the product market. At the same time, knowledge sharing involves two externalities: a technology spillover and a product rivalry effect. It is assumed that the technology spillover raises the quality of the product, but occurs only if the competitor inside the R&D cooperation shares its knowledge. Meanwhile, using the competitor's technology could increase the similarity of both supplied products. Therefore, the product rivalry effect increases the substitutability of products supplied by firms inside the R&D cooperation. Thus, for firms inside the cooperation, spillovers involve a positive impact by increasing the quality of products and a negative impact by increasing the competition. The costs of innovation and/or production for firms are not presented in the model, so that the impact of the competition and the spillovers on behavior in terms of knowledge sharing can be highlighted.

Our model suggests that innovation arising from the R&D cooperation, as well as the presence of a competitor outside the cooperation, increase the knowledge sharing within the cooperation. Conversely, the intensity of competition and the product rivalry effect, resulting from knowledge sharing, decrease the knowledge sharing. Less predictably, the technology spillover also reduces knowledge sharing. The presence of a technology spillover can encourage free-riding behavior. In some cases, a firm does not wish to share its knowledge when its partner in the collaboration shares its knowledge. In this case, the firm benefits from the technology spillover of its partner while its partner does not benefit from its technology. The firm with this behavior obtains an advantage in the product market but, unfortunately, this also leads to a lower innovation level since a firm refuses to share its knowledge. This negative effect of the technology spillover can nevertheless be reversed when the firm outside the cooperation competes strongly with firms within the cooperation. These results suggest that public authorities could promote knowledge

[4] In the example of the *Amaizing* consortium, firms would share either their current strategic parent varieties, that are useful for the consortium, or old parent varieties that they no longer use in their process of new variety creation, useless it is for the consortium.

sharing through public laboratories and by establishing PPP in R&D. To be optimal, it is preferable to establish PPP in R&D with firms that are not confronted with intense rivalry in the markets, and that have the same competitor. Furthermore, when the aim is to encourage knowledge sharing, cooperation should not imply a significant increase in product rivalry. To this end, public laboratories can serve as intermediaries between the different firms within the cooperation. Thus, access to knowledge could be total for public laboratories, while remaining very limited for firms. Public laboratories benefiting from the access of private knowledge could consequently innovate more effectively and spread these new innovations among all parties of the PPP in R&D.

The paper is organized as follows. In section 2 the economics literature related to the problematics, mainly on R&D cooperation, is reviewed. Section 3 presents the theoretical model. Section 4 shows the resolution of the model. Section 5 discusses the results of the model. Section 6 suggests some extensions of the model. Section 7 concludes.

2 Literature

Our research questions relate to the literature on R&D cooperation and knowledge sharing. Many authors have studied these problematics, starting with Katz (1986) and d'Aspremont and Jacquemin (1988). They modeled R&D cooperation in a Cournot framework where in a first stage, firms cooperate by maximizing the joint profit for the choice of R&D and, in a second stage, firms compete by maximizing their profit with respect to their quantities. The spillover plays a role by lowering the production cost. d'Aspremont and Jacquemin (1988) find that, with few firms and high spillovers, R&D cooperation is advantageous for firms. Katz (1986) shows that high levels of competition decrease effective R&D, whereas strong spillovers increase it. Moreover, when R&D influences the output, cooperation could reduce incentives to conduct R&D because it would help the firm's rivals. Various authors furthered this understanding by introducing asymmetry, dynamics, absorptive capacities and knowledge (Katz et al., 1990; Kamien et al., 1992; Motta, 1992; Suzumura, 1992; Ziss, 1994; Salant and Shaffer, 1998; Petit and Tolwinski, 1999; Cellini and Lambertini, 2009, among others). The main differences with the theoretical model developed in the next section are twofold: first, spillovers not only affect on the spread of technologies (through the cost function or the quality of the product), they also act directly on the differentiation of products; an second, there is a discrete choice related to the behavior of firms in terms of knowledge sharing. Aside from the R&D effort Sakakibara (2003) integrates into the model of d'Aspremont and Jacquemin (1988) complementary knowledge modeled as Cohen and Levinthal (1989). Before the maximization of profits in relation to the R&D effort and quantities, competitors have to choose the knowledge sharing ratio. The model suggests when rivals control complementary knowledge, cooperation increases the endogenous spillover ratio and R&D efforts. However, because of the difficulty of finding analytical results with a continuous function of knowledge sharing, we prefer a discrete choice. Contrary to this part of the economic literature, our research questions are related not to the establishment of R&D cooperation but to the free-riding behavior in terms of knowledge sharing inside the cooperation.

With a different theoretical model Peréz-Castrillo and Sandonís (1997) analyzed R&D cooperation where they introduced uncertainty on the cost of the R&D cooperation as a function of knowledge sharing behavior. Collaborators could know the cost only after the decision on knowledge sharing. To avoid free-riding behavior they introduced penalties in case one firm decided to leave the cooperation after the decision on knowledge sharing. They found that profitable R&D cooperations would not be established because of the incentive problem on knowledge sharing due to uncertainty on the cost. Introducing penalties is a possibility to reduce this incentive problem. The public authorities can also reduce the incentive problem by subsidizing the innovation value provided by the cooperation. However, subsidizing the cost of the R&D cooperation could be harmful for the cooperation. Compared to Peréz-Castrillo and Sandonís (1997), this paper aims at disentangling the impacts of spillovers implied by the knowledge sharing. Other authors (such as Bhattacharya et al., 1992; Gandal and Scotchmer, 1993; Pastor and Sandonís, 2002), introduced asymmetric information that may lead to a free-riding behavior. In the following model, the free-riding behavior is caused only by the spillover effects.

An original model, initially developed by Samaddar and Kadiyala (2006) (and expanded later by Ding and Huang, 2010), takes into account the R&D effort and the knowledge sharing. They differentiated between current research creation and prior knowledge. Unlike the previous articles, competitors are in a Stackelberg framework, with a leader and a follower, for decisions on the R&D effort and the knowledge sharing. However, in this theoretical model the stage of competition does not exist (the marginal gain is represented by a constant). The main result of this model is that the participation rate of the leader is positively affected by the marginal gain of the follower. However, the leader would participate only if its marginal gain were high enough compared to the marginal gain of the follower, whereas the follower always has positives incentives to collaborate.

The field of network theory also studies R&D cooperation. Like d'Aspremont and Jacquemin (1988), Goyal and Moraga-González (2001) and Goyal and Joshi (2003) build a theoretical model with Cournot competition where R&D and spillovers reduce the unit cost. They highlight that, in a Cournot competition with homogeneous goods, R&D effort is negatively influenced by cooperation. In this literature, empirical studies set out, partially, to test whether similarity between firms increases cooperative behavior. Cantner and Graf (2006), Hanaki et al. (2010) and Tomasello et al. (2017) use patent statistics to test the effect of similarity. Cantner and Graf (2006) employed citation data and found a positive effect. Tomasello et al. (2017) also obtained a positive impact but they used categories of patents (IPC classification) instead of citations. Conversely, Hanaki et al. (2010) found a negative effect with subcategories of patents. These results may reflect the fact that firms producing substitutable goods have more difficulties to cooperate, potentially due to the product rivalry effect (the negative result found by Hanaki et al. (2010) using subcategories of patents representing a narrow range of technologies) than do firms producing complementary goods (the positive result found by Tomasello et al. (2017) using categories of patents representing a wide range of technologies). Given moreover the fact that the product rivalry effect has been empirically identified by Bloom et al. (2013), we add a product rivalry effect when firms share their knowledge in the theoretical model.[5]

[5]The article of Bloom et al. (2013) is not specifically on R&D cooperation but on the global effect of spillovers in the economy.

3 The Model

3.1 Assumptions

The model includes two types of agent: three mono-product firms and a representative consumer. The firms supply horizontally differentiated products and compete in a Cournot oligopoly.[6] In some cases, the products also have different levels of quality. This difference in terms of quality leads to a different reservation price: a_i for the firm F_i, $i = \{1, 2, 3\}$. Firms F_1 and F_2 collaborate in R&D cooperation whereas firm F_3 is outside the cooperation. There is no fixed cost to join the cooperation. More generally, firms endure neither other kinds of fixed costs nor marginal costs.

The success of the cooperation depends crucially on the behavior of firms regarding knowledge sharing. In fact, the cooperation needs the prior knowledge of firms to produce a new innovation.[7] Here, the knowledge sharing is a discrete choice for firms F_1 and F_2. If both firms share their prior knowledge, the R&D cooperation leads to an innovation ω that will increase the quality of goods supplied by firms F_1 and F_2.[8] When only one firm shares its prior knowledge, the cooperation yields to a lower innovation $\omega_2 = \frac{\omega}{2}$ and if both firms reject the knowledge sharing, there is no longer innovation created within the cooperation ($\omega_3 = 0$).[9]

Assumption 1. *The innovation, stemming from the R&D cooperation, raises the reservation price of firms inside the R&D cooperation by*
- ω *when both firms share their knowledge,*
- $\omega_2 = \frac{\omega}{2}$ *when only one firm shares its knowledge,*
- $\omega_3 = 0$ *otherwise.*

As Bloom et al. (2013) highlighted, spillovers take two forms: there is a technology spillover λ and a product rivalry effect δ. Regarding the technology spillover, when the firm F_i shares its knowledge, the firm F_j inside the R&D cooperation will use this prior knowledge that will be useful to increase the F_j's product quality. Thus, the technology spillover additively raises the reservation price by λ.

Assumption 2. *The technology spillover raises the reservation price of firm F_i by λ if its competitor within the R&D cooperation shares its knowledge.*[10]

When both firms share their knowledge, the product rivalry effect will additively raise the substitutability of both products by δ. If only one firm shares its knowledge, the

[6]The Appendix C presents some aspects of the Bertrand competition.

[7]As explained by Samaddar and Kadiyala (2006) there is a difference between prior knowledge and current knowledge. Current knowledge is provided by the R&D cooperation (the innovation) whereas prior knowledge is the stock of knowledge provided by firms (a knowledge created or acquired before the cooperation). Samaddar and Kadiyala (2006) show examples of R&D cooperation becoming useless due to the lack of cooperation in the sharing of prior knowledge.

[8]The innovation, ω, will have similar impacts in the following theoretical model and in the model of d'Aspremont and Jacquemin (1988). Indeed, the effect of an innovation reducing the unit cost or increasing the reservation price has the same consequences in terms of strategic interactions (Spence, 1984) for a quadratic utility and a linear cost function.

