R&D efficiency gains due to cooperation

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Abstract

A theoretical and widely-quoted finding is that levels of cooperative R&D exceed noncooperative R&D levels when technological spillovers are relatively large, while the opposite holds for relatively small technological spillovers. We qualify this result by showing that for relatively small technological spillovers the comparison is not driven by *the extent* of technological spillover, but by *the increase* in technological spillover due to cooperation in R&D. In particular, an agreement to cooperate in R&D always raises R&D efforts if the post-cooperative technological spillover rate is 'high enough'.

Keywords: cooperative R&D; noncooperative R&D; increasing technological spillovers.

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1 Introduction

Due to the ever increasing complexity of innovations and the concomitant rise in development cost many claim that today even large firms do not have all necessary assets for developing new technologies. A natural means for firms to keep up with the Darwinian process of technological change is then to combine research efforts. By now policy makers have recognized firms' need to join innovative activities. In Europe, the United States and Japan firms are allowed to form R&D cooperatives. This relaxation of antitrust policies, initiated in the 1980s, triggered the establishment of a substantial body of literature dealing with the economics of (strategic) research and development (R&D).

A seminal contribution within this sphere of economic analysis is that of Claude d'Aspremont and Alexis Jacquemin [1988] (henceforth referred to as AJ). They show that cooperative R&D levels exceed noncooperative R&D levels whenever technological spillovers are relatively large (i.e. above 50%), while the opposite holds for relative small technological spillovers (i.e. below 50%). Since then this result has been replicated in many other studies.[1] And although the percentage may change or may depend on other characteristics (such as the extent to which products are differentiated), the basic message remains the same: above some level of technological spillover an R&D cooperative will devote more resources to R&D than would a competitive R&D market.

The explanation for this general finding lies in the interaction between two externalities associated with process-innovating R&D investments (see Kamien *et al.* [1992] and Hinloopen [1997]).[2] On the one hand, devoting resources to R&D increases the innovator's efficiency of production and consequently rewards it with a larger market share at the expense of its competitors (the so-called *combined-profits* externality). On the other hand, there is the free flow of innovative information from an innovator to its competitors

[1] One of the reasons for the contribution of AJ to trigger so many subsequent papers is its simplicity. Using a linear duopoly with Cournot competition leaves ample room for generalizations of all kind (see e.g. Hinloopen [2000a] (and the references therein) who analyzes a differentiated oligopoly with both Cournot and Bertrand competition). There are however some problems related to AJ's treatment of technological spillovers, as explained below.

[2] Most studies considering strategic R&D deal with process-innovating research, i.e. technological progress that leads to a reduction in marginal cost of production. Notable exceptions are Motta [1992] and Rosenkranz [1995], who consider product innovations. The widely used justification for considering process-innovating R&D only is that newly developed products in most cases satisfy an already fulfilled need in a more efficient way. Product innovations can therefore be seen as process innovations

(the technological spillover), thereby increasing the latter's production efficiency (the so-called *competitive-advantage* externality). With respect to the incentive to invest in R&D the first of these two externalities can be either positive or negative, while the second is unambiguously negative. In deciding how much to invest in R&D individual firms always take into account the competitive-advantage externality. R&D cooperatives, in addition, internalize the combined-profits externality. Indeed, the analysis of AJ was the first to (implicitly) reveal that in case of relatively large technological spillovers the combined profits externality is positive and outweighs the competitive-advantage externality (for more on this interaction see Hinloopen [1997]).

A common feature of many studies considering strategic R&D, including that of AJ, is that the rate of technological spillover is exogenously given. That is, the intensity of technological spillover is not affected by firms cooperating in R&D (a notable exception is Choi [1993]). It is to be expected however that the extent to which technological information flows freely within an R&D cooperative is at least as intense as among R&D competitors (for an early recognition of this point see Katz [1986]).

The present paper examines the above mentioned general finding, that cooperative R&D efforts exceed noncooperative R&D efforts if the technological spillover rate is relatively high, under the assumption of an *increasing spillover rate due to cooperation in R&D*. For this examination we could build on the model of AJ, like many others did. There are however some intuitive and technical problems with this model due to the way technological spillovers are modelled. First, AJ model technological knowledge as to spill over *after* the R&D process is finished. That is, the technological spillover relates to R&D outputs rather than R&D inputs. It is questionable however whether that is an adequate representation of reality. Geroski [1995] for instance identifies three channels through which R&D spillovers can occur: (i) researchers exchange ideas during casual encounters, at seminars and through publications, (ii) researchers move between employers thereby taking with them their (tacit) knowledge, and (iii) by observing the actions of one researcher, another can deduct the line of reasoning that lies behind these actions. None of these channels relates exclusively to final R&D products. Rather, technological spillovers occur *during* the R&D process.

Second, in AJ R&D efforts of one firm can be *perfectly additive* to the R&D efforts of its competitor. This assumption is questionable on at least three accounts. If there are technological spillovers one would think that the firms among which these spillovers occur are conducting research within the same area. Hence there will always be, at least, some duplication of research efforts, thereby decreasing the effective amount of knowledge that spills over. Further, it is questionable that the novel part of competitors' research efforts perfectly match one's own R&D activities. There will always be, at least, some research results that are of no immediate use, thus, again, diminishing the effective technological spillover. Also, differences in corporate culture, research strategies, internal organization and so on hamper firm's ability to appreciate to the full rival's research efforts, yet again diminishing the maximum technological spillover. In sum, it is questionable that the AJ model is valid for high levels of technological spillover. But this then also questions the validity of their widely quoted finding since that depends precisely on spillovers being of a size they are not likely to be!

Third, AJ consider additive output spillovers in combination with diminishing returns to R&D. This combination can yield counter-intuitive results. Suppose the technological spillover is high, that one firm invests little in R&D, that another invests much more in R&D and that this latter firm considers spending an extra euro on R&D. In this situation it could very well be that the best thing for this firm to do would be to actually donate the extra euro to it's competitor, let her do the R&D and appropriate the results through the technological spillover. Given that the competitor hasn't spent much on R&D and that technological spillovers are substantial, this strategy could yield more effective R&D results than would spending the euro directly on R&D.[3] This behaviour certainly is not observed in reality![4]

For these reasons we build on the model of Kamien *et al.* [1992] of strategic R&D, since in their formulation R&D spills over during the R&D process (see also Hinloopen [2000b]). Moreover, as explained in detail by Amir [2000], this model does not carry the economic anomaly implicit in the combination of diminishing returns to R&D and additive output spillovers. However, also in Kamien *et al.* [1992] R&D efforts carried out by independent firms can be perfectly additive. Indeed, we slightly adjust their framework to accommodate the notion that R&D inputs should not be treated as perfectly additive. In particular, we introduce an upper-bound on the level of technological spillover, defined as *the maximum level of spillover that can emerge between firms if they cooperate in R&D*.[5]

Our analysis reveals that the level of cooperative R&D efforts indeed

[3] This argument is due to Amir [2000]. Note that it holds for any level of technological spillover, as long as the difference in R&D spending between the two firms is large enough.

[4] In addition, in the AJ model cooperation in R&D could lead to asymmetric equilibria for low levels of technological spillover (see Salant and Shaffer [1998]), a situation not considered by AJ. We also restrict ourselves to symmetric equilibria, not in the least because firms are inclined to increase the technological spillover if they cooperate in R&D (as explained in Section 5 below), thus diminishing the practicalc relevance of Salant and Shaffer [1998].

[5] See Section 2 (Definition 1). Note however that the gist of the paper (that is, Propositions 1 and 2) does not crucially depend on this adjustment.

exceeds the level of noncooperative R&D when technological spillovers are relatively large (the usual result). However, when technological spillovers are relatively small it is *not their size* that dictates the comparison of R&D levels, *but their increase* due to cooperation (Proposition 1). In particular, also if technological spillovers are relatively small, an R&D-cooperative agreement is still likely to raise effective R&D efforts if the agreement induces a sufficient increase in technological spillover.

The intuition for this finding is that members of the R&D cooperative realize that increasing the rate of technological spillover is likely to increase joint profits due to the concomitant efficiency gain of a single firm's R&D efforts. Cooperating firms are thus inclined to enhance the combined-profits externality (an externality that is positive for 'large enough' spillovers and that is absent in a competitive research market). Accordingly, even if pre-cooperative technological spillovers are relatively small, the R&D-cooperative agreement can yield an increase in R&D activity.

This result is the continuous analogue of the analysis of Kamien *et al.* [1992].[6] Observe that they consider two cases only; one in which the technological spillover is not affected by the R&D cooperative agreement (leading to the formation of R&D cartels), and one in which technological spillovers are maximal due to cooperation (leading to the formation of RJV cartels). The latter case is one where, as in AJ, independently carried out R&D is perfectly additive. In this paper we consider all intermediate cases as well; that is, R&D cooperative agreements that induce an increase in technological spillover, but not necessarily to the potential maximum.[7]

We also show that total surplus is increasing in R&D efforts, up to some point. The equilibrium levels of cooperative and noncooperative R&D are shown to be below this upper-bound (Proposition 2). Hence, whenever a cooperative R&D agreement yields an increase in R&D efforts, it also enhances total surplus. Indeed, conventional wisdom would hold that R&D cooperatives are not desirable if pre-cooperative technological spillovers are small. We show that quite the opposite holds if in this case the cooperative agreement yields an increase in technological spillover that is 'large enough'.

[6] Do note that we built on a stylized version of the model of Kamien *et al.* [1992] (see also footnote 5 below). We conjecture however that the essence our results is robust with respect to possible generalizations (see also the concluding remarks in Section 6 below).

[7] The assumption that cooperation in R&D implies full information sharing as well is quite common in the literature. A notable analysis is that of Beath *et al.* [1998], who carefully model the act of doing R&D as a two-stage process; in stage one knowledge is created, in stage two it is used to lower cost of production. Return rates to scale can be both constant and diminishing at either stage of the R&D process. Also, at both stages technological spillovers can emerge. Do note that also Beath *et al.* [1998] assume spillovers to be maximal when firms cooperate in R&D.

Our results have an immediate implication for policy. Rather than acquiring only as good an approximation of technological spillovers as possible in order to assess the desirability of the formation of a particular R&D cooperative, policy makers, in addition, have to assess the likely increase in technological spillover between potential R&D partners due to the cooperative agreement. Indeed, in case technological spillovers are small but this increase is thought to be large 'enough', there is still good reason to allow the formation of the proposed cooperative. In Section 5 we describe a relatively simple procedure to assess whether or not a proposed R&D cooperative is likely to yield the potentially required increase in technological spillover.

We continue as follows. In the next section the model is explained followed by an analysis of cooperative and noncooperative R&D in Section 3. The central proposition of the paper is presented in Section 4 and its policy implications are spelled out in Section 5. Section 6 concludes. In order to compare our results with of the bulk of the related literature, the analysis of Section 3 is replicated for the celebrated model of AJ (in the Appendix). Qualitatively the results are identical, thus adding to the robustness of our findings.

2 The model

Market demand is captured by

$$p = a - bQ, \tag{1}$$

where Q is total quantity supplied and a and b are some positive constants. We assume that $Q < a/b$.

The industry consists of two firms producing with constant marginal cost A (with $A < a$). Each firm can lower these by conducting R&D. That is, each firm i can devote resources to process-innovating research activities. Note that R&D typically caries a positive externality; if one firm conducts R&D another firm can absorb part of this effort without having to pay for it.[8] Accordingly, if firm i invests x_i in R&D, its *effective* R&D investments X_i are given by

$$X_i = x_i + \beta x_j, \tag{2}$$

[8] It is now understood that firms have to conduct at least some R&D themselves to be able to absorb the results of other firms' R&D efforts (for an early recognition of this point see Cohen and Levinthal [1989]). We ignore this issue since it would not alter our main proposition while adding to the technical complexity of the analysis (see also Kamien and Zang [2000]).

$i, j = 1, 2,\ i \neq j$ (unless stated otherwise, $i, j = 1, 2,\ i \neq j$ throughout the rest of the paper). In (2) β represents the technological spillover. Kamien *et al.* [1992] allow it to take on any value between 0 and 1. In the latter case R&D efforts are perfectly additive. As elaborated upon in the Introduction, this situation is highly unlikely. We therefore introduce an upper-bound on technological spillover.

Definition 1 *The upper-bound on technological spillovers,* $\overline{\beta} \in (0,1)$*, is the maximum level of spillover that can emerge between firms if they cooperate in R&D.*

This upper-bound typically is influenced by the extent to which cooperating firms' research agendas overlap, by partners' abilities to learn from each other, by participants' willingness to contribute intellectually to the cooperative, and so on. In any case, it restricts the parameter space β in that $\beta \in [0, \overline{\beta})$.

The reduction in marginal cost brought about by R&D investments is determined by the R&D production function f. This function is a mapping from effective R&D inputs to reductions in marginal cost. In line with Kamien *et al.* [1992] we assume that f is increasing in X_i at a decreasing rate, with $f(0) = 0$ and $\lim\limits_{X \to \infty} f(X) < \infty$. If firm i's cost of R&D equal x_i, its profits are

$$\pi_i = pq_i - [A - f(X_i)]\, q_i - x_i. \tag{3}$$

Following Amir [2000] we set

$$f(X_i) = \sqrt{X_i/\gamma}. \tag{4}$$

Note that in this set-up R&D efforts spills over during the research process, that research efforts can never be perfectly additive and that the counter-intuitive implications of additive output spillovers with diminishing returns to R&D is not present.

3 Market equilibria

Maximizing (3) over quantities yields[9]

$$\widetilde{q_i}(x_i, x_j) = \frac{1}{3b}\left[(a - A) + 2\sqrt{(x_i + \beta x_j)/\gamma} - \sqrt{(x_j + \beta x_i)/\gamma}\right]. \tag{5}$$

[9] A tilde refers to a conditional equilibrium expression. It is left to the reader to verify that the second-order condition is always met.

Concomitant first-stage equilibrium profits conditional on R&D investments then equal

$$\widetilde{\pi}_i(x_i, x_j) = \frac{1}{9b}\left[(a-A) + 2\sqrt{(x_i+\beta x_j)/\gamma