2005s-24

Partner Selection in R&D Cooperation

Gamal Atallah

Série Scientifique
Scientific Series

Montréal
Juin/June 2005

CIRANO
Centre interuniversitaire de recherche en analyse des organisations

ISSN 1198-8177

Partner Selection in R&D Cooperation

Gamal Atallah [*]

Résumé / *Abstract*

Ce papier analyse les incitations à la coopération technologique entre des firmes différenciées par leur niveau d'efficacité. Trois firmes dotées de coûts de production différents investissent dans la R&D visant à réduire leurs coûts de production, avant de se concurrencer en quantités. Les firmes peuvent coopérer en R&D, ce qui implique la coordination des investissements en R&D et le partage d'information. Il est démontré que les préférences quant au choix du partenaire dépendent des externalités de recherche et du différentiel de coûts. Lorsque les externalités de recherche sont faibles (élevées), une firme préfère coopérer avec le partenaire le plus (moins) efficace qui est disponible. À mesure que le différentiel de coûts augmente, les firmes efficaces (inefficaces) préfèrent coopérer avec les partenaires les plus (moins) efficaces plus souvent. Pour des niveaux d'externalités très élevés, une firme préfère être exclue de la coopération en R&D. La configuration d'équilibre est que les firmes les plus efficaces coopèrent lorsque les externalités sont faibles, alors que toutes les firmes coopèrent pour des niveaux intermédiaires des externalités. Lorsque les externalités sont élevées, l'équilibre est que toutes les firmes coopèrent lorsque le différentiel de coûts est suffisamment faible, mais dépend de la structure de négociation lorsque ce différentiel est élevé. Le modèle constitue une généralisation du modèle de concurrence en R&D avec des firmes symétriques.

Mots clés : coopération en R&D, consortiums de recherche, firmes asymétriques, externalités de recherche

In this paper we extend the R&D cooperation model to asymmetric firms, focusing on the incentives for cooperating with firms characterized by different levels of efficiency. Three firms differentiated by their cost levels invest in cost-reducing R&D before competing in output. Firms may cooperate in R&D, which implies both R&D coordination and perfect information sharing. It is found that firms' preferences over whom to cooperate with depend on spillovers and on cost differences between firms. With low (high) spillovers, a firm prefers to cooperate with the most (least) efficient among the remaining firms. As the cost differential between firms increases, efficient (inefficient) firms prefer to cooperate with the most (least) efficient firm more often. For very high spillovers, a firm prefers to be excluded from R&D cooperation. The equilibrium configuration is that the most efficient firms cooperate for low spillovers, while all firms cooperate for intermediate spillovers. For high spillovers, the equilibrium is for all firms to cooperate when the cost differential is sufficiently low, but depends on the bargaining mechanism when the cost differential is high. The model constitutes a generalization of the standard R&D model with symmetric firms.

Keywords: *asymmetric firms, R&D cooperation, R&D spillovers, research joint ventures*

Codes JEL : L13, O33

[*] CIRANO and Department of Economics, University of Ottawa, P.O. Box 450, STN. A, Ottawa, Ontario, K1N 6N5, Canada, email : gatallah@uottawa.ca.

1. Introduction

Research alliances are a common way of developing new technologies and products. Firms have to determine whether to develop their new technologies independently or in conjunction with other firms, and in-house or through outsourcing. If firms decide to collaborate technologically, one major question they have to address is the choice of their collaboration partners. Should firms collaborate with firms who use technologies close to their own? Or they should they prefer partners with different technological skills so as to maximize the complementarity in technology development? Should they collaborate with equally sized/efficient firms? Or should they pair with larger or smaller firms? The goal of this paper is to explore how firms choose their R&D collaboration partners in the presence of asymmetries between firms.

Much of the literature on R&D collaboration has focused on collaboration between symmetric firms (examples include d'Aspremont and Jacquemin, 1988 and Kamien et al., 1992). In practice, however, firms are asymmetric in many respects: efficiency levels, type of technology, environment, etc. In a sample of 668 alliances that took place between 1986 and 1991, Kesteloot and Veugelers (1997) find that 36% of all alliances are between asymmetric partners (only one partner is on the Fortune 500 list), while this figure rises to 48% for research alliances. Mowery (1988) reports that large firms in the aerospace industry prefer to cooperate with specialized firms who cannot threaten their leadership. Based on a sample of European RJVs under the Eureka program, Navaretti et al. (2002) conclude that RJVs are most likely to be formed between firms with intermediate levels of asymmetries, although "asymmetries are on average very large both for real and potential couples." (p. 37). In the pharmaceutical biotech sector, the majority of R&D partnerships take place between groups of large and small firms (Powell, 1998; Rothaermel, 2000; Hagedoorn and Roijakkers, 2002; De Rond, 2003; Roijakkers et al., 2005). Clearly, a significant portion of R&D alliances take place between asymmetric firms.

One way of capturing such asymmetries is to consider differences in production costs. We model an industry composed of three firms, differentiated by their cost levels. We analyze the preferences of each firm as to with whom it prefers to cooperate, and which cooperation configurations are most likely to emerge. Cooperation takes the form of R&D coordination and information sharing.

It will be shown that the choice of cooperation partners depends on the level of technological spillovers and on the cost differences between firms. When spillovers are sufficiently low, any firm prefers to collaborate with the most efficient among the other firms. As spillovers become sufficiently high, the preferences of firms shift toward collaborating with less efficient firms. As the cost differential between firms increases, efficient firms prefer to cooperate with the most efficient firm more often, whereas inefficient firms prefer to cooperate with the less efficient firm more often. For very high spillovers, a firm prefers to be excluded from R&D cooperation, letting the other firms collaborate. The explanation for these results lies in the interplay of how close is a competitor to a given firm, and how important the technology of that competitor is.

When all possible cooperative structures are considered, with high spillovers, the most efficient firms prefer a cooperative structure involving all three firms, while the least efficient firm prefers to be excluded from cooperation (when the cost differential is neither too low nor too high). Welfare is highest when all firms cooperate, followed by when a more efficient pair of firms cooperates; and for most spillover levels, the worst outcome is the absence of cooperation. The equilibrium configuration is that the most efficient firms cooperate for low spillovers, while all firms cooperate for intermediate spillovers. For high spillovers, the equilibrium is for all firms to cooperate when the cost differential is sufficiently low, but depends on the bargaining mechanism when the cost differential is high.

The model sheds light on the choice of R&D collaboration partners when not only the size of the research joint venture (RJV), but also its composition, matters. In the literature, most studies assume that all industry members engage in the research consortium. Given that most papers model duopolistic industries, this is an acceptable assumption in those settings. Some papers have looked more closely at the membership of the consortium (De Bondt and Wu, 1997; Katz, 1986; De Bondt et al., 1992; Poyago-Theotoky, 1995; Kamien and Zang, 1993; Yi, 1998, 1999; Yi and Shin, 2000; Atallah, 2003). However, in these papers firms are typically symmetric, so even if those models inform us about the size of the consortium, they have little to say about the identity of its members.

A few studies have analyzed the incentives for cooperation between asymmetric firms. Röller et al. (1997) find that large firms have fewer incentives to form RJVs with smaller firms, and that RJVs tend to be formed by firms of similar size. However, under R&D competition there are no spillovers in their model. But in common with our model, they assume that R&D cooperation entails R&D coordination and perfect spillovers. Empirically, they find that similarity in size increases the likelihood that firms will form an RJV. Baerness (1999) analyzes the private versus social incentives for R&D cooperation between asymmetric firms. In his model a low-cost and a high-cost firm may decide to form an RJV. He finds that when initial asymmetries are important, R&D cooperation may reduce welfare because it reinforces the initial asymmetry in costs, and helps the larger firm maintain its dominant position. Kesteloot and Veugelers (1997) analyze R&D cooperation in an asymmetric duopoly, allowing for differences in market size, production costs, and technological capabilities. They find that larger initial asymmetries between firms may induce the smallest firm to prefer not to cooperate. Veugelers and Kesteloot (1996) analyze the effects of bargaining on profits sharing between two asymmetric R&D partners. They find that cooperation is more difficult to establish when spillovers are high. Navaretti et al. (2002) study the incentives of two heterogeneous firms to form RJVs, allowing for substitute/complementary research paths and substitute/complementary products. They find that RJVs reduce asymmetries between the cooperating partners. There are no R&D spillovers in their model. Halmenschlager (2004) analyzes a 3-firm oligopoly where two small laggards can cooperate in R&D before competing in output with a larger firm. The leader does not perform any R&D, however, and the two small firms are symmetric. Atallah (2005) analyzes cooperation between two firms which differ in their spillover rates, and finds that asymmetries in spillovers make agreeing on cooperation more difficult.

With the exception of Halmenschlager (2004), those papers have in common that they are based on duopolies, which restricts the choice of firms to either cooperation or not. With more than two firms, as in the current paper, the choices are much more complicated, and, as will be seen, the noncooperative equilibrium is never an attractive equilibrium for any of the firms, irrespective of the levels of spillovers and of cost differences. The current paper is the first to explicitly analyze the incentives for different types of firms to cooperate with different types of partners.

The paper is also indirectly related to the literature on mergers between asymmetric firms. Faulli-Oller (2002) analyzes such mergers and finds that merger profitability increases when the initial cost difference between the merging firms is larger, because after the merger all output is produced using the lowest cost technology. Thomas (2004) analyzes mergers between asymmetric firms in a procurement setting, and finds that the identity of the merging firms, and the effect of the merger on costs, determine whether the merger is profitable or not, and whether it increases or decreases the final price. Cost asymmetries affect the profitability of mergers as well as the profitability of R&D cooperation.

The paper is organized as follows. The next section presents the model and its solution. Section 3 analyzes how R&D, production costs, profits and welfare vary with the composition of the research consortium, with spillovers, and with the cost differential between firms. Section 4 examines the cooperative configurations most likely to arise in equilibrium. The last section concludes.

2. The model

Three firms producing a homogenous good compete a la Cournot. Firms are denoted 1, 2, and 3. Inverse demand is given by $p=A-y_1-y_2-y_3$, where y_i is the output of firm i. The marginal cost of firm i prior to innovation is α_i. Without loss of generality, we assume that $\alpha_1<\alpha_2<\alpha_3$.

Each firm can invest in R&D to reduce its costs. Let x_i denote the R&D output of firm i, which costs γx_i^2. Each firm also benefits through spillovers from the R&D of other firms, represented by $\beta\in[0,1]$. By default, firms engage in R&D noncooperatively. However, they may elect to cooperate in R&D. Cooperation in R&D involves both the coordination of R&D investments to maximize joint profits, and information sharing, so that the spillover rate between cooperating firms is set to 1. Hence, if firm i is cooperating with firm j, each firm benefits also from the portion $1-\beta$ of the other firm's technology.

The marginal cost of firm i is given by

$$c_i = \alpha_i - x_i - \beta\sum_{j\neq i} x_j - (1-\beta)\sum_{j\neq i} \lambda_{ij} x_j, \qquad i = 1,2,3 \qquad \textbf{(1)}$$

where $\lambda_{ij}=1$ if firms i and j are cooperating, and $\lambda_{ij}=0$ otherwise. Output is always chosen noncooperatively.

The profit of firm i is given by

$$\pi_i = (p - c_i)y_i - \gamma x_i^2 \qquad \textbf{(2)}$$

The cooperative structure of the industry is fixed exogenously before the start of the game. The game has two stages. In the first stage firms invest in R&D, taking into account whether they have cooperation partners or not. In the second stage they compete on the output market.

3. Results

Consider first the output stage. At this stage the costs of all firms are taken as given. Equilibrium output of firm *i* is given by

$$y_i = \frac{A - 3c_i + \sum_{j \neq i} c_j}{4} \qquad \textbf{(3)}$$

We now turn to the second stage. Equilibrium R&D depends explicitly on the cooperative structure. There are three possibilities: no cooperation; cooperation among all firms; and cooperation between a pair of firms, with the third firm not cooperating with any other firm.

In the case of no cooperation the R&D output of firm *i* is given by

$$x_i^n = \frac{(3-2\beta)[A(4\gamma+5\beta-2\beta^2-3) - \alpha_i(12\gamma-\beta+2\beta^2-3) + (4\gamma-3\beta+2\beta^2)\sum_{j\neq i}\alpha_j]}{(4\gamma+5\beta-2\beta^2-3)(16\gamma-4\beta+4\beta^2-3)} \qquad \textbf{(4)}$$

When all firms join the research alliance, the R&D output of firm *i* is given by

$$x_i^{all} = \frac{3A - \alpha_1 - \alpha_2 - \alpha_3}{16\gamma - 9} \qquad \textbf{(5)}$$

The last case is when a pair of firms is cooperating and the third firm does not cooperate. Let firms *i* and *j* cooperate, with firm *k* not cooperating. Then, the R&D output of each cooperating firm is given by

$$x_i^{ij} = \frac{(2-\beta)[A(8\gamma+10\beta-4\beta^2-6) - (\alpha_i+\alpha_j)(8\gamma+2\beta-3) + \alpha_k(8\gamma+4\beta^2-6\beta)]}{4(16\gamma^2-25\gamma-2\beta^4+7\beta^3-\beta^2(8\gamma+4)+\beta(28\gamma-7))} \qquad \textbf{(6)}$$

and the R&D of the non-cooperating firm is given by

$$x_k^{ij} = \frac{(3-2\beta)[2A(\gamma+3\beta-\beta^2-2) + (\alpha_i+\alpha_j)(2\gamma-2\beta+\beta^2) - 2\alpha_k(3\gamma+\beta-2)}{2(16\gamma^2-25\gamma-2\beta^4+7\beta^3-\beta^2(8\gamma+4)+\beta(28\gamma-7))} \qquad \textbf{(7)}$$

Note that when all firms join the RJV, R&D investments depend on the average initial marginal cost of all firms.[2] However, from (6) and (7) it is clear that this is not true when some firms remain

[2] This result was also noted by Röller et al. (1997).

outside the RJV.

Analyzing the solutions obtained above analytically is cumbersome and intractable. Following the custom in this literature, we use numerical simulations. We consider a particular relationship between firms' costs. We assume that $\alpha_2=\alpha_1+z$, and $\alpha_3=\alpha_1+2z$, $z>0$, so that the efficiency gap between firms 1 and 2 is the same as the efficiency gap between firms 2 and 3. By varying z, we can study the robustness of the results to different degrees of asymmetries between firms. Our main interest lies in the effect of spillovers on firms' incentives. Henceforth, we fix the other parameters of the model as follows: $A=1000$, $\gamma=60$, $\alpha_1=50$. We first analyze the results when $z=50$. Later we will check how the results are modified for different values of z.

We first analyze how R&D investments and production costs compare between the different scenarios, then we analyze the profitability of cooperation.

3.1 R&D

We first examine how R&D investments vary with spillovers. Figures 1 through 3 illustrate the evolution of R&D expenditures by each firm under the different scenarios. *n* denotes no cooperation, *all* denotes cooperation by all three firms; a pair of numbers (in superscript) means that these two firms are cooperating in R&D. Each figure comprises five curves, comparing the R&D output of a given firm from the five possible structures.

[Figures 1, 2, and 3 here]

In all cases except under *all*, R&D investments decrease with spillovers. Spillovers reduce the net benefits of the innovating firm and/or of the research alliance and increase the benefits to outsiders; firms respond by reducing their R&D investments. Under *all*, R&D investments are independent of spillovers, because of perfect information sharing.

Figures 1 through 3 also allow us to compare R&D investment levels between the different scenarios. A firm spends more on R&D, the more efficient is its cooperating partner. Moreover, a firm always spends more on R&D if it is cooperating with exactly one firm than either a) there is no cooperation; or b) the two other firms are cooperating together. R&D spending by a firm is very close between the no cooperation case and the case where the two other firms are cooperating, with the difference between the two changing signs many times with spillovers.

The scenario *all* tends to yield less R&D than some or all forms of cooperation for low spillovers (this is always true when exactly two firms are cooperating), and tends to yield the highest R&D levels for high spillovers. With low spillovers, *all* tends to be inferior because it decreases R&D due to perfect information sharing; however, with high spillovers, *all* yields more R&D, because, even though the externality is higher with *all*, it is internalized.

3.2 Production costs

The net effect of R&D investments on production costs depends on the level of R&D of a firm, the level of R&D of the other firms, the level of spillovers, and its cooperating partners. Figures 4 through 6 illustrate how production costs for each firm compare between the different scenarios, and how they vary with spillovers. Under no cooperation, production costs first decrease then increase with spillovers. The initial decrease is due to the benefits of increased diffusion; the subsequent increase is due to the continuous decline of R&D with high spillovers. The same pattern obtains whenever a firm is excluded from cooperation: while the two other firms are cooperating, the production costs of the excluded firm first decrease then increase with spillovers; the explanation is the same as in the no cooperation case.

[Figures 4, 5, and 6 here]

Whenever a firm is cooperating with the most efficient among the other firms, its production costs are always increasing with spillovers. This is because spillovers do not affect the incentives for R&D provided by R&D cooperation; and the increased spillovers induce the consortium as well as the non-cooperating firm to reduce their R&D spending, which results in increased production costs for the cooperating firms.

This result also obtains when firms 1 and 3 are cooperating. However, a different picture emerges when firms 2 and 3, the least efficient firms in the industry, form a consortium. In this case the production costs of firms 2 and 3 first decease and then increase with spillovers. The initial decrease is due to the fact that higher spillovers make the consortium benefit more from the technology of firm 1; because of the size of firm 1, this reduces their production costs, even though it also reduces their R&D as well as the R&D of firm 1. We see how the net impact of spillovers on production costs depends on the identity of the cooperating firms.

We now compare production costs for given levels of spillovers across the different scenarios. *all* always yields the lowest levels of production costs, for all spillover levels and for all firms. This is even though, as discussed above, it does not always yield more R&D, especially for low spillovers; this is due to the diffusion effect of perfect information sharing. No cooperation yields the highest production costs, except for spillovers close to zero, where the production costs of a firm are higher when it is excluded from cooperation than under no cooperation.

For firm 1, the ranking of the different pair-wise cooperative scenarios in terms of production costs does not depend on spillovers: its costs are lower when it cooperates with firm 2, then with firm 3, then when it is excluded. For firms 2 and 3, however, this ranking depends on spillovers. For low spillovers, the ranking is similar to firm 1's ranking: each firm has lower costs when it cooperates with firm 1, then with each other, then when the firm is excluded. For high spillovers, however, the ranking changes. For instance, for high spillovers, firm 2 has a lower cost when it is excluded from cooperation than when it cooperates with firm 3. This is because with high spillovers, firm 2 prefers to free-ride on the information received from the consortium (combined with higher R&D) formed of firms 1 and 3, without giving away its own proprietary information. For firm 3, the ranking is even more complicated. For intermediate spillovers (for example, at β=0.8), firm 3 has lower costs when it cooperates with firm 1, then when it is excluded, then when it cooperates with firm 2. The explanation is the same as for firm 2 (with high spillovers). With high spillovers, however, firm 3 has the lowest cost when it is excluded, then when it cooperates with firm 1, then with firm 2. In this case, the benefits of free-riding with high spillovers are so important that firm 3 has lower costs when it is excluded than when it cooperates with either firm 1 or firm 2.

Note that when the most efficient firms in the industry form the RJV, the initial asymmetry in costs is reinforced, as the least efficient firm loses ground compared to the other two firms. When, however, the least efficient firms form an RJV, the initial asymmetry is reduced, because the advantage of the most efficient firm is reduced. This is in contrast with Röller et al. (1997) who find that RJVs preserve the cost asymmetry between firms; this is because of the special duopoly case they consider. This is also in contrast to Baerness (1999) who argues that when initial asymmetries are important, R&D cooperation may reduce welfare because it reinforces the initial asymmetry in costs, and helps the larger firm maintain its dominant position. Here it is shown that when the more realistic case of more than two firms is considered, R&D cooperation may increase or decrease the variance of costs, and hence the welfare effects are much more complex than predicted by a restrictive duopoly model.

Now that we understand how R&D investments and production costs compare between the different scenarios and how they are affected by spillovers, we can use this information to understand the incentives for cooperation.

3.3 Profits

Figures 7 through 9 illustrate how firms' profits vary with spillovers. We first note some regularities. In all cases, when the other firms are cooperating, the profits of the non-cooperating firm increase with spillovers. This is because spillovers are maximized between cooperating firms, hence an increase in spillovers benefits mainly the non-cooperating firm. Second, the profits of any firm when all firms are members of the consortium are independent of spillovers, because the spillover rate is set to 1 under cooperation. Third, with no cooperation, the profits of all firms first increase then decrease with spillovers. They first increase due to the benefits of diffusion; however, further increases in spillovers reduce R&D substantially, which reduces firms' profits.

We now consider the profits of each firm separately. Figure 7 illustrates the profits of firm 1. Note that whether firm 1 cooperates with firm 2 or firm 3, its profits are declining with spillovers. This is because higher spillovers increase the leakage from the consortium to the non-cooperating firm, with little benefit to the consortium (in terms of greater leakages from the non-cooperating firm to the consortium). Especially that the non-cooperating firm in this case is either firm 2 or 3, hence its technology investments are less important than those of firm 1, and in net firm 1 loses from higher spillovers.

[Figure 7 here]

Consider the profits of firm 1 under the different scenarios. Comparing cooperation with 2 and 3, we see that for low spillovers, firm 1 prefers to cooperate with firm 2, whereas with high spillovers it prefers to cooperate with firm 3. The preferences of firm 1 between firms 2 and 3 can be understood by decomposing the effect of changes in the cooperative structure on costs and profits. Consider the passage from the structure 12 to the structure 13. This change in cooperative structure changes the costs of all three firms. From figures 4 through 6 we know that this passage increases c_1 and c_2; it reduces c_3 for most levels of spillovers, but actually increases c_3 for very high spillovers. The change in profits due to these changes in costs can be decomposed in the following fashion:

$$
\begin{aligned}
\pi_1^{13}(c_1^{13},c_2^{13},c_3^{13}) - \pi_1^{12}(c_1^{12},c_2^{12},c_3^{12}) = {} & [\pi_1^{13}(c_1^{13},c_2^{13},c_3^{13}) - \pi_1(c_1^{13},c_2^{13},c_3^{12})] \\
& + [\pi_1(c_1^{13},c_2^{13},c_3^{12}) - \pi_1(c_1^{13},c_2^{12},c_3^{12})] \\
& + [\pi_1(c_1^{13},c_2^{12},c_3^{12}) - \pi_1^{12}(c_1^{12},c_2^{12},c_3^{12})] \\
= {} & E_3 + E_2 + E_1
\end{aligned}
\qquad \textbf{(8)}
$$

The term E_i (i=1,2,3) represents the effects on firm'1 profits of the change in c_i, holding the costs of other firms constant. Figure 7a plots this decomposition, as well as the total change in profits. Firm 1 loses from the increase in its own cost (E_1<0), it gains from the increase in c_2 (E_2>0); it loses from the change in c_3 when it decreases (E_3<0 for low/intermediate spillovers), and gains from the change in c_3 when it increases (E_3>0) for very high spillovers. Note that the gain from the increase in the cost of firm 2 declines with spillovers, because this increase in cost is induced mainly by a reduction in x_2, and this reduction benefits firm 1 most when spillovers are low. Similarly, the loss from the decrease in c_3 declines with spillovers, because this decrease is induced by an increase in x_3, and this increase benefits firm 1 most when spillovers are high. Finally, the loss from the increase in c_1 declines with spillovers because this increase is induced mostly by a decrease in x_1, and this decrease is less harmful to firm 1 when spillovers are high.

[Figure 7a here]

More important, consider the net effect on profits, which depends on the magnitudes of these three effects. For low spillovers, where $\Delta\pi_1$ is below the horizontal axis, the loss from the decrease in own cost and the decrease in c_3 dominates the gain from the increase in c_2, hence firm 1 loses with the passage from 12 to 13. As spillovers increase, the loss from the increase in c_1 and the decrease in c_3 declines more rapidly than the gain from the decrease in c_2, hence $\Delta\pi_1$>0. For extremely high spillovers, firm 1 actually gains from the increase in c_2 and the increase in c_3, and these effects dominate the loss from the increase in its own cost, hence $\Delta\pi_1$>0. A similar decomposition could be made to compare any pair of cooperative structures.

Figure 7 also illustrates the preferences of firm 1 over the other cooperative structures. In general, the worst scenario for firm 1 is that firms 2 and 3 cooperate. However, this is not true for very high levels of spillovers, where firm 1 prefers to let firms 2 and 3 cooperate rather than cooperating with either of them. With high spillovers, firm 1 prefers to let the other firms increase their R&D expenditures through the venture, while it reduces its own R&D when it is not cooperating with anyone. Nonetheless, for high levels of spillovers, the structure *all* is better for firm 1 than any other structure. With high spillovers, given that technology is leaking anyway, the best firms can do is to all join the research consortium, internalize this externality and share information.

Consider now figure 8, which illustrates firm 2's profits. When firm 2 cooperates with firm 1, its profits decline with spillovers, for the reasons mentioned above. However, when it cooperates with firm 3, its profits are increasing with spillovers. The reason for this is that when firm 2 cooperates with firm 3, higher spillovers allow the consortium to benefit more from the technology of firm 1; given that firm 1 is the market leader, this benefit is substantial, and dominates the effect of the leakage from the consortium to firm 1.

[Figure 8 here]

As to the choice of partners, a similar pattern is observed here: firm 2 prefers to cooperate with firm 1 when spillovers are low, but prefers to cooperate with firm 3 for high spillovers. The explanation is the same as above. As was done for firm 1, the change in π_2 from the passage from the structure 12 to the structure 13 is decomposed into the effects of the change in the cost of each firm:

$$\begin{aligned}\pi_2^{23}(c_1^{23},c_2^{23},c_3^{23}) - \pi_2^{12}(c_1^{12},c_2^{12},c_3^{12}) &= [\pi_2^{23}(c_1^{23},c_2^{23},c_3^{23}) - \pi_2(c_1^{23},c_2^{23},c_3^{12})] \\ &+ [\pi_2(c_1^{23},c_2^{23},c_3^{12}) - \pi_2(c_1^{23},c_2^{12},c_3^{12})] \\ &+ [\pi_2(c_1^{23},c_2^{12},c_3^{12}) - \pi_2^{12}(c_1^{12},c_2^{12},c_3^{12})] \qquad \textbf{(9)} \\ &= \quad E_3 + E_2 + E_1\end{aligned}$$

Figure 8a illustrates this decomposition. With low/intermediate spillovers, the loss from the rise in c_2 and the decline in c_3 dominates the gain from the increase in c_1, hence $\Delta\pi_2<0$. As spillovers increase, even though c_3 rises with the passage from 12 to 23, the loss from the increase in c_2 dominates the gain from the rise in c_1 and c_3, hence $\Delta\pi_2<0$. For very high spillovers, the gain from the rise in c_1 and c_3 comes to dominate, hence $\Delta\pi_2>0$.

[Figure 8a here]

As for the noncooperative scenario (going back to figure 8), its ranking is much better for firm 2 than for firm 1. Even that for low and moderate spillovers, firm 2 prefers no cooperation to cooperating with firm 3. Firm 3 is a close competitor to firm 2; with low spillovers, firm 2 prefers to preclude firm 3 from benefitting from its technology; as spillovers increase, firm 3 is getting much of firm 2's technology anyway, hence firm 2 prefers to mate with firm 3 so as to improve its competitive position relative to firm 1. Finally, similarly as for firm 1, for high levels of spillovers firm 2 prefers the structure where all firms cooperate.

Consider finally figure 9. When firm 3 cooperates with firm 1, its profits first increase then decrease with spillovers. They first increase because the consortium benefits from the technology of firm 2; however, they decrease after that because of the losses due to the leakage from the consortium to firm 2. The profits of firm 3 are increasing in spillovers when it cooperates with firm 2. In this case, the consortium always gains through the higher leakages from firm 1. The impact of spillovers on the profits of a firm when it cooperates with one other firm is very sensitive to the identity of the cooperating firms: it can be increasing, decreasing, or take the shape of an inverted U.

[Figure 9 here]

The same pattern observed above is found here: firm 3 prefers to cooperate with firm 1 for low spillovers, and prefers cooperation with firm 2 with high spillovers. The decomposition of the change in profits of firm 3 following the passage from 13 to 23 is as follows:

$$\begin{aligned}
\pi_3^{23}(c_1^{23},c_2^{23},c_3^{23}) - \pi_3^{13}(c_1^{13},c_2^{13},c_3^{13}) &= [\pi_3^{23}(c_1^{23},c_2^{23},c_3^{23}) - \pi_3(c_1^{23},c_2^{23},c_3^{13})] \\
&+ [\pi_3(c_1^{23},c_2^{23},c_3^{13}) - \pi_3(c_1^{23},c_2^{13},c_3^{13})] \\
&+ [\pi_3(c_1^{23},c_2^{13},c_3^{13}) - \pi_3^{13}(c_1^{13},c_2^{13},c_3^{13})] \qquad \textbf{(10)} \\
&= \quad E_3 + E_2 + E_1
\end{aligned}$$

Figure 9a illustrates this decomposition. For low/intermediate spillovers, the loss from the rise in c_3 and the decline in c_2 dominates the gain from the rise in c_1, hence $\Delta\pi_3<0$. As spillovers increase, firm 2 actually comes to have a higher cost with 23 than with 12; still, in this range the loss from the rise in c_3 dominates, and $\Delta\pi_3<0$. As spillovers increase further, the gain from the rise in c_1 and c_2 dominates the loss from the rise in c_3, hence $\Delta\pi_3>0$.

[Figure 9a here]

And (similarly as for firm 2) with low spillovers (going back to figure 9), firm 3 prefers no cooperation to cooperating with firm 2. Cooperation with one other partner is more valuable for the most efficient firm than for the other firms.

Proposition 1. *In a* 3-*firm oligopoly with symmetric differences in production costs, when cooperation involves only two firms, a firm prefers to cooperate with the most efficient available partner when spillovers are low, while it prefers to cooperate with the least efficient available partner when spillovers are high.*

Contrarily to the other firms, firm 3 prefers cooperation by all firms for low and intermediate spillovers, and prefers cooperation by the other two firms for high spillovers. Firm 3 is the weakest of all firms, with the smallest investment in technology. Therefore it gains significantly, and loses a little, from sharing information with other firms. For low and intermediate spillovers, firm 3 prefers to associate with both firms, to benefit as much as possible from information sharing. It prefers this to mating with only one of the firms, which precludes it from fully benefitting from the technology of the outsider. However, for high spillovers, it is even better to let the other two firms cooperate, benefit from the leakages, and keep (part of) its technology secret.

Proposition 2. *In a* 3-*firm oligopoly with symmetric differences in production costs, with high spillovers, the most efficient firms prefer a cooperative structure involving all three firms, while the least efficient firm prefers to be excluded from cooperation* (*when the cost differential is neither too low nor too high*).

In a sense this creates a paradox: if we exclude the structure *all*, no firm wants to cooperate for high spillovers. Each firm would prefer that the other firms form a partnership, while it performs research on its own. But if all firms follow this path, and if there is no coordination or communication mechanism, firms may find themselves in a prisoner's dilemma situation, where each firm waits for the others to cooperate, resulting in an equilibrium where no cooperation takes place. And this is even though each firm would prefer some form of cooperation to this total absence of cooperation.

We see that the incentives for cooperation, and their relationship to spillovers, vary greatly depending on firms' efficiency. Market leaders have different preferences from smaller players.

Röller et al. (1997) find that the high cost firm always prefers to participate in the RJV, since the RJV preserves initial cost asymmetries, while R&D competition exacerbates them. While the low-cost firm prefers not to participate in the RJV when products are highly substitutable and the cost asymmetry is large, for exactly the same reason: it prefers the mode which reinforces initial asymmetries. Kesteloot and Veugelers (1997) analyze R&D cooperation in an asymmetric duopoly, allowing for differences in market size, production costs, and technological capabilities. They find that larger asymmetries between firms may induce the smaller firm to prefer not to cooperate.

The results we obtain here are different. In our model the most efficient firm always prefers to cooperate with at least one of the other firms compared to no cooperation. And even the high cost firm always prefers some form of cooperation to no cooperation. Our model is more general, since there are three firms instead of two and spillovers may exist even without R&D cooperation.

Here, with three partners, the choice is more complicated, because several cooperation partners are available, and a change in spillovers may change the preferred partner, rather than inducing a firm to prefer no cooperation. In fact, as shown above, for all firms and for any spillover levels, the noncooperative structure is dominated by at least two cooperative structures. Hence, the second choice to cooperating with a partner is another partner, rather than not cooperating at all. Moreover, as will be shown, changes in the asymmetries in costs have no discernable effects on the results.

The availability of more partners to choose from affects cooperation incentives in two ways. First, as explained above, even if a small firm finds cooperation with a large partner unprofitable, there are other firms with whom to cooperate. Second, cooperation with a partner is more attractive when there are many outsiders because it improves the competitive position of each cooperating firm relative to outsiders, an effect which is not present in a duopoly, and which makes cooperation profitable more often in an oligopoly. Moreover, refusing to cooperate with a partner may induce that partner to cooperate with a third firm, which may leave the refusing firm technologically lagging behind the research consortium.

To check for robustness, figures 10 through 12 show the equivalent graphs when z=5. Here the differences in efficiency are much less important in absolute and relative terms. The figures show that the shape and rankings of the curves are very similar to that of figures 7 through 9. Perhaps the exception lies in the profits of firm 3 from the structure 13. With this new configuration, these profits are monotonically decreasing in spillovers, and dominate the profits of the structure *all* for low levels of spillovers (whereas above these profits first increased and then decreased with spillovers, and were always lower than the profits of *all*). This difference can be explained as follows. As the cost disadvantage of firm 3 becomes less important, its profits from 13 do not increase with β as before, because now the loss from the leakages to firm 2 dominates the gains from getting firm 2's technology.

[Figures 10, 11, and 12 here]

In order to further test the robustness of the results, we verify whether the rankings of profits are maintained for different levels of cost efficiencies. We are mainly interested in the choice of one firm between the two other firms; hence for a given firm, we compare its profits from cooperating with each of the other partners. For instance, for firm 1, the relevant comparison is between π_1^{12} and π_1^{13}.

Figure 13 shows how the comparison between π_1^{12} and π_1^{13} depends on spillovers and on the efficiency gap. Along the curve, $\pi_1^{12}=\pi_1^{13}$. To the right of the curve, $\pi_1^{12}<\pi_1^{13}$; to the left, $\pi_1^{12}>\pi_1^{13}$. This is consistent with the results obtained above: when spillovers are low enough, firm 1 prefers to cooperate with firm 2; when they are high enough, it prefers to cooperate with firm 3. What is new on this graph is how the critical value of the spillover depends on the cost differential. The positive slope of the curve means that as the cost differential increases, the critical spillover is higher, and firm 1 prefers to cooperate with firm 2 for a wider range of spillovers. As the cost differential increases, firm 2 is less of a serious competitor to firm 1, hence firm 1 can prefer to cooperate with firm 2 even as spillovers are relatively high. As the cost differential becomes very large, firm 1 always prefers to cooperate with firm 2 to cooperating with firm 3. Read otherwise, the figure says that the higher the spillover level, the higher the cost differential compatible with firm 1 preferring to cooperate with firm 2. As the cost differential increases, it takes a higher spillover rate for the switch (from the more efficient to the less efficient firm) to occur. Alternatively, as the potential partner becomes less efficient, it takes higher values of spillovers to want to associate with it. This figure shows that the results obtained above are robust: firm 1 prefers to cooperate with the most (least) efficient among the remaining firms when spillovers are sufficiently low (high). The only thing that is sensitive to the level of the cost differential is the separating spillover level.[3]

[Figure 13 here]

One result which is in the same spirit as Röller et al. (1997) is the effect of the degree of cost asymmetries. As mentioned above, they find that greater cost asymmetries make it more likely that the low-cost firm prefers not to cooperate with the high cost firm. In our model, when cost asymmetries increase, the range of spillovers such that firm 1 prefers to cooperate with firm 2 rather than with firm 3 increases; this is clear from figure 13.

Figure 14 shows the equivalent graph for firm 2. Along the curve, $\pi_2^{12}=\pi_2^{23}$. To the right of the curve, $\pi_2^{12}<\pi_2^{23}$, and to the left, $\pi_2^{12}>\pi_2^{23}$. In this case the curve has a negative slope, meaning that when the cost differential is higher, the separating spillover rate is lower. Read otherwise, the higher the spillover rate, the lower is the cost differential inducing firm 2 to prefer to cooperate with firm 3. This is because π_2^{12} decreases with spillovers, while π_2^{23} increases with them, as explained above (see figure 8). Hence, as spillovers increase, firm 2 shifts its preference gradually from cooperating with firm 1 to cooperating with firm 3. When the cost differential is low, firm 1 is not much more efficient than firm 2; hence firm 2 does not lose much from cooperating with it. When, however, the cost differential is large, firm 1 is much more efficient than firm 2; firm 2 prefers to mate with firm 3 so as to avoid letting firm 1 benefit from its technology.

[Figure 14 here]

Figure 15 performs the same exercise for firm 3. To the right of the curve, $\pi_3^{13}>\pi_3^{23}$; to the left, $\pi_3^{13}<\pi_3^{23}$. The curve has a negative slope, hence the interpretation is along the lines of figure 8 for firm 2.

[Figure 15 here]

Proposition 3. *In a* 3-*firm oligopoly with symmetric differences in production costs, the critical spillover level separating cooperation with the most/least efficient available partner is decreasing in the production cost of the firm under consideration. Moreover, it is increasing in the cost*

[3] It would be straightforward to generalize this result to the case of more than three firms. One would expect that the preference of firm 1 would be for the next most efficient firm for the lowest levels of spillovers; then for the second next most efficient firm for slightly higher levels of spillovers; etc.

differential for the most efficient firm, and decreasing in the cost differential for the least efficient firms.

Note that in most cases the structure *all* is not the preferred structure by firms for low and moderate spillovers: firms prefer to cooperate with a subset of the remaining firms. This allows them to share information with some firms, while reinforcing their competitive position relative to other firms.

3.4 Welfare

It is straightforward to compare the welfare effects of the different scenarios. Figure 16 illustrates how welfare[4] from the different scenarios varies with spillovers. In all cases except the *all* case, welfare first increases then decreases with spillovers. It first increases due to the benefits of increased diffusion, but then decreases because of the decline in R&D (by the outsider(s)) which results from high spillovers. In the *all* case, welfare is independent of spillovers because of perfect information sharing.

[Figure 16 here]

We can also compare the welfare levels across scenarios from that figure. Because the structure *all* always yields the lowest marginal costs for all firms (see figures 4 through 6), it is this structure which yields the highest level of welfare. The figure shows that for all spillover levels, $W^{12}>W^{13}>W^{23}$. Hence, if cooperation is to take place among a pair of firms (or, more generally, among a subset of firms), society prefers that cooperation takes place between the most efficient pairs.[5] The differences in welfare levels are much smaller for higher levels of spillovers; in this case information is diffusing anyway, therefore it matters little who is cooperating with whom. The noncooperative structure tends to yield the lowest levels of welfare, except for very low spillovers where it is preferable to the structure 23. This is because in this case cooperation between firms 2 and 3 reduces their production costs and increases their market share at the expense of firm 1; hence a larger portion of output is produced by high cost firms, which results in lower social welfare than

[4] Defined as the sum of profits and consumer surplus.

[5] Although the comparison between the structure 13 and the structure 23 is likely to be sensitive to the degree, and especially the symmetry, of cost differences.

the absence of cooperation.

Proposition 4. *In a* 3*-firm oligopoly with symmetric differences in production costs, where cooperation involves both R&D coordination and information sharing, for all* $\beta \neq 0$*,*
$W^{all} > W^{12} > W^{13} > W^{23}$.

4. Equilibrium configuration

We now turn to the equilibrium cooperative structure. What structure will constitute an equilibrium, for each possible level of spillovers? This turns out to be a tedious question. Different equilibrium concepts could be used regarding coalition formation. Rather than arbitrarily impose a specific bargaining structure, we use the simple but intuitive criterion that if the first choices of a group of firms coincide, this choice will be implemented. As we will see, this criterion yields a clear prediction of the equilibrium outcome for a wide range of spillovers.

For low spillovers, both firms 1 and 2 prefer to cooperate, leaving firm 3 out (see figures 7 and 8). Hence whatever the bargaining mechanism, this is the most likely outcome for these levels of spillovers. For intermediate spillovers, all three firms prefer the structure *all*, hence this is the likely outcome in this case.

However, for higher levels of spillovers the picture is much more complicated, because firms have diverging preferences. For high spillovers we can see that firms 1 and 2 would prefer the structure *all*, but firm 3 prefers to be excluded from cooperation, i.e. it prefers the structure 12. However, for high spillovers the structure 12 is not very appealing to either firms 1 or 2, and this is where the bargaining is likely to become very involved. Because if one of them turns to 3 and proposes cooperation, firm 3 may refuse, hoping to get 1 and 2 to cooperate. But if 3 fails to convince 1 and 2 to cooperate, it will likely accept, given that *all* is its second choice for high enough spillovers. Hence the equilibrium with high spillovers is likely to be either *all* or 12, depending on the outcome of bargaining.

In this situation, where the first choices of firms don't coincide, it is necessary to consider not only the first choice of each firm, but also the second and subsequent choices. This is because if a firm cannot obtain its preferred choice (because the other partner refuses, say), it will try to get its second preferred choice, etc. Moreover, when a firm is offered cooperation by another firm, it will consider what it would gain by accepting or refusing this offer, and this will depend on the profits it would make from the other available alternatives, both superior and inferior to the one being offered. This leads to a complicated bargaining game, the outcome of which is difficult to predict without imposing some bargaining structure.

Note that when the cost differential is low (figure 11), the range of spillovers where firm 3 prefers to be excluded from cooperation is very narrow, and is expected to vanish when the cost differential becomes very low. Hence, in this case, firm 3 is more likely to agree to the structure *all* for high spillovers.

It is of interest that the noncooperative equilibrium is dominated by most combinations of cooperation for most levels of spillovers. Hence it is an unlikely contender for the equilibrium.

Proposition 5. *In a* 3-*firm oligopoly with symmetric differences in production costs, the equilibrium configuration is that the most efficient firms cooperate for low spillovers, while all firms cooperate for intermediate spillovers. For high spillovers, the equilibrium will be for all firms to cooperate when the cost differential is sufficiently low, but will depend on the bargaining mechanism when the cost differential is high.*

Moreover, in some cases the structure *all* may not be feasible. There are many reasons why all industry members may not be members of the research consortium. Antitrust authorities may be more skeptical of a consortium encompassing all industry members. When the number of firms becomes large, the high transaction and coordination costs will almost certainly limit the consortium to a subset of the industry. When several consortia form, by definition each of them has a different composition, although some firms may be part of several consortia. And indeed, empirical evidence shows that most consortia are composed of many, but not all, industry members (Combs, 1986; Snyder and Vonortas, 2000).

The analysis becomes more complicated when we eliminate the structure *all* because the divergence between firms' preferences becomes greater when we eliminate it. In a sense, the structure *all* is a focal equilibrium, at least for high spillovers, on which firms can coordinate.

5. Conclusions

In this paper we have modeled R&D cooperation between asymmetric firms. Because of their larger size and stronger technological capabilities, larger firms can better exploit the benefits of R&D cooperation, or, as Zanfei (1994:262) notes: "exploit faster and more effectively the knowledge developed through cooperation." It was shown how firms' preferences over whom to cooperate with depend on spillovers and on cost asymmetries. Generally, with low spillovers, a firm prefers to cooperate with the most efficient among the remaining firms; whereas with high spillovers, it prefers to cooperate with the less efficient. As the cost differential between firms increases, efficient firms prefer to cooperate with the most efficient firm more often, whereas inefficient firms prefer to cooperate with the less efficient firm more often. The equilibrium configuration is that the most efficient firms cooperate for low spillovers, while all firms cooperate for intermediate spillovers. For high spillovers, the outcome is harder to predict, and will depend on the bargaining structure. The model constitutes a generalization of the standard R&D model with symmetric firms.

While going from two to three firms may not seem a big change, the 3-firm model provides many insights which cannot be captured in the duopoly model, and which extend far beyond the specific 3-firm market structure. With only two firms, the only choice for firms is either to form an RJV or not. And, in particular, the only thing that matters is how the formation of the RJV affects the relative competitive position of each firm relative to the other. Whereas when there are more than two firms, the formation of an RJV among any subset of firms affects not only the competitive position of the cooperating firms relative to each other, but also the competitive position of each of the cooperating firms relative to non-members. An RJV of two firms that might not be profitable in a 2-firm industry might be profitable to both firms in a less concentrated industry. In a sense, an advantage of some degree of competition (certainly beyond duopoly) is that it makes RJVs profitable more often, especially when firms are asymmetric. Many studies have noted that asymmetries in costs (Baerenss, 1999; Röller et al., 1997; Kesteloot and Veugelers, 1997) or in spillovers (Atallah, 2005) make agreeing on cooperation more difficult. The current model shows that this problem is less acute when the RJV comprises only a subset of firms in the industry.

The paper shows the importance of accounting, simultaneously, for R&D spillovers, asymmetries between firms, and the presence of outsiders, to understand the motives and incentives for R&D cooperation by heterogeneous firms. In particular, the presence of an outsider affects the gains and losses from cooperating with a given partner, making any analysis based on a restrictive duopoly model highly incomplete.

The model can be extended in many ways. Here it was assumed that the cost differences between firms were symmetric. One could consider a more general model where the gap between firms' costs is not constant. In this paper an industry with three firms was considered. A generalization would be to see how the results extend to an industry composed of an arbitrary number of firms. Here only one cooperative venture was allowed to form; it would be interesting to explore the simultaneous participation by each firm into many research alliances. Finally, the result that firms' preferences for cooperation depend on the partner's type may lead potential cooperation partners to try to pretend to possess different levels of production or technological capabilities so as to make themselves more attractive to other firms. Modeling these incentives requires the use of an asymmetric information framework.

References

Atallah, G., 2003, 'Information Sharing and the Stability of Cooperation in Research Joint Ventures', *Economics of Innovation and New Technology*, 12(6):531-54.

Atallah, G., 2005, 'R&D Cooperation with Asymmetric Spillovers', *Canadian Journal of Economics*, forthcoming.

Baerenss, A., 1999, *R&D Joint Ventures: The Case of Asymmetric Firms*, Working Paper 99-17, Center for Economic Analysis, Department of Economics, University of Colorado at Boulder.

Combs, K.L., 1986, *A Summary of Research Joint Ventures Filed with the Justice Department*, unpublished mimeograph.

d'Aspremont, C., and Jacquemin, A., 1988, 'Cooperative and Noncooperative R&D in Duopoly with Spillovers', *American Economic Review*, 78:1133-37.

De Bondt, R., Wu, C., and Lievens, D., 1992, *Stable Strategic R&D Cartels*, Onderzoeksrapport NR. 9204, Departement Toegepaste Economische Wetenschappen, Katholieke Universiteit Leuven.

De Bondt, R., and Wu, C., 1997, 'Research Joint Venture Cartels and Welfare', in Poyago-Theotoky, J.A. (ed.), *Competition, Cooperation, Research and Development*, St. Martin's Press Inc., N.Y.

De Rond, M., 2003, *Strategic Alliances as Social Facts: Business, Biotechnology, and Intellectual History*, Cambridge University Press, Cambridge.

Faulli-Oller, R., 2002, 'Mergers between asymmetric firms: profitability and welfare', *The Manchester School*, 70(1):77-87.

Hagedoorn, J., and Roijakkers, N., 2002, 'Small Entrepreneurial Firms and Large Companies in Inter-firm R&D Networks - the International Biotechnology Industry', in Hitt, M., Ireland, R., Camp, S., and Sexton, D. (eds.), *Strategic Entrepreneurship: Creating a New Integrated Mindset*, Blackwell, Oxford.

Halmenschlager, C., 2004, 'R&D-Cooperating Laggards versus a Technological Leader', *Economics of Innovation and New Technology*, 13(8):717-32.

Kamien, M.I., and Zang, I., 1993, 'Competing Research Joint Ventures', *Journal of Economics and Management Strategy*, 2(1):23-40.

Kamien, M.I., Muller, E., and Zang, I., 1992, 'Research Joint Ventures and R&D Cartels', *American Economic Review*, 82(5):1293-1306.

Katz, M.L., 1986, 'An analysis of cooperative research and development', *RAND Journal of Economics*, 17(4):527-43.

Kesteloot, K., and Veugelers, R., 1997, 'R&D Cooperation between Asymmetric Partners', in Poyago-Theotoky, J.A. (ed.), *Competition, Cooperation, Research and Development: The Economics of Research Joint Ventures*, St. Martin's Press Inc., N.Y.

Mowery, D.C., 1988, 'Joint Ventures in the US Commercial Aircraft Industry', in Mowery, D.C. (ed.), *International Collaborative Ventures in US Manufacturing*, Ballinger, Cambridge MA.

Navaretti, G.B., Bussoli, P., Ulph, D., and von Graevenitz, G., 2002, *Information sharing, research coordination and membership of research joint ventures*, CEPR Working Paper No. 3134.

Powell, W., 1998, 'Learning from Collaboration: Knowledge and Networks in the Biotechnology and Pharmaceutical Industries', *California Management Review*, 40:228-40.

Poyago-Theotoky, J.A., 1995, 'Equilibrium and Optimal Size of a Research Joint Venture in an Oligopoly with Spillovers', *Journal of Industrial Economics*, 43(2):209-25.

Roijakkers, N., Hagedoorn, J., and van Kranenburg, H., 2005, 'Dual market structures and the likelihood of repeated ties - evidence from pharmaceutical biotechnology', *Research Policy*, 34:235-45.

Röller, L.H., Tombak, M.M., and Siebert, R., 1997, *Why Firms Form Research Joint Ventures: Theory and Evidence*, Discussion paper 97-6, Social Science Research Center WZB, Berlin.

Rothaermel, F., 2000, ‘Technological Discontinuities and the Nature of Competition’, *Technology Analysis and Strategic Management*, 12:149-60.

Snyder, C., and Vonortas, N., 2000, *Multimarket and Multiproject Contact in Research Joint Ventures*, Paper presented at the *AEA* 2000 Meetings.

Thomas, C.J., 2004, ‘The competitive effects of mergers between asymmetric firms’, *International Journal of Industrial Organization*, 22:679-92.

Veugelers, R., and Kesteloot, K., 1996, ‘Bargained Shares in Joint Ventures Among Asymmetric Partners: Is the Matthew Effect Catalyzing?’ *Journal of Economics*, 64(1):23-51.

Yi, S.S., 1998, ‘Endogenous formation of joint ventures with efficiency gains’, *RAND Journal of Economics*, 29(3):610-31..

Yi, S.S., 1999 , ‘Asymmetric Research Joint Ventures and Market Concentration’, *Japanese Economic Review*, 50(3):309-20.

Yi, S.S., and Shin, H., 2000, ‘Endogenous formation of research coalitions with spillovers’, *International Journal of Industrial Organization*, 18:229-56.

Zanfei, A., 1994, ‘Technological Alliances Between Weak and Strong Firms: Cooperative Ventures with Asymmetric Competences’, *Revue d’Économie Industrielle*, 67(1):255-80.

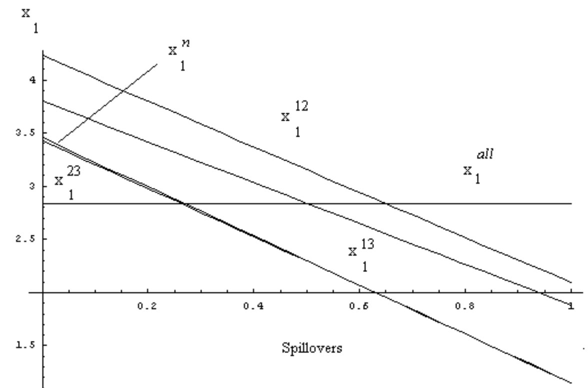

Figure 1 - R&D investments by firm 1

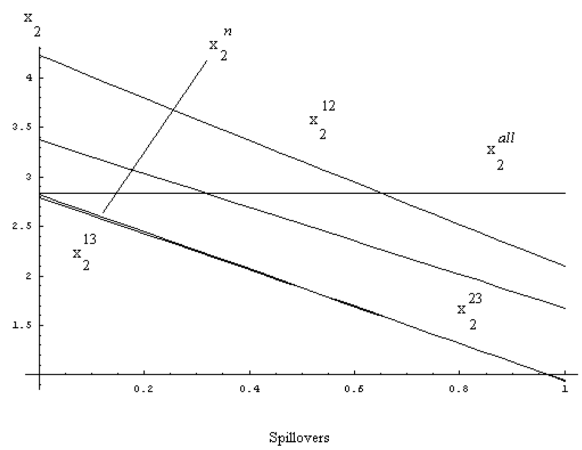

Figure 2 - R&D investments by firm 2

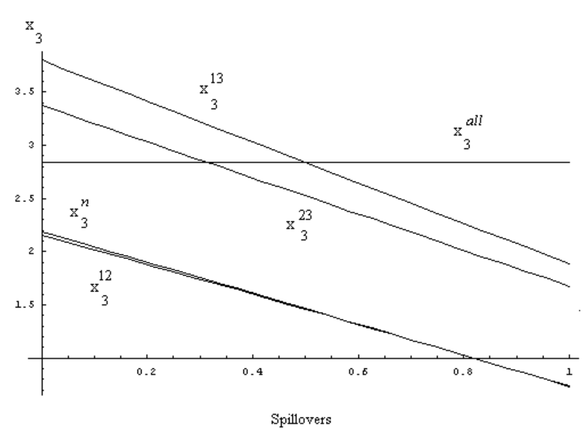

Figure 3 - R&D investments by firm 3

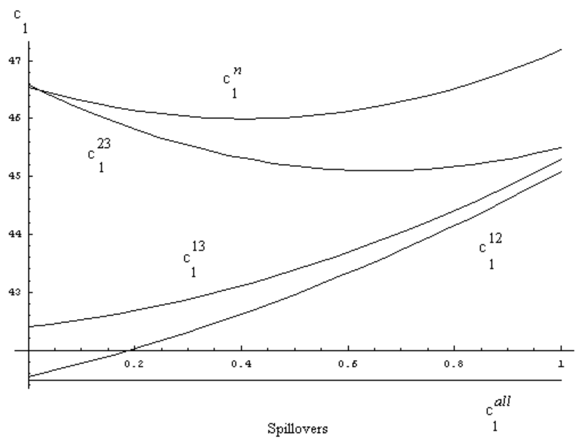

Figure 4 - Marginal cost of firm 1

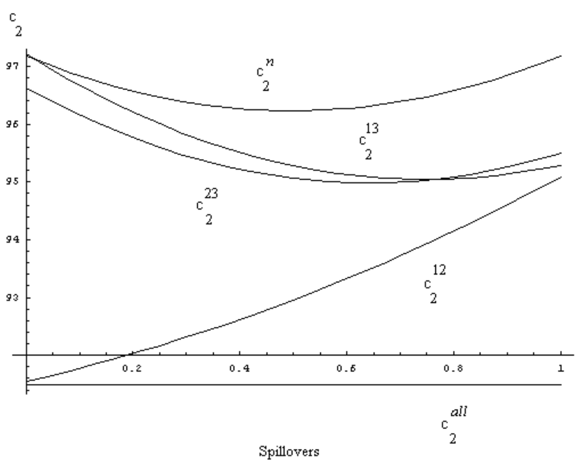

Figure 5 - Marginal cost of firm 2

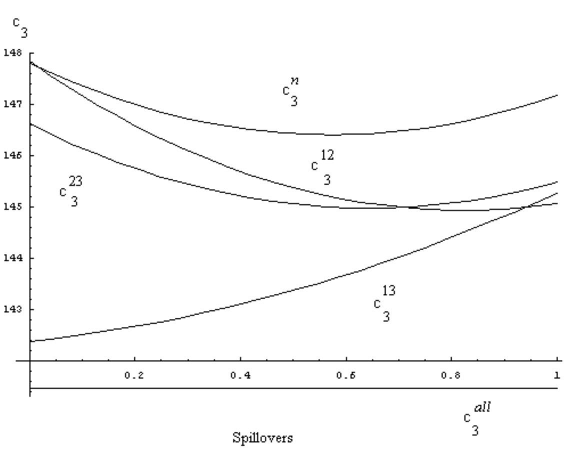

Figure 6 - Marginal cost of firm 3

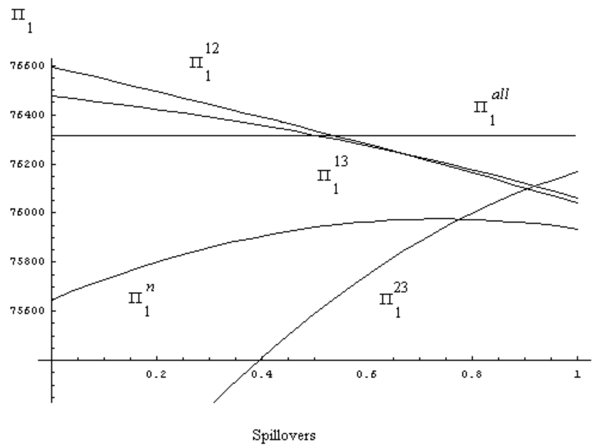

Figure 7 - Profits of firm 1, z=50

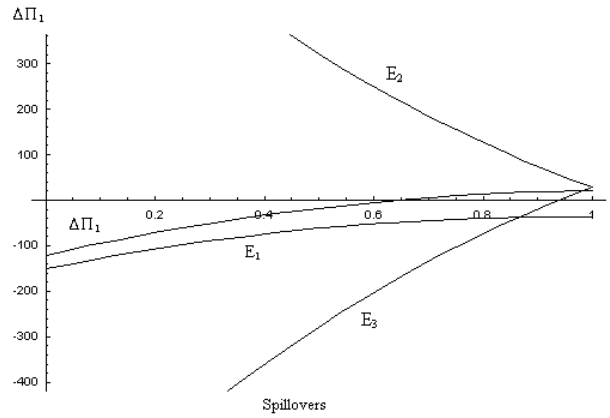

Figure 7a - Decomposition of the effect of going from 12 to 13 on π_1

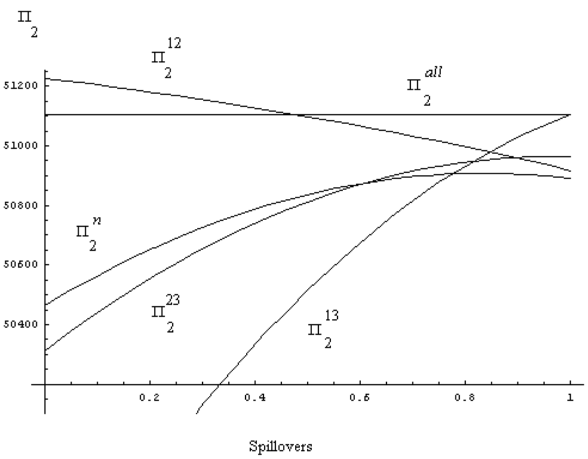

Figure 8 - Profits of firm 2, z=50

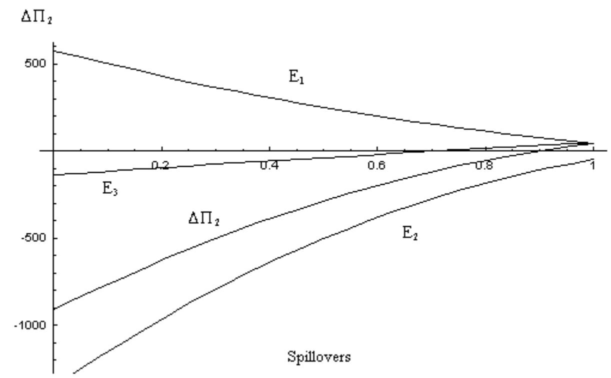

Figure 8a - Decomposition of the effect of going from 12 to 23 on π_2

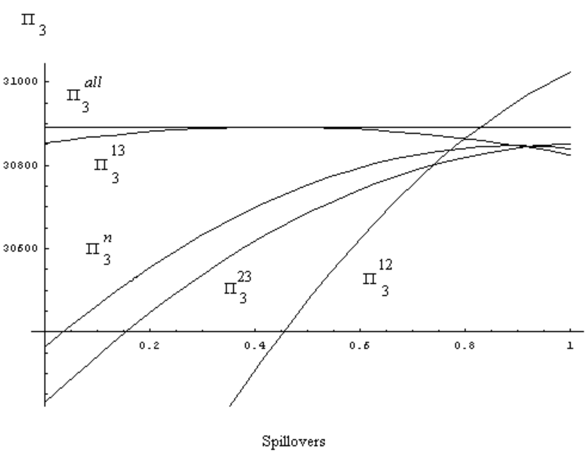

Figure 9 - Profits of firm 3, z=50

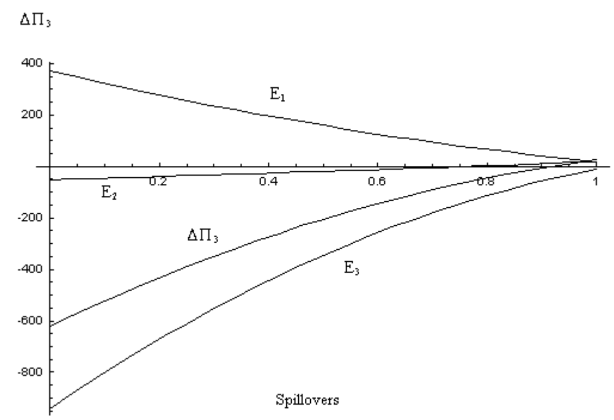

Figure 9a - Decomposition of the effect of going from 13 to 23 on π_3

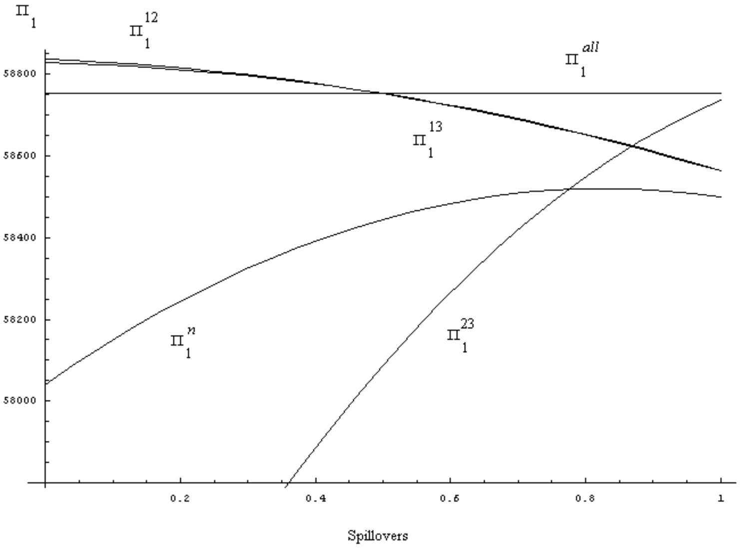

Figure 10 - Profits of firm 1, z=5

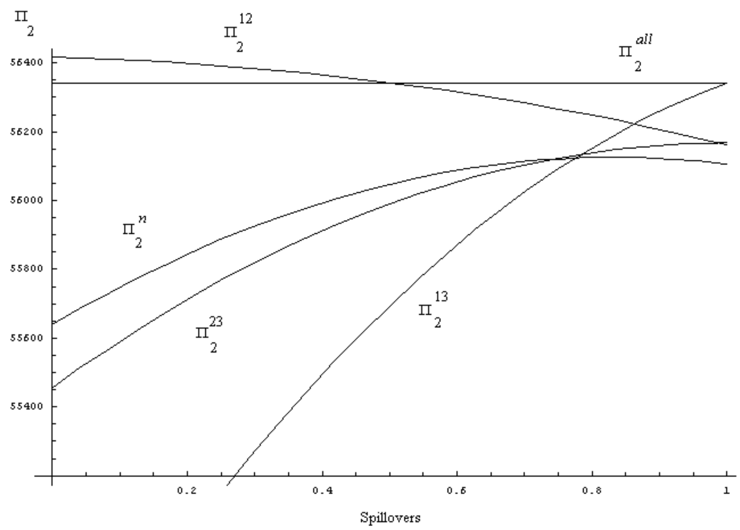

Figure 11 - Profits of firm 2, z=5

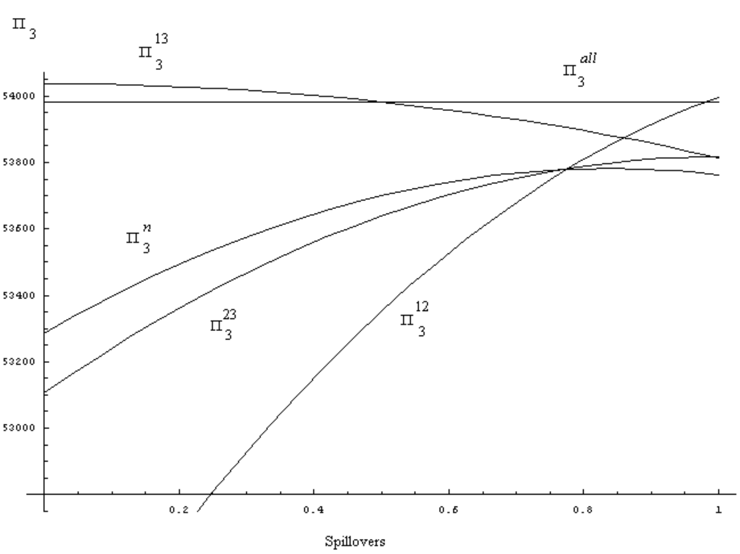

Figure 12 - Profits of firm 3, z=5

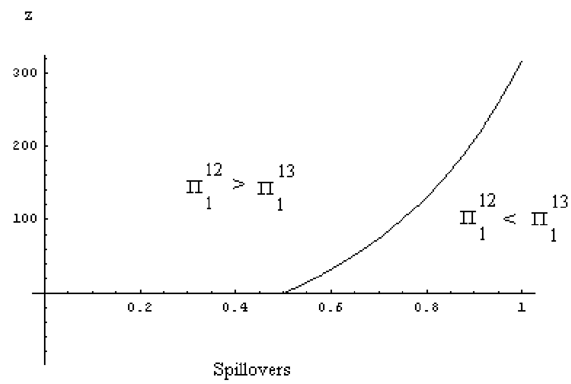

Figure 13 - Critical value of z for firm 1

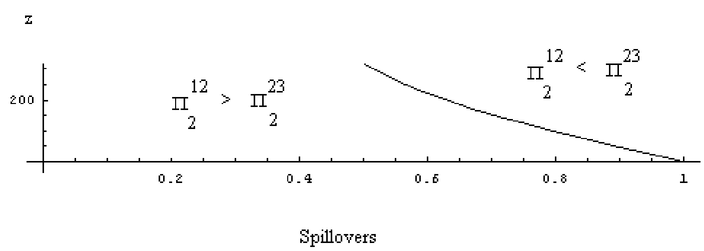

Figure 14 - Critical value of z for firm 2

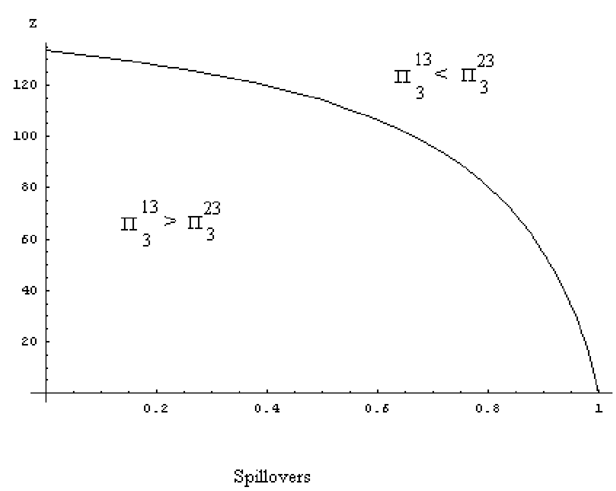

Figure 15 - Critical value of z for firm 3

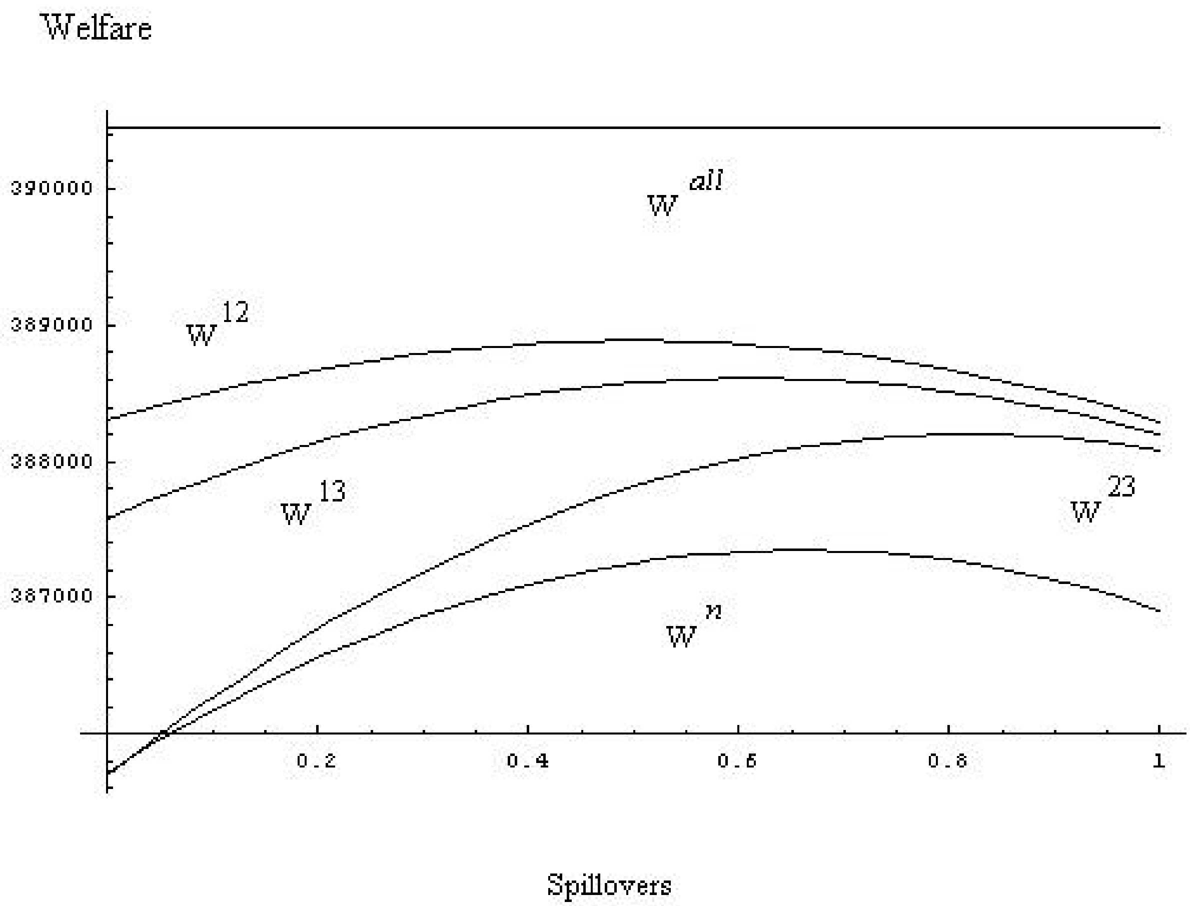

Figure 16 - Welfare