[9]These choices in terms of values for ω_2 and ω_3 are made to keep the model the most as simple as possible. Keeping the order $\omega > \omega_2 > \omega_3$, other values can be chosen without changing qualitatively the results discussed later in the paper. A discussion on this point is made more precisely at the end of Section 4.2.

[10]The technology spillover can also be related to the absorptive capacity of the partners inside the R&D cooperation. Here, it is assumed that the absorptive capacity of both firms is the same.

product rivalry effect will be $\delta_2 = \frac{\delta}{2}$.[11]

Assumption 3. *The product rivalry effect increases the substitutability parameter by*
- δ *when both firms share their knowledge,*
- $\delta_2 = \delta/2$ *when only one firm share its knowledge,*
- 0 *otherwise.*

Compared to d'Aspremont and Jacquemin (1988) and a large part of the economic literature on R&D cooperation, spillovers do not affect the unit cost of production. In terms of strategic interaction, with linear demands and linear costs, the impacts of technology spillovers remain similar even if they affect on the reservation price and not the cost function. The product rivalry effect adds the idea that spillovers do not only affect firm's stock of knowledge but also the differentiation of their products.

The game has two stages. First, firms within the R&D cooperation have to choose whether they share their knowledge by maximizing their profits. This first stage is a game with two players (F_1 and F_2) and two possible actions (accept or refuse the knowledge sharing). Second, firms compete in a Cournot oligopoly. Since firms are rational, perfectly informed and profit maximizing, we use backward induction and the concept of subgame perfectness to resolve the game.

3.2 Consumer's demand

The heterogeneity of supplied products and the taste for diversity of the representative consumer[12] are represented through a quasi-linear utility function as in Bowley (1924), Spence (1976) and Dixit (1979)

$$U(q_1, q_2, q_3) = x_0+a_1q_1+a_2q_2+a_3q_3-(\beta_1q_1^2+\beta_2q_2^2+\beta_3q_3^2+2gq_1q_2+2\eta q_1q_3+2\eta q_2q_3)/2, \quad (1)$$

where x_0 represents a competitive *numéraire* sector and q_i is the quantity supplied by firm F_i. Elasticity parameters β_i are normalized to unity ($\beta_1 = \beta_2 = \beta_3 = 1$). It is assumed that reservation prices, a_i, are higher than zero and substitutability parameters, g and η, are included in $[0, 1[$. Note that for substitutability parameters equal to one, products would be perfectly homogeneous and for substitutability parameters equal to 0, firms would be monopolist. The maximization of the consumer surplus, which is $SC = U(.) - \sum_{i=1}^{3} p_i * q_i$, with respect to quantities leads to the following system of inverse demands

$$\begin{cases} p_1(q_1, q_2, q_3) &= a_1 - q_1 - gq_2 - \eta q_3, \\ p_2(q_1, q_2, q_3) &= a_2 - gq_1 - q_2 - \eta q_3, \\ p_3(q_1, q_2, q_3) &= a_3 - \eta q_1 - \eta q_2 - q_3. \end{cases} \quad (2)$$

The level of the reservation price and the substitutability parameter between firms F_1 and F_2 depends crucially on the behavior of each firm regarding knowledge sharing in the R&D cooperation. In fact, four cases can arise:
- case A: both firms share their knowledge,
- case B: only firm F_1 shares its knowledge,

[11] A change in this assumption will not qualitatively change the results discussed later in the paper but will increase the space of parameter values where there are multiple equilibria, and will potentially create a space of parameter values where there is no longer a SPNE.

[12] In the biotech sector, such as the Amaizing consortium, consumers could be farmers. Therefore, the diversity of soil (e.g. depending on pests, some varieties could be more suited for some soil) would be modeled as consumers' taste for diversity.

- case C: only firm F_2 shares its knowledge,
- case D: no one shares its knowledge.

Following Assumption 3, in case A both firms accept the knowledge sharing $g = \gamma + \delta$, where γ represents the substitutability between products of firms F_1 and F_2 before the R&D cooperation. In the case B and C, only one firm shares its knowledge, $g = \gamma + \delta/2$. In case D, both firms refuse the knowledge sharing, so that g is simply equal to γ. In all cases, the reservation price will be equal to α for the firm outside the R&D cooperation (F_3). This means that F_3 does not participate in the R&D cooperation. It is considered that there is intellectual property on the innovation stemming from the R&D cooperation. Therefore, as long as F_3 is not in the R&D cooperation, it does not benefit from the innovation and technology spillover. It follows that $a_3 = \alpha$, and is not subject of the product rivalry effect (δ).[13] Following Assumptions 1 and 2, for both firms in the R&D cooperation, in the case A, the reservation price will be equal to $a_i = \alpha + \omega + \lambda$, for $i = \{1, 2\}$, with α the reservation price before the cooperation, ω the innovation arising from the R&D cooperation, and λ the technology spillover. If only the firm F_1 (F_2) shares its knowledge, then the innovation will be $\frac{\omega}{2}$ and only firm F_2 (F_1) will obtain the technology spillover λ. Knowing these assumptions and maximizing the consumer surplus with respect to quantities leads to the inverse demands presented in Table 1, which represents the knowledge sharing game. It is assumed that the demands for each product and in each case are positive. For this, it is assumed that $\omega < \frac{\alpha(2+\gamma+\delta-2\eta)}{2\eta}$ and $\lambda < \frac{\alpha(2+\gamma+\delta-2\eta)-2\omega\eta}{2\eta}$.[14]

Table 1 – Inverse demands in each case of the knowledge sharing game

		Firm 2	
	Actions	Accepts	Refuses
Firm 1	Accepts	$p_1^A = \alpha + \omega + \lambda - q_1 - (\gamma+\delta)q_2 - \eta q_3$ $p_2^A = \alpha + \omega + \lambda - (\gamma+\delta)q_1 - q_2 - \eta q_3$ $p_3^A = \alpha - \eta q_1 - \eta q_2 - q_3$	$p_1^B = \alpha + \frac{\omega}{2} - q_1 - (\gamma + \frac{\delta}{2})q_2 - \eta q_3$ $p_2^B = \alpha + \frac{\omega}{2} + \lambda - (\gamma + \frac{\delta}{2})q_1 - q_2 - \eta q_3$ $p_3^B = \alpha - \eta q_1 - \eta q_2 - q_3$
	Refuses	$p_1^C = \alpha + \frac{\omega}{2} + \lambda - q_1 - (\gamma + \frac{\delta}{2})q_2 - \eta q_3$ $p_2^C = \alpha + \frac{\omega}{2} - (\gamma + \frac{\delta}{2})q_1 - q_2 - \eta q_3$ $p_3^C = \alpha - \eta q_1 - \eta q_2 - q_3$	$p_1^D = \alpha - q_1 - \gamma q_2 - \eta q_3$ $p_2^D = \alpha - \gamma q_1 - q_2 - \eta q_3$ $p_3^D = \alpha - \eta q_1 - \eta q_2 - q_3$

4 Resolution of the knowledge sharing game

This section shows the resolution of the two-stage game beginning with the Cournot competition and finishing with the choice of firms F_1 and F_2 in terms of knowledge sharing.

[13] Considering other values for a_3, such as $a_3 > \alpha$ or $a_3 < \alpha$, will not qualitatively change the results presented in the next sections. A discussion on this point is made more precisely at the end of section 4.2.

[14] This restriction comes from the equilibrium quantities in case A; in case B and C the restriction is lower (in the sense that ω and λ can be higher to keep positive demands) with $\omega < \frac{\alpha(4+2\gamma+\delta-4\eta)}{2\eta}$ and $\lambda < \frac{\alpha(4+2\gamma+\delta-4\eta)-2\omega\eta}{2\eta}$. In case D, the demands are always positive.

4.1 Stage 2: the Cournot competition

The profit of firms F_i is given by

$$\Pi_i^K = p_i^K(.) * q_i^K \tag{3}$$

where K represents the four situations regarding the firms' behavior with regard to knowledge sharing, $K = \{A, B, C, D\}$. $p_i^K(.)$ is the inverse demand of firm F_i in the situation K. Knowing the inverse demands provided by Table 1 and maximizing the profit function of firms F_1, F_2 and F_3 with respect to quantities leads to the results displayed in Table 2. Since elasticity parameters (β) have been fixed at 1, equilibrium prices and quantities are equal in the Cournot competition. Therefore, the profits are not presented but they are simply obtained by the square of the equilibrium quantities. The consumer surplus and the welfare for each case are shown in Appendix A.

Table 2 – Equilibrium quantities in each case of the knowledge sharing game

		Firm 2	
	Actions	Accepts	Refuses
Firm 1	Accepts	$q_1^{A*} = \frac{\alpha(2-\eta)+2(\lambda+\omega)}{2(2+\gamma+\delta-\eta^2)}$ $q_2^{A*} = \frac{\alpha(2-\eta)+2(\lambda+\omega)}{2(2+\gamma+\delta-\eta^2)}$ $q_3^{A*} = \frac{\alpha(2+\gamma+\delta-2\eta)-2\eta(\lambda+\omega)}{2(2+\gamma+\delta-\eta^2)}$	$q_1^{B*} = \frac{\alpha(2-\eta)+\omega}{4+2\gamma+\delta-2\eta^2} - \frac{2\lambda(2\gamma+\delta-\eta^2)}{(4-2\gamma-\delta)(4+2\gamma+\delta-2\eta^2)}$ $q_2^{B*} = \frac{\alpha(2-\eta)+\omega}{4+2\gamma+\delta-2\eta^2} + \frac{2\lambda(4-\eta^2)}{(4-2\gamma-\delta)(4+2\gamma+\delta-2\eta^2)}$ $q_3^{B*} = \frac{\alpha(4+2\gamma+\delta-4\eta)-2\eta(\lambda+\omega)}{2(4+2\gamma+\delta-2\eta^2)}$
	Refuses	$q_1^{C*} = \frac{\alpha(2-\eta)+\omega}{4+2\gamma+\delta-2\eta^2} + \frac{2\lambda(4-\eta^2)}{(4-2\gamma-\delta)(4+2\gamma+\delta-2\eta^2)}$ $q_2^{C*} = \frac{\alpha(2-\eta)+\omega}{4+2\gamma+\delta-2\eta^2} - \frac{2\lambda(2\gamma+\delta-\eta^2)}{(4-2\gamma-\delta)(4+2\gamma+\delta-2\eta^2)}$ $q_3^{C*} = \frac{\alpha(4+2\gamma+\delta-4\eta)-2\eta(\lambda+\omega)}{2(4+2\gamma+\delta-2\eta^2)}$	$q_1^{D*} = \frac{\alpha(2-\eta)}{2(2+\gamma-\eta^2)}$ $q_2^{D*} = \frac{\alpha(2-\eta)}{2(2+\gamma-\eta^2)}$ $q_3^{D*} = \frac{\alpha(2+\gamma-\eta)}{2(2+\gamma-\eta^2)}$

The innovation and the initial reservation price increase the profit of firms F_1 and F_2 in all cases. The technology spillover raises the profit of F_1 and F_2 in case A and for the firm that does not share its knowledge while the other one does (Π_1^C and Π_2^B). Surprisingly, the technology spillover also increases the profit of the firm that shares its knowledge while the other one does not (Π_1^B and Π_2^C) but only for $\eta > \sqrt{\delta}$ and $\gamma < \frac{1}{2}(\eta^2 - \delta)$. By contrast, the degree of substitutability, γ, and the product rivalry effect, δ, have negative impacts on F_1 and F_2 profits in case A and for Π_1^B and Π_2^C. In fact, a stronger substitutability increases the competition between F_1 and F_2 that decreases profits. However, the effect of γ and δ on the firm that does not share its knowledge, while the other one does, is ambiguous. This result comes from two countervailing effects, greater competition decreases profits, but since firms obtain higher quality from the technology spillover, if products become more homogeneous, then the representative consumer will prefer the better quality, which increases profits of the firms with the highest reservation price. Moreover, the substitutability parameter between the outside firm and the other firms has a similar ambiguous effect, in cases A, B and C, for the same reasons. For the outside firm F_3, the effects of parameters are simpler. The initial reservation price increases its profits as well as the competition between F_1 and F_2 (γ and δ) whereas the innovation, the technology spillover and its degree of substitutability, η, reduce its profit.

If it is assumed that $\eta = 0$, then firms F_1 and F_2 will be in a duopoly and F_3 will be a monopolist in its own market sector. In this particular situation, Π_1^B and Π_2^C will always be reduced by a rise of the technology spillover.[15] More interestingly, the impact of the technology spillover is stronger on Π_1^C and Π_2^B than on Π_1^A and Π_2^A.[16] As a consequence, the profits Π_1^C and Π_2^B may be higher than Π_1^A and Π_2^A due to the effect of the technology spillover even if the innovation is lower in cases B and C. In this situation, one firm could have a free-riding behavior in terms of knowledge sharing since it would obtain a larger profits in the case where it does not share its knowledge whereas the other firm does. Nevertheless, this effect could be reduced or even disappear with $\eta > 0$. Keeping a stronger effect of the technology spillover on Π_1^C and Π_2^B requires, with an outside competitor, to stay at $\eta < \sqrt{2\gamma}$, or $\eta > \sqrt{2\gamma}$ and $\gamma > \overline{\gamma}_1$ with $\overline{\gamma}_1 = \frac{1}{4}\big(-4-2\delta+3\eta^2+\sqrt{(4-\eta^2)(4-4\delta-\eta^2)}\big)$. Therefore, there is probably less free-riding behavior when the level of competition with the firm outside the R&D cooperation is high and that of competition with the other firm within the R&D cooperation is low.

4.2 Stage 1: the knowledge sharing game

In order to solve the first stage of the model, threshold values have to be found. These thresholds will indicate when a firm wants to share its knowledge depending on the behavior of the other firm. Knowing that firms are symmetrical, thresholds are similar for firm F_1 and F_2. Therefore, the first threshold is for $\Pi_1^A > \Pi_1^C$ and $\Pi_2^A > \Pi_2^B$ such that a firm will want to share its knowledge even if the other firm also shares theirs

$$\omega > \frac{\alpha\delta(2-\eta)}{(4+2\gamma-2\eta^2)} + \frac{2(2\gamma+\delta-\eta^2)}{(4-2\gamma-\delta)}\lambda + \frac{\delta(4+2\gamma+\delta-2\eta^2)}{(2+\gamma-\eta^2)(4-2\gamma-\delta)}\lambda, \tag{4}$$

where the right-hand side of this inequality is denoted $\Omega_1(.)$. The second threshold is for $\Pi_1^B > \Pi_1^D$ and $\Pi_2^C > \Pi_2^D$ such that firms will want to share its knowledge even if the other firm does not share theirs

$$\omega > \frac{\alpha\delta(2-\eta)}{(4+2\gamma-2\eta^2)} + \frac{2(2\gamma+\delta-\eta^2)}{(4-2\gamma-\delta)}\lambda, \tag{5}$$

where the right-hand side of this inequality is denoted $\Omega_2(.)$. $\Omega_1(.)$ is higher than $\Omega_2(.)$ for all variable values inside each threshold (the last term of the threshold $\Omega_1(.)$ is positive). This result leads to the following Lemma

Lemma 1.

- *For $\omega > \Omega_1(.)$*
  Both firms accept the knowledge sharing
- *For $\Omega_1(.) > \omega > \Omega_2(.)$*
  There are multiple equilibria[17]
- *For $\omega < \Omega_2(.)$*
  Both firms reject the knowledge sharing

The Lemma 1 leads to the following Corollary

[15] The partial derivatives of quantities q_1^B and q_2^C w.r.t λ are $\frac{\partial q_1^B}{\partial\lambda} = \frac{\partial q_2^C}{\partial\lambda} = \frac{1}{4+2\gamma+\delta} - \frac{1}{4-2\gamma-\delta}$, which are negatives.

[16] The analysis of partial derivatives leads to $\frac{\partial q_1^C}{\partial\lambda} > \frac{\partial q_1^A}{\partial\lambda}$ and $\frac{\partial q_2^B}{\partial\lambda} > \frac{\partial q_2^A}{\partial\lambda}$, $\frac{8}{(4-2\gamma-\delta)(4+2\gamma+\delta)} > \frac{1}{2+\gamma+\delta}$.

[17] Here, there are three possible equilibria. Two pure strategy equilibria wherein one firm shares its knowledge while the other firm does not share its knowledge. The third equilibrium is the mixed strategy: for values of ω lower than Ω_1 but still close of Ω_1, both firms have a high probability of sharing knowledge and for values of ω close to Ω_2 and still higher than Ω_2, both firms have a low probability of sharing knowledge. In this situation, the game becomes an anti-coordination game like the Chicken/Hawk–dove game.

Corollary 1. *The higher the innovation, ω, the more firms F_1 and F_2 will accept the knowledge sharing.*

As expected, the innovation obtained from the R&D cooperation, which directly increases the reservation price, also increases the knowledge sharing. A large innovation will have a value higher than both thresholds and will lead to the knowledge sharing. We assume that the innovation is divided by two when only one firm shares its knowledge (B or C) compared to the situation where both firms share their knowledge (A). Corollary 1 will not change with a lower ($\omega_2 < \frac{\omega}{2}$) or a higher ($\omega_2 > \frac{\omega}{2}$) innovation in cases B and C. However, when $\omega_2 < \frac{\omega}{2}$, there are potentially other multiple equilibria: either both firms share their knowledge or both firms refuse knowledge sharing (or a mixed strategy).[18] And, when $\omega_2 > \frac{\omega}{2}$, it increases the presence of multiple equilibria where only one firm shares its knowledge (the range of parameters where ω is between $\Omega_1(.)$ and $\Omega_2(.)$ will be higher).

It is easy to check that the initial reservation price, α has a positive impact on each threshold (a negative impact on knowledge sharing).[19] This impact could be surprising but it comes from the assumption on how the innovation is modeled. In fact, the innovation is added up to the initial reservation price. Therefore, if the initial reservation price is very high, the innovation has to be high enough to become of interest to firms. This is specifically crucial since obtaining this innovation depends on the knowledge sharing that will increase the competition between firms. Moreover, it is assumed that the initial reservation price, α, is the same for firms inside the R&D cooperation and for those outside of it.[20] If the initial reservation price is higher (lower) for the firm outside the R&D cooperation, this would decrease (increase) each threshold and thus potentially increase (reduce) the knowledge sharing.[21]

5 Discussion of the results

In this section, there is a discussion on the impacts of competition and spillovers on the behavior of firms regarding the knowledge sharing inside an R&D cooperation and what the policy to improve the knowledge sharing could be.

5.1 In terms of knowledge sharing

First, it is interesting to check what occurs when the outside firm has no impact on the behavior of firms inside the R&D cooperation, such as $\eta = 0$, to disentangle the effects of this outside firm and the effects of spillovers in terms of knowledge sharing. The knowledge held by firms is highky strategic and its sharing involves an increase in the competition (δ). For this reason, firms could be discouraged from sharing their knowledge. The product market rivalry effect, δ, increases both thresholds. Surprisingly, the technology spillover seems to also be an obstacle for the knowledge sharing even if it enhances the quality

[18] Thus the game can turn into a coordination game instead of an anti-coordination game since the marginal gain from free-riding is too low. The game can stay an anti-coordination game if the value of the technology spillover is sufficiently high.

[19] The partial derivatives of each threshold w.r.t. α are $\frac{\partial \Omega_1(.)}{\partial \alpha} = \frac{\partial \Omega_2(.)}{\partial \alpha} = \frac{\delta(2-\eta)}{(4+2\gamma-2\eta^2)}$. They are positive for all values of γ, δ and η considered in the model.

[20] In the example in the introduction, the *Amaizing* consortium, two firms outside the consortium are the first and the second firms in terms of market share (Monsanto owned by Bayer and Pioneer Hi-Bred owned by DowDupont). Their reservation prices could, in fact, be higher than firms inside the cooperation.

[21] A different initial reservation price for the outside firm, such as α_3, would only change the first term of each threshold: $\frac{2\alpha\delta-\alpha_3\delta\eta}{(4+2\gamma-2\eta^2)}$ instead of $\frac{\alpha\delta(2-\eta)}{(4+2\gamma-2\eta^2)}$.

of products. In fact, there is free-riding behavior when the value of the innovation is between both thresholds and comes mainly from the technology spillover. As explained in the previous section, the technology spillover sharply increases the profits of the firm that refuses knowledge sharing while its competitor shares its knowledge. This increase is lower when both firms share their knowledge. Moreover, due to the free-riding behavior, if the technology spillover becomes too strong, the effort of one firm in terms of knowledge sharing is no longer sufficient. In that case, both firms prefer will preferto deny the knowledge sharing since only the competitor will benefit from it. These impacts arising from spillovers are summarized in Proposition 1

Proposition 1. *Without an outside competitor, the technology spillover and the product rivalry effect have a negative impact on the behavior of knowledge sharing.*

Proof 1. *See Appendix B.*

In this analysis, as spillovers are based on the sharing of prior knowledge, the results found in Proposition 1 are different to those of the economic literature. R&D cooperation models are mainly based on the idea of cost sharing of the current innovation. The absolute impact of the firm outside the R&D cooperation on knowledge sharing can be analyzed simply by making the differences between both thresholds, (4) and (5), and these same thresholds by setting $\eta = 0$ $(\Omega_x(.) - \Omega_x(.|\eta = 0))$. These differences, for both thresholds, are negative. Thus, the presence of an outside competitor encourages knowledge sharing. This result leads to Proposition 2

Proposition 2. *The presence of an outside competitor encourages the knowledge sharing.*

Proof 2. *See Appendix B.*

The R&D cooperation allows firms to supply higher quality products compared to the firm outside the R&D cooperation, thanks to the innovation, ω, and the technology spillover, λ. Thus, firms are encouraged more to share their knowledge in the presence of an outside competitor since they will obtain a higher demand for their products compared to the outside competitor. The product rivalry effect continues however to negatively affect knowledge sharing. For the technology spillover, which increases the quality of the product, the result depends on the level of competition between firms. If the outside competitor competes sharply both firms ($\eta > \sqrt{2\gamma}$) and the competition between both inside firms is low enough ($\gamma < \overline{\gamma}_1$), then the technology spillover has a positive impact on the behavior of knowledge sharing. This result leads to Proposition 3. Therefore, an outside competitor has two impacts on knowledge sharing behaviors: a direct effect on the level of thresholds, and an indirect effect that reduces the free-riding behavior through a change of the impact of the technology spillover.

Proposition 3. *The presence of an outside competitor could lead to a positive impact of the technology spillover on the knowledge sharing behavior.*

Proof 3. *See Appendix B.*

The impact of the initial degree of substitutability (γ), that represents the level of competition between both firms inside the R&D cooperation, is more ambiguous. In fact, for a low value of γ, a rise of the degree of substitutability affects positively the behavior in terms of knowledge sharing. On the other hand, for a medium or a high value of γ, its increase negatively affects the behavior in terms of knowledge sharing. This effect of the degree of substitutability leads to the Proposition 4. This result is in line with the literature on R&D cooperation (e.g. Kamien et al., 1992) except for the low value of the degree of substitutability.

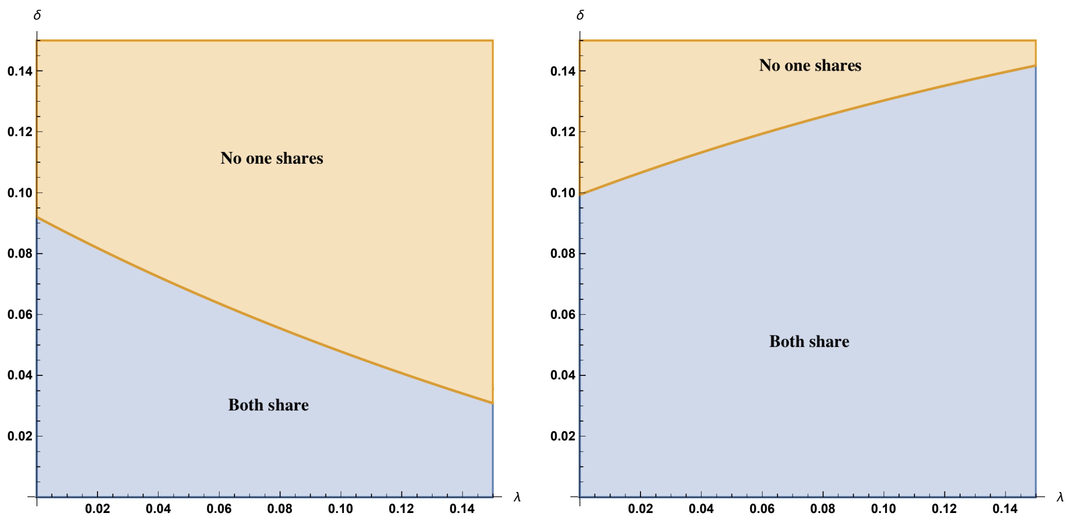
Proposition 4. *A low value of the initial degree of product substitutability stimulates the knowledge sharing.*

Proof 4. *See Appendix B.*

5.2 Establishment of Public-Private R&D Partnerships through public labs

As highlighted by the literature (Samaddar and Kadiyala, 2006), knowledge sharing is not obviously efficient in R&D cooperation. Public authorities can affect the behavior of firms' knowledge sharing by establishing Public-Private R&D Partnerships through public labs. More specifically, the public authority could play a role in determining how the prior and strategic knowledge is spread inside the PPP, and could choose the partners of the PPP. With the aim of discussing this point, the Figure 1 represents graphically the results of Propositions 1, 2 and 3.[22]

Figure 1 – Impacts of spillovers on the behavior of knowledge sharing



(a) For $\eta = 0.15$ (b) For $\eta = 0.85$

One of the first aspects on which the public authorities could play a crucial role is the choice of partners in the PPP. A PPP in R&D is mainly established to foster innovation of national or regional firms. However, according to Proposition 4, the public authorities should be aware of horizontal competition between firms that could be harmful to the PPP. Highly competitive firms in the product market could reject the idea of knowledge sharing, to shields themselves from an increase of the competition, even if it is crucial for fostering innovation in the PPP.

[22]The Figure 1 was created using the Mathematica software where we set $\alpha = 1$, $\omega = 0.04$ and $\gamma = 0.15$. The parameter values were set to highlight the problematics and to respect the necessary conditions for obtaining positive demands, specifically for the firm outside the PPP. Moreover, Figure 1 has been simplified using the risk dominance concept to avoid multiple equilibria (see Harsanyi et al., 1988; Harsanyi, 1995). Without this concept of equilibrium, multiple equilibria would be a thin space at the frontier between both pure strategy equilibria.

Another essential aspect is the existence of competitors outside the PPP. In the example of Amaizing, the partners knew how crucial it is for them to collaborate with the aim of improving their performance, against the top two firms in the maize sector (Monsanto and Pioneer Hi-Bred). Therefore, the presence of strong competitors outside the PPP can sharply improve behavior in terms of knowledge sharing. As shown by the Figure 1, the presence of a competitor outside the PPP directly increases the behavior of knowledge sharing (Proposition 2) and if the outside competitors compete strongly with firms inside the PPP, technology spillovers could positively affect knowledge sharing (Proposition 3). Public authorities should therefore promote, through public laboratories, PPP in R&D in sectors where there are substantial competitors. In Europe, competition in the development of AI and/or robotics emerging from US, Japan, South Korea or China are examples where firms should have a collaborative behavior in PPP in R&D, due to the context of heavy international competition.

One of the main conditions to enhance knowledge sharing is related to spillovers. Figure 1(a) presents the impacts of spillovers, the technology spillover (λ) and the product market rivalry effect (δ). They negatively affect the behavior of firms in terms of knowledge sharing. Using public labs as intermediaries between firms could give incentives to firms for sharing their knowledge. If the public labs have total access to knowledge, they could use it to innovate and to share the innovation at all partners of the PPP without sharing this necessary prior knowledge to other firms. It is therefore crucial to send a clear message to firms that their strategic prior knowledge will not be divulged to all partners if they are to encourage knowledge sharing inside the PPP and thus support its success. However, in the case of the Figure 1(b), when the outside firm competes strongly with firms inside the PPP, technology spillovers could positively affect the behavior of firms in terms of knowledge sharing. In this specific situation, it could be therefore adequate to let some prior knowledge spreading between private partners inside the PPP.

In the example of the Amaizing consortium, there are two interesting cases. There exist six major kinds of maize variety and two of them are mainly present in Amaizing. We will call these here American varieties and European varieties.[23] Sharing genetic resources of American varieties inside the consortium seems not to have raised any problem for firms. On the other hand, it has been much more difficult to make firms share their knowledge on European varieties. This behavior follows the results arising from the model. European firms endure strong competition coming from American firms (such as Monsanto and Pioneer Hi-Bred) on American varieties, whereas strong competition on European varieties is from other European firms in the consortium.

Public authorities, in this context, try mainly to promote innovation by fostering knowledge sharing in PPP. One other main objective could be maximizing the welfare. Unfortunately, the model developed here can only show ambiguous effects on the welfare, specifically in the case of the Figure 1(a). For example, the impact of the technology spillover is positive on the welfare but the welfare is a discontinuous function of the technology spillover without the mixed strategy (see Appendix A). In fact, for a value of the technology spillover, the SPNE change from a situation where both firms share their knowledge to a situation where only one firm shares its knowledge. The welfare is the lower since there

[23] They are called more specifically dent corn and flint corn. Both of them originate from America. Most of the R&D in Europe is on flint corn, which is better suited to the conditions of Northern Europe, whereas the most cultivated corn in US is dent corn.

is less innovation and less technology spillover (both increase the quality of products), but the welfare continues to be an increasing function of the technology spillover. Moreover, it is not possible to find analytically if the welfare is at its maximum just before the change of SPNE from the situation where both firms share their knowledge to the situation where one firm shares its knowledge (threshold $\Omega_1(.)$) compared to the point just before the change of SPNE from the situation where one firm shares its knowledge to the situation where both firms refuse knowledge sharing (threshold $\Omega_2(.)$). In fact, the product rivalry effect negatively affects the welfare, and its impact is lower when one firm shares its knowledge compared to the situation when both firms share their knowledge. The product rivalry effect has a negative impact on the welfare because of lower profits and lower diversity of products, even if prices are lower due to the higher competition (see Appendix A). Using the mixed strategy, the welfare function becomes continuous. With numerical example, when the SPNE is the mixed strategy, the welfare seems to be decreasing in the technology spillover. In fact, the technology spillover reduces the probability of firms agreeing to knowledge sharing (in the case of Figure 1(a)). Due to the complexity of the welfare function when there is a mixed strategy, it is not possible to ground this numerical result analytically. It could nevertheless be possible for the public authorities to have as their main objective maximizing knowledge sharing, and as a second objective maximizing the welfare only when knowledge sharing is at its maximum. Considering that condition, it is possible to found a threshold value of the technology spillover where the welfare is at its maximum when both firms share their knowledge. However, this policy could be highly complex in the reality, due to the uncertainty on the real value of innovation and spillovers.

6 Robustness

6.1 Bertrand competition

Regarding the Bertrand competition, the results are qualitatively similar (see Appendix C). The higher levels of competition due to the Bertrand framework lead to a slight increase of the area where firms prefer to refuse knowledge sharing (comparison between Figure 1(a) and Figure 3(a)). Similarly, when the competitor outside the R&D cooperation supplies closer substitute, and at the same time products supplied by firms inside the R&D cooperation are not close substitutes, the technology spillover positively affects the behaviors in terms of knowledge sharing. This effect occurs even for lower values of the parameter of substitutability (η) due to the higher levels of competition in the Bertrand framework.

6.2 A technology leader vs a laggard firm

Most firms inside R&D cooperation are not symmetric (e.g. size, technology advantage, etc.). The introduction of asymmetries between firms is shown in the Appendix D, where there is no outside competitor. The results of a numerical simulation in the figure 4, regarding the impacts of spillovers implied by the knowledge sharing can also be found when firms are asymmetric. An intensification of the product rivalry effect involves a lower space of parameter values $\{\lambda, \delta\}$ where both firms accept knowledge sharing (comparison between Figures 4(a) and 4(b) and Figures 4(c) and 4(d)). Similarly, a rise of the technology spillover implies the same result (comparison between Figures 4(a) and 4(c) and Figures 4(b) and 4(d)). However, since the technology spillovers differ between those of firm F_i and those of its partner (λ_j), there is logically a positive impact of partner (λ_j)'s technology spillover on the behavior of the firm F_i in terms of knowledge sharing. Furthermore, in this situation, another result can be highlighted: if the technology spillover of the technology leader, that affects the laggard firm, is too small then the technology leader experiences more incentives to accept knowledge sharing than does the laggard firm. In fact, the market rivalry effect will affect the laggard firm more negatively than it will affect the technology leader, because the technology leader will gain a part of the laggard firm's market share.

6.3 A stage of entry in a PPP in R&D

Before the knowledge sharing between partners within R&D cooperation takes place, there is the open question of whether or not the firms actually want to enter into the R&D cooperation? Here, it is assumed that firms will collaborate with a public lab even if there is only one firm that agrees to enter into the collaboration. Therefore, the question of entry is only relevant for PPP in R&D and not for a standard R&D cooperation without a public lab. In Appendix E, an earlier stage is added, where both firms decide to enter or not into the PPP. Interestingly, if both firms anticipate that neither them will share their knowledge, they will both still prefer to enter into the PPP. In fact, if one firm refuses do so, its competitor will always enter and share its knowledge with the public lab since there will no longer be spillovers. Therefore, the competitor will gather a part of the market share of the firm that refuses to enter into the PPP owing to the innovation that increases the quality of its product. At the stage of knowledge sharing, for the cases where either both firms or only one firm agrees to knowledge sharing, one firm may refuse to enter into the PPP due to the product rivalry effect. In the specific case where only one firm agrees to knowledge sharing, even the free-riding firm (the one that refuses knowledge sharing) could refuse to enter into the PPP. This situation could occur only when the level of technology spillover, λ, and of innovation, $\omega/2$, are low and the product rivalry effect, $\delta/2$, is sufficiently high. Then the profits of the free-riding firm will be lower than in the situation where it refuses to enter in the PPP. However, these cases occur only if $\eta > \sqrt{2\gamma}$ and the value of the technology spillover (λ) is very low. Thus, this can negate Proposition 3 but only for a very low value of the technology spillover. In line with the results reported in the economic literature, the technology spillover has a positive impact on the choice of entering into the PPP except under some conditions, for the firm that shares its knowledge while its partner in the PPP refuses to do likewise (when the technology spillover increases only the quality of the competitor's product). The technology spillover involves free-riding behavior at theknowledge sharing stage but there is no free-riding behavior at the entry stage since firms can still refuse knowledge sharing during the cooperation.

7 Conclusion

The aim of this analysis is to study the firm's behavior in terms of knowledge sharing in R&D cooperation, and what the incentives for knowledge sharing given by a PPP in R&D could be. A theoretical model, based on the R&D cooperation literature, has been developed to disentangle the effects of spillovers, of the scale of competition between partners, and of the presence of competitors outside R&D cooperation on behavior in terms of knowledge sharing that is crucial for the success of R&D cooperation.

As expected, the level of innovation obtained thanks to the R&D cooperation and the presence of a firm outside the R&D cooperation positively influences the behavior in terms of knowledge sharing. On the contrary, the level of horizontal differentiation between firms in the R&D cooperation and the product rivalry effect arising from the knowledge sharing negatively affect the firms' incentives to share their knowledge. The technology spillover, also arising from the knowledge sharing, likewise reduces their incentives to share their knowledge. More precisely, the technology spillover can involve free-riding behavior, where one firm refuses to share its knowledge while it waits for the other firms to do so first. This effect of the technology spillover can be reversed if the outside competitor is a strong rival in the product market and the product rivalry between firms inside the R&D cooperation is low.

From these results on the firms' behavior in terms of knowledge sharing inside R&D cooperation, some policies to promote efficient PPP in R&D can be highlighted. While for some PPP in R&D their efficiency depends only on the sharing of cost behavior, for others the knowledge sharing is crucial to their success. For these specific PPP in R&D, it is essential to build the PPP with private partners that do not face an excessive level of product rivalry. Moreover, if the private partners inside the PPP face mutual competitors, it positively affects their behavior in terms of knowledge sharing. This situation exists in many Hi-tech markets in Europe facing the competition from Asia and North America, such as the development of AI, robotics or car batteries for examples. One crucial point to ensure a successful PPP in R&D is the negative effect of both spillovers: the technology spillover and the product rivalry effect. To limit their effects, public labs could be used as intermediaries for holding the prior knowledge of firms. Firms could fully share their knowledge with public labs, which would use it to create new innovations. This would avoid the spread of the strategic prior knowledge of firms to their competitors in the product market. With this aim, public authorities could convince firms that their strategic knowledge will not be divulged to other private partners of the PPP.

One other crucial aspect, which is not studied in this paper, is the establishment and the terms of the contract between partners of R&D cooperation and/or PPP in R&D. For the specific case of PPP in R&D, public authorities could be considered as the principal. In the economic literature, Niedermayer and Wu (2013) analyze the breaking up clauses in a research consortium, where one firm is considered as the principal. It would be interesting to analyze, in a future research, the impacts of secret contracts and various incentive tools that can require a public authority over the firms' behavior in terms of knowledge sharing. Moreover, pre-contracts could also be a tool for fostering knowledge sharing in PPP, either by giving better incentives to firms that have the expected behavior or by punishing firms that try to free-ride.

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A Consumer surplus and Welfare for each case of the knowledge sharing game

Since both firms in the R&D cooperation are symmetric, the consumer surplus and the welfare are similar in the cases B and C of the knowledge sharing game. The consumer surplus of the knowledge sharing game are

$$\begin{aligned}
CS^A =& \frac{1}{8\left(\gamma+\delta-\eta^2+2\right)^2}\Big(\alpha^2\left(\gamma^2-2\eta^2(\gamma+\delta+9)-4\eta(\gamma+\delta)+2\gamma\delta+12\gamma+\delta^2+12\delta+8\eta^3+12\right) \\
&-4(\lambda+\omega)^2\left(2(\gamma+\delta+1)-3\eta^2\right)-4\alpha(\lambda+\omega)\left(\eta(\gamma+\delta)-4(\gamma+\delta+1)-2\eta^3+6\eta^2\right)\Big) \\
CS^{B,C} =& \frac{1}{8(2\gamma+\delta-4)^2\left(2\gamma+\delta-2\eta^2+4\right)^2}\Big(\alpha^2(2\gamma+\delta-4)^2 \\
&*\left(4\gamma^2+4\gamma(\delta-2\eta(\eta+2)+12)+\delta^2-4\delta\eta(\eta+2)+24\delta+8\eta^2(4\eta-9)+48\right) \\
&+4\lambda^2\left(-4\eta^4(2\gamma+\delta-2)+\eta^2(2\gamma+\delta)(2\gamma+\delta+32)-12(2\gamma+\delta)^2-80\eta^2+64\right) \\
&+8\lambda\omega(2\gamma+\delta-4)^2\left(2\gamma+\delta-3\eta^2+2\right)+4\omega^2(2\gamma+\delta-4)^2\left(2\gamma+\delta-3\eta^2+2\right) \\
&-4\alpha(2\gamma+\delta-4)^2(\lambda+\omega)\left(2\gamma(\eta-4)+\delta(\eta-4)-4(\eta-3)\eta^2-8\right)\Big) \\
CS^D =& \frac{\alpha^2\left(-2(\gamma+9)\eta^2-4\gamma\eta+\gamma(\gamma+12)+8\eta^3+12\right)}{8\left(\gamma-\eta^2+2\right)^2}
\end{aligned}$$

The welfare of the knowledge sharing game are

$$\begin{aligned}
W^A =& \frac{1}{8\left(\gamma+\delta-\eta^2+2\right)^2}\Big(\alpha^2\big(3\gamma^2-2\eta^2(\gamma+\delta+3)-4\eta(3\gamma+3\delta+8) \\
&+6\gamma\delta+20\gamma+3\delta^2+20\delta+8\eta^3+36\big) \\
&-4\alpha(\lambda+\omega)\left(\eta(3\gamma+3\delta+8)-4(\gamma+\delta+3)-2\eta^3+2\eta^2\right)+4(\lambda+\omega)^2\left(2(\gamma+\delta+3)-\eta^2\right)\Big) \\
W^{B,C} =& \frac{1}{8\left(2\gamma+\delta-2\eta^2+4\right)^2}\Big(\alpha^2\big(12\gamma^2+4\gamma(3\delta-2\eta(\eta+6)+20)+3\delta^2 \\
&-4\delta\eta(\eta+6)+40\delta+8\eta(\eta(4\eta-3)-16)+144\big) \\
&+\frac{4\lambda^2\left(-4\eta^4(2\gamma+\delta-6)+\eta^2\left(3(2\gamma+\delta)^2-112\right)-4(2\gamma+\delta)^2+192\right)}{(2\gamma+\delta-4)^2}+4\omega^2\left(2\gamma+\delta-\eta^2+6\right) \\
&-4\alpha(\lambda+\omega)\left(\eta(6\gamma+3\delta+16)-4(2\gamma+\delta+6)-4\eta^3+4\eta^2\right)+8\lambda\omega\left(2\gamma+\delta-\eta^2+6\right)\Big) \\
W^D =& \frac{\alpha^2\left(3\gamma^2-2(\gamma+3)\eta^2-4(3\gamma+8)\eta+20\gamma+8\eta^3+36\right)}{8\left(\gamma-\eta^2+2\right)^2}
\end{aligned}$$

The partial derivatives of the welfare functions give some indications of the impacts of parameters on the welfare. These impacts are summarized in Table 3. The calculations of partial derivatives have been made using the Mathematica software due to the fact that welfare functions are cumbersome.

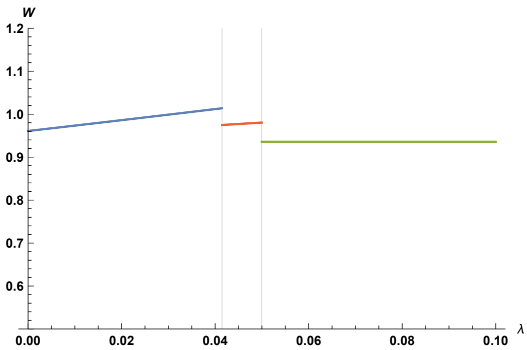
Table 3 – Impacts of parameters on the welfare

	α	ω	λ	γ	δ	η
W^A	+	+	+	-	-	?
$W^{B,C}$	+	+	+	?	?	?

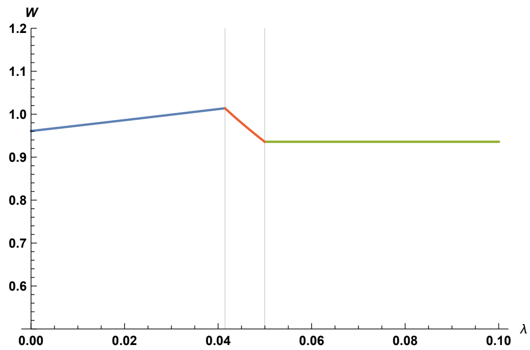
Parameters α, λ and ω enhance the quality of products and thereby predictably positively affect the welfare. An increase of γ, δ or η increases the substitutability of products which reduces their diversity. With the Bowley utility function (and $\beta = 1$) this negative impact on the welfare is greater than the impacts of the increasing competition that reduces prices. Thus γ and δ negatively affect W^A. However, it is more ambiguous for $W^{B,C}$ and for the effect of η. In fact, for these situations the representative consumers choose less diversity but a higher quality of product which has an ambiguous effect on the welfare.

Figure 2 represents two numerical examples of the global welfare function that follows the numerical example of Figure 1 without using the risk dominance concept. In the Figure 2, the welfare function is represented either with each pure strategy equilibrium (both accept knowledge sharing, one accepts knowledge sharing and both refuse knowledge sharing) in Figures 2(a) and 2(c) or using the mixed strategy instead of the pure strategy where only one accepts knowledge sharing in Figures 2(b) and 2(d). Moreover, Figures 2(a) and 2(b) follow Figure 1(a) more precisely, (with $\eta = 0.15$), and Figures 2(c) and 2(d) follow Figure 1(b) more precisely, (with $\eta = 0.85$). Figure 2 is discussed in Section 5.2.

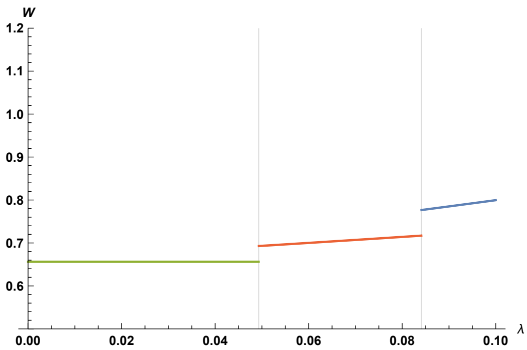
Figure 2 – Impacts of the technology spillover on the Welfare



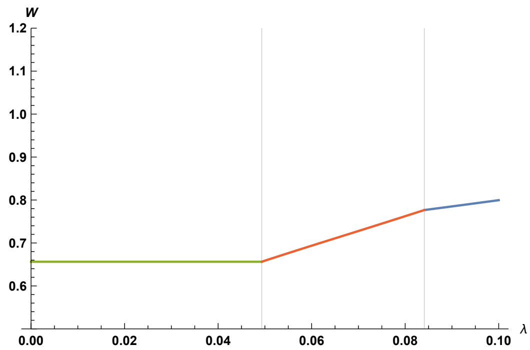
(a) Pure strategy, $\eta = 0.15$ and $\delta = 0.07$



(b) Mix strategy, $\eta = 0.15$ and $\delta = 0.07$



(c) Pure strategy, $\eta = 0.85$ and $\delta = 0.12$



(d) Mix strategy, $\eta = 0.85$ and $\delta = 0.12$

B Proof of propositions 1-4

For the Proof of Proposition 1, the partial derivatives of $\Omega_1(.|\eta = 0)$ and $\Omega_2(.|\eta = 0)$ w.r.t. λ and δ are

$$\frac{\partial \Omega_1}{\partial \lambda} = \frac{2(2\gamma+\delta)}{4-2\gamma-\delta} + \frac{\delta(4+2\gamma+\delta)}{(2+\gamma)(4-2\gamma-\delta)},$$
$$\frac{\partial \Omega_2}{\partial \lambda} = \frac{2(2\gamma+\delta)}{4-2\gamma-\delta},$$
$$\frac{\partial \Omega_1}{\partial \delta} = \frac{\alpha}{2+\gamma} + \frac{2\lambda(2\gamma+\delta)}{(4-2\gamma-\delta)^2} + \frac{2\lambda}{4-2\gamma-\delta} + \frac{\lambda(\delta+(4+2\gamma+\delta))}{(2+\gamma)(4-2\gamma-\delta)} + \frac{\delta\lambda(4+2\gamma+\delta)}{(2+\gamma)(4-2\gamma-\delta)^2},$$
$$\frac{\partial \Omega_2}{\partial \delta} = \frac{\alpha}{2+\gamma} + \frac{2\lambda(2\gamma+\delta)}{(4-2\gamma-\delta)^2} + \frac{2\lambda}{4-2\gamma-\delta}.$$

For all values of parameters assumed in the model, these four partial derivatives are positives. Thus an increase of λ or δ implies a rise of thresholds for sharing knowledge.

For the Proof of Proposition 2, the differences $(\Omega_1(.)-\Omega_1(.|\eta = 0))$ and $(\Omega_2(.)-\Omega_2(.|\eta = 0))$ lead to

$$\Omega_1^D = -\frac{2\eta^2\lambda}{4-2\gamma-\delta} - \frac{\alpha\delta\eta(2+\gamma-2\eta)}{2(2+\gamma)(2+\gamma-\eta^2)} + \frac{\lambda\delta^2\eta^2}{(2+\gamma)(4-2\gamma-\delta)(2+\gamma-\eta^2)},$$
$$\Omega_2^D = -\frac{2\eta^2\lambda}{4-2\gamma-\delta} - \frac{\alpha\delta\eta(2+\gamma-2\eta)}{2(2+\gamma)(2+\gamma-\eta^2)}.$$

For all values of parameters assumed in the model, these two differences are negatives. Thus, the presence of an outside competitor reduces the thresholds for sharing knowledge.

For the Proof of Proposition 3, the partial derivatives of $\Omega_1(.)$ and $\Omega_2(.)$ w.r.t. λ and δ are

$$\frac{\partial \Omega_1}{\partial \lambda} = \frac{2(2\gamma+\delta-\eta^2)}{4-2\gamma-\delta} + \frac{\delta(4+2\gamma+\delta-2\eta^2)}{(4-2\gamma-\delta)(2+\gamma-\eta^2)},$$
$$\frac{\partial \Omega_2}{\partial \lambda} = \frac{2(2\gamma+\delta-\eta^2)}{4-2\gamma-\delta},$$
$$\frac{\partial \Omega_1}{\partial \delta} = \frac{2\alpha-\alpha\eta}{4+2\gamma-2\eta^2} + \frac{2\lambda(2\gamma+\delta-\eta^2)}{(4-2\gamma-\delta)^2} + \frac{2\lambda}{4-2\gamma-\delta} + \frac{\lambda(\delta+(4+2\gamma+\delta-2\eta^2))}{(4-2\gamma-\delta)(2+\gamma-\eta^2)} + \frac{\delta\lambda(4+2\gamma+\delta-2\eta^2)}{(4-2\gamma-\delta)^2(2+\gamma-\eta^2)},$$
$$\frac{\partial \Omega_2}{\partial \delta} = \frac{2\alpha-\alpha\eta}{4+2\gamma-2\eta^2} + \frac{2\lambda(2\gamma+\delta-\eta^2)}{(4-2\gamma-\delta)^2} + \frac{2\lambda}{4-2\gamma-\delta}.$$

For $\eta > \sqrt{2\gamma}$ and $\gamma < \overline{\gamma}_1$, the partial derivatives of $\Omega_1(.)$ and $\Omega_2(.)$ with respect to λ have a negative value. Therefore, for these specific values of η and γ, the technology spillover reduces the thresholds for sharing knowledge. On the other hand, the product rivalry effect continues to positively affect each threshold for all values of parameters assumed in the model.

For the Proof of the Proposition 4, the partial derivatives of $\Omega_1(.)$ and $\Omega_2(.)$ w.r.t. γ

are

$$\frac{\partial \Omega_1}{\partial \gamma} = \frac{4\lambda}{4-2\gamma-\delta} + \frac{4\lambda(2\gamma+\delta-\eta^2)}{(4-2\gamma-\delta)^2} - \frac{2(2\alpha\delta-\alpha\delta\eta)}{(4+2\gamma-2\eta^2)^2} + \frac{2\delta\lambda}{(4-2\gamma-\delta)(2+\gamma-\eta^2)}$$
$$+ \frac{2\delta\lambda(4+2\gamma+\delta-2\eta^2)}{(4-2\gamma-\delta)^2(2+\gamma-\eta^2)} - \frac{\delta\lambda(4+2\gamma+\delta-2\eta^2)}{(4-2\gamma-\delta)(2+\gamma-\eta^2)^2},$$
$$\frac{\partial \Omega_2}{\partial \gamma} = \frac{4\lambda}{4-2\gamma-\delta} + \frac{4\lambda(2\gamma+\delta-\eta^2)}{(4-2\gamma-\delta)^2} - \frac{2(2\alpha\delta-\alpha\delta\eta)}{(4+2\gamma-2\eta^2)^2}.$$

The partial derivatives of $\Omega_1(.)$ and $\Omega_2(.)$ w.r.t. γ are negative for $\lambda < \bar{\lambda}_1$ and $\lambda < \bar{\lambda}_2$, respectively. $\bar{\lambda}_1$ and $\bar{\lambda}_2$ are as follows

$$\bar{\lambda}_1 = (\alpha\delta(2-\eta)(4-2\gamma-\delta)^2)/\Big(2\left(\delta^3 - 2(\delta(\delta+8)+40)\eta^2 + 16\delta + 64\right.$$
$$\left. 4\gamma^2\left(\delta-\eta^2+4\right) + 4\gamma\left(\delta^2 - 2(\delta+6)\eta^2 + 4\delta + 2\eta^4 + 16\right) + 4(\delta+8)\eta^4 - 4\eta^6\right)\Big),$$
$$\bar{\lambda}_2 = \frac{\alpha\delta(4-2\gamma-\delta)^2}{8(2+\eta)\left(2+\gamma-\eta^2\right)^2}.$$

For all values of parameters assumed in the model, $\bar{\lambda}_1$ and $\bar{\lambda}_2$ are positive. The initial degree of substitutability, γ, has a negative impact on $\bar{\lambda}_1$ and $\bar{\lambda}_2$ while the product rivalry effect, δ, has a positive impact for all values of parameters assumed in the model. Moreover, for $\alpha = 1$, the maximum values of $\bar{\lambda}_1$ and $\bar{\lambda}_2$ are reached at $\{\gamma = 0; \delta = 1; \eta = 1\}$ at the values $\frac{3}{10}$ and $\frac{3}{8}$, respectively. The Table 4 presents how $\bar{\lambda}_1$ and $\bar{\lambda}_2$ evolve, depending on the value of γ. The value of α is fixed at 1 and $\delta = 0.1$. When the value of the technology spillover is equal to zero, the substitutability parameter always has a negative impact on the thresholds of the knowledge sharing game. For positive values of the technology spillover, a rise of the substitutability parameter increases $\bar{\lambda}_1$ and $\bar{\lambda}_2$ until a point where the technology spillover will be higher than $\bar{\lambda}_1$ and $\bar{\lambda}_2$. In this situation, the substitutability parameter begins to positively affect the thresholds of the knowledge sharing game. Therefore, obtaining a positive impact of the initial degree of substitutability on the behavior in terms of knowledge sharing mostly requires a low value of this initial degree of substitutability.

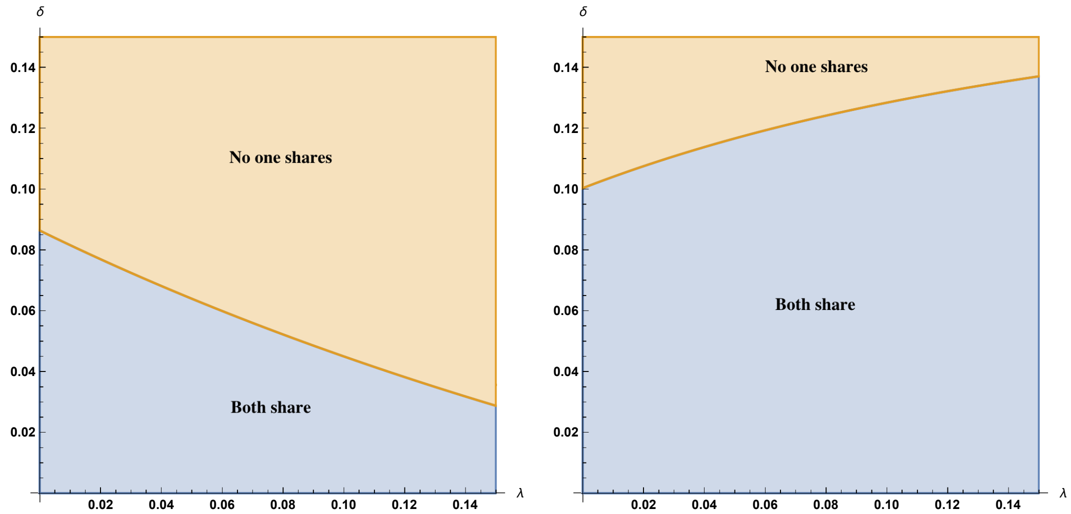
Table 4 – Impacts of γ on $\bar{\lambda}_1$ and $\bar{\lambda}_2$

$\eta = 0.15$	$\gamma = 0$	$\gamma = 0.1$	$\gamma = 0.2$	$\gamma = 0.3$	$\gamma = 0.4$	$\gamma = 0.5$
$\bar{\lambda}_1 =$	0.0221	0.0180	0.0147	0.0120	0.0096	0.0078
$\bar{\lambda}_2 =$	0.0226	0.0184	0.0150	0.0122	0.0099	0.0080
$\eta = 0.85$						
$\bar{\lambda}_1 =$	0.0397	0.0307	0.0239	0.0186	0.0145	0.0113
$\bar{\lambda}_2 =$	0.0409	0.0316	0.0246	0.0192	0.0150	0.0117

C Competition *à la* Bertrand

In the Bertrand competition, the prices and quantities equilibria are no longer equal. Accordingly, the profit functions are more complex in this situation. The resolution of the game in the Bertrand competition is not presented here. Following the assumptions of Section 3.1 and the example of Figure 1, a numerical example, with Figure 3, is shown to highlight the slight differences that a Bertrand competition implies compared to a Cournot competition.

Figure 3 – Impacts of spillovers on knowledge sharing with a Bertrand competition



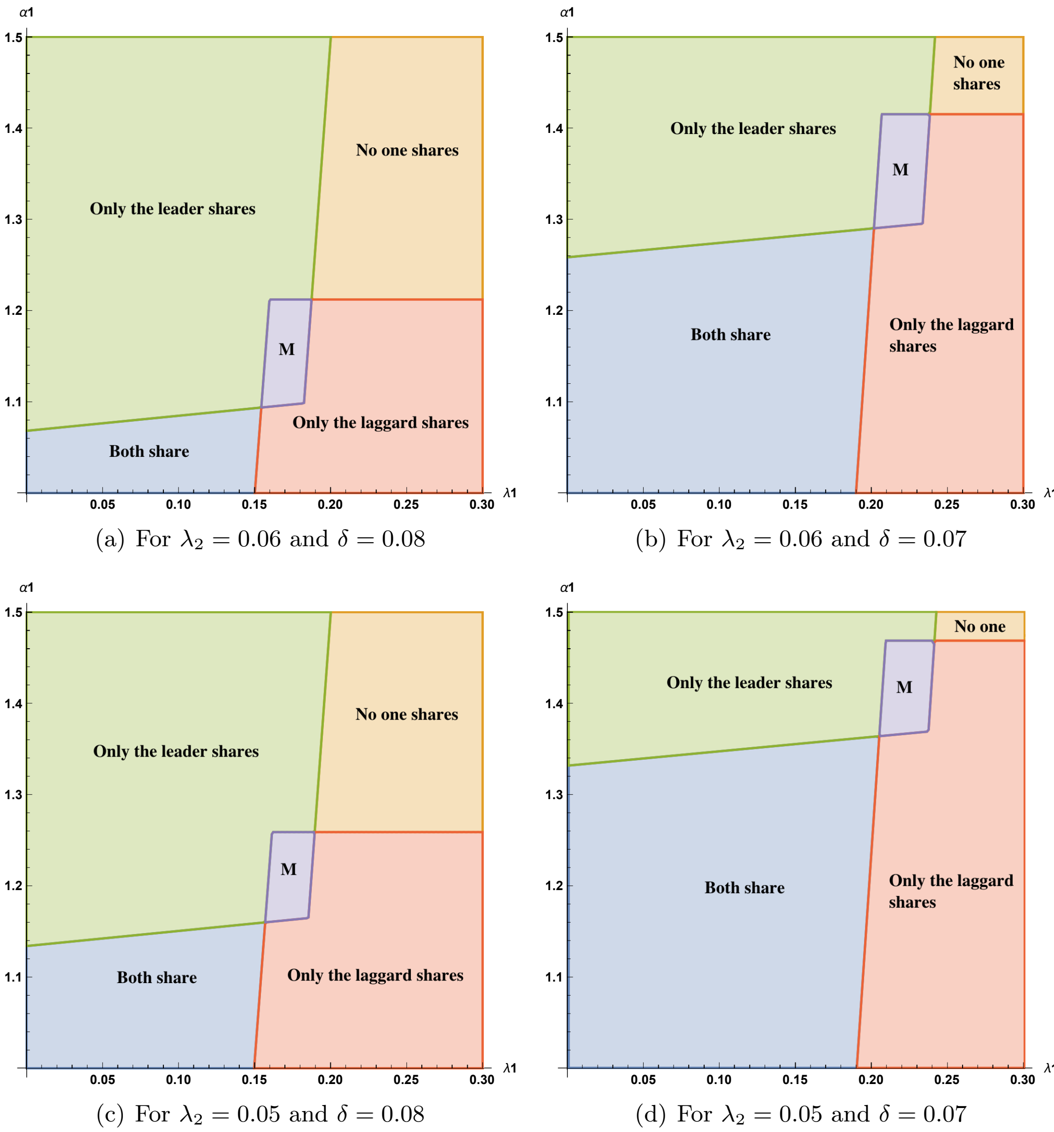
(a) For $\eta = 0.15$ (b) For $\eta = 0.65$

Since the strategic variable is the price and no longer the quantity, the intensity of competition is higher. This impacts the results numerically (and analytically) but qualitatively the results are similar. In fact, the qualitative results of the model depend heavily on the free-riding behavior due mostly to the technology spillover. In Figure 3(a), there is a slight increase of situations where both firms reject knowledge sharing. Figure 3(b) is similar to Figure 1(b) because of a reduction of the value of η. In fact, the value of η is 0.85 in Figure 1(b) and it is 0.65 in Figure 3(b). For a value of η at 0.85, the greater intensity of competition would imply an exit of the product market of the outside firm.

D Asymmetric firms

A numerical simulation has been done where asymmetries on several parameters have been introduced, without taking into account a firm outside the consortium (F_3 is out of the market). It is considered that the firm F_1 is a technology leader and supplies a higher quality product compared to the firm F_2, the laggard firm. More specifically, the heterogeneity affects the quality of the product before the collaboration (α_i), the technology spillover (λ_i), the product rivalry effect (δ_i) and the innovation (ω_i) in the sense that the knowledge shared by the technology leader is more crucial than that of the laggard firm. Four numerical examples are shown in Figure 4 where we set $\alpha_2 = 1$, $\gamma = 0.1$, $\omega_1 = 0.04$ and $\omega_2 = 0.02$, which leads to $\omega = 0.06$ when both firms agree to knowledge sharing. The substitutability parameter γ is low enough to maintain positive demand for the firm F_2. In Figures 4(a) and 4(b) we set $\lambda_2 = 0.06$, where the difference derives from the product rivalry effect. In Figure 4(a), we set $\delta_1 = 0.053$ and $\delta_2 = 0.027$ which leads to $\delta = 0.08$ when both firms share their knowledge. In Figure 4(b), we set $\delta_1 = 0.047$ and $\delta_2 = 0.023$ that leads to $\delta = 0.07$ when both firms share their knowledge. It is similar for Figures 4(c) and 4(d) but the technology spillover from firm F_2 is lower at $\lambda_2 = 0.05$.

Figure 4 – Impacts of spillovers with asymmetric firms



(a) For $\lambda_2 = 0.06$ and $\delta = 0.08$

(b) For $\lambda_2 = 0.06$ and $\delta = 0.07$

(c) For $\lambda_2 = 0.05$ and $\delta = 0.08$

(d) For $\lambda_2 = 0.05$ and $\delta = 0.07$

In the purple area, denoted M, there are multiple equilibria similar to that discussed in the footnote 17. Other values of parameters can lead to a coordination game as discussed in footnote 18. Here, both spillovers continue to negatively affect the behavior in terms of knowledge sharing. The technology spillover from the rival nevertheless logically and positively affects the knowledge sharing of each firm. Analytical results can be found but only with less heterogeneity.

E Participation in the PPP in R&D

In the model developed in the paper, the question of the entry into the PPP in R&D is not raised. In this Appendix, a stage is added where both firms can choose to enter into the PPP before the knowledge sharing stage. It is assumed that even if only one firm decides to enter into the R&D cooperation, this firm will collaborate with the public lab and then produce an innovation thanks to that cooperation. The structure of this new game is presented in the Table 5. The action e_i means that firm i enters in the PPP, and ne_i means the opposite (similarly for the knowledge sharing stage with a_i and r_i). Here, if one firm refuses to enter the PPP, it cannot share its knowledge.

When only one firm decides to enter the PPP, the firm that does not enter will not have access to the innovation and spillovers. If the firm inside the PPP shares its knowledge, it obtains an innovation $\omega/2$ from the public lab and there are no longer any spillovers since the other firms are outside the PPP. Consequently, the situation where the firm inside the PPP refuses the knowledge sharing is always dominated. In fact, the firm inside the PPP benefits from the innovation that leads to higher profits compared to its competitors, thanks to the higher quality of its product. Thus, in this case, the firm always enters the PPP.

In the case where both firms enter the PPP, the game at the second stage is the same as the one presented in the body of the paper. When both firms agree to knowledge sharing at the second stage ($\omega > \Omega_1(.)$), one firm can refuse to enter the PPP iif

$$\Omega_1(.) < \omega < \frac{2(2-\gamma)\left(\alpha\delta(2-\eta) - 2\lambda\left(2+\gamma-\eta^2\right)\right)}{16 - 2\gamma^2 + \gamma\left(2\delta+\eta^2+4\right) - (\delta+10)\eta^2 + \eta^4},$$

where the right-hand side of this inequality is denoted $\Omega_3(.)$. $\Omega_3(.)$ is higher than $\Omega_1(.)$ only if $\eta > \sqrt{2\gamma}$ and $\lambda < \frac{\alpha\delta(2-\eta)(4-2\gamma-\delta)\left(\eta^2-2\gamma\right)}{8\gamma^2\delta+4\eta^4(\gamma+2(\delta+5))-2\eta^2(8\gamma(\delta+2)+(\delta+8)^2)+4\gamma(\delta+4)^2+32(\delta+4)-4\eta^6}$. The SPNE are as follows

- for $\Omega_3(.) < \Omega_1(.) < \omega$ or $\Omega_1(.) < \Omega_3(.) < \omega$, there is one pure strategy where both firms agree to enter the PPP at the first stage,
- for $\Omega_1(.) < \omega < \Omega_3(.)$, there are two pure strategy equilibria wherein one firm agrees to enter the PPP while the other firm does not enter the PPP or they adopt a mixed strategy during the first stage.

When only one firm agrees to knowledge sharing at the second stage ($\Omega_1(.) > \omega > \Omega_2(.)$), the firm that refuses to share its knowledge also refuses to enter the PPP iif

$$\Omega_2(.) < \omega < \frac{2(2-\gamma)(2-\eta)\left(\alpha\delta(4-2\gamma-\delta) - 4(2+\eta)\lambda\left(2+\gamma-\eta^2\right)\right)}{(4-2\gamma-\delta)\left(16-\eta^2(2\gamma+\delta+12)+2\gamma(\delta+4)+2\eta^4\right)},$$

where the right-hand side of this inequality is denoted $\Omega_4(.)$. $\Omega_4(.)$ is higher than $\Omega_2(.)$ only if $\eta > \sqrt{2\gamma}$ and $\lambda < \frac{\alpha\delta(2-\eta)(4-2\gamma-\delta)\left(\eta^2-2\gamma\right)}{4(\gamma-\eta^2+2)(2\gamma\delta-(\delta+8)\eta^2+\eta^4+16)}$. The firm that agrees to share its knowledge refuses to enter in the PPP iif

$$\Omega_2(.) < \omega < \frac{2(2-\gamma)\left(\alpha\delta(2-\eta)(4-2\gamma-\delta) + 4\lambda\left(2+\gamma-\eta^2\right)\left(2\gamma+\delta-\eta^2\right)\right)}{(4-2\gamma-\delta)\left(16-\eta^2(2\gamma+\delta+12)+2\gamma(\delta+4)+2\eta^4\right)},$$

where the right-hand side of this inequality is denoted $\Omega_5(.)$. $\Omega_5(.)$ is higher than $\Omega_2(.)$

only if $\eta > \sqrt{2\gamma}$ and $\eta \leq \sqrt{2\gamma+\delta}$ or $\eta > \sqrt{2\gamma+\delta}$ and $\lambda < \frac{\alpha\delta(2-\eta)(4-2\gamma-\delta)}{4(2+\gamma-\eta^2)(\eta^2-2\gamma-\delta)}$. For all parameter values of the model $\Omega_5(.)$ is higher than $\Omega_4(.)$. The SPNE are as follows

- for $\omega > \Omega_5(.) > \Omega_4(.) > \Omega_2(.)$ or $\omega > \Omega_5(.) > \Omega_2(.) > \Omega_4(.)$ or $\omega > \Omega_2(.) > \Omega_5(.) > \Omega_4(.)$, both firms agree to enter the PPP at the first stage,
- for $\Omega_5(.) > \omega > \Omega_4(.) > \Omega_2(.)$ or $\Omega_5(.) > \omega > \Omega_2(.) > \Omega_4(.)$, only the firm that does not share its knowledge at stage 2 agrees to enter the PPP at the first stage,
- for $\Omega_5(.) > \Omega_4(.) > \omega > \Omega_2(.)$, there are two pure strategy equilibria wherein one firm agrees to enter in the PPP while the other firm does not enter the PPP or they adopt a mixed strategy during the first stage.

Table 5 – The model with an entry stage in the PPP

Stage 1 Entry	Stage 2 Knowledge sharing	Stage 3 Competition: inverse demands for F_1 and F_2
$\{e_1, e_2\}$	$\{a_1, a_2\}$	$p_1 = \alpha + \omega + \lambda - q_1 - (\gamma+\delta)q_2 - \eta q_3$
		$p_2 = \alpha + \omega + \lambda - q_2 - (\gamma+\delta)q_1 - \eta q_3$
	$\{r_1, a_2\}$	$p_1 = \alpha + \omega/2 + \lambda - q_1 - (\gamma+\delta/2)q_2 - \eta q_3$
		$p_2 = \alpha + \omega/2 - q_2 - (\gamma+\delta/2)q_2 - \eta q_3$
	$\{a_1, r_2\}$	$p_1 = \alpha + \omega/2 - q_1 - (\gamma+\delta/2)q_2 - \eta q_3$
		$p_2 = \alpha + \omega/2 + \lambda - q_1 - (\gamma+\delta/2)q_2 - \eta q_3$
	$\{r_1, r_2\}$	$p_1 = \alpha - q_1 - \gamma q_2 - \eta q_3$
		$p_2 = \alpha - q_2 - \gamma q_1 - \eta q_3$
$\{ne_1, e_2\}$	$\{r_1, a_2\}$	$p_1 = \alpha - q_1 - \gamma q_2 - \eta q_3$
		$p_2 = \alpha + \omega/2 - q_2 - \gamma q_1 - \eta q_3$
	$\{r_1, r_2\}$	$p_1 = \alpha - q_1 - \gamma q_2 - \eta q_3$
		$p_2 = \alpha - q_2 - \gamma q_1 - \eta q_3$
$\{e_1, ne_2\}$	$\{a_1, r_2\}$	$p_1 = \alpha + \omega/2 - q_1 - \gamma q_2 - \eta q_3$
		$p_2 = \alpha - q_2 - \gamma q_1 - \eta q_3$
	$\{r_1, r_2\}$	$p_1 = \alpha - q_1 - \gamma q_2 - \eta q_3$
		$p_2 = \alpha - q_2 - \gamma q_1 - \eta q_3$
$\{ne_1, ne_2\}$	$\{r_1, r_2\}$	$p_1 = \alpha - q_1 - \gamma q_2 - \eta q_3$
		$p_2 = \alpha - q_2 - \gamma q_1 - \eta q_3$

When both firms refuse knowledge sharing at the second stage ($\omega < \Omega_2$), for all parameter values, they agree to enter the PPP at the first stage. If one firm refuses to enter the PPP, the other firm will enter it and the firm that refuses will lost a part of its market share since the firm inside the PPP benefits from the innovation $\frac{\omega}{2}$. Therefore, both firms prefer to enter the PPP even if they anticipate that there will be no knowledge sharing. Obviously, introducing a cost of entry in the PPP should reduce the incentive to enter it in these situations. However, these results should continue to exist if the cost is not too high.

The impact of the technology spillover (λ) is different regarding the entry into the PPP compared to the behavior in terms of knowledge sharing. The technology spillover acts negatively at the thresholds Ω_3 and Ω_4. For the thresholds Ω_5, the technology spillover also acts negatively but only if $\eta > \sqrt{2\gamma + \delta}$. In this case, the sharing firm loses a part of its profits due to the competition with its free-riding partner but it earns more thanks to the competition with the outside firm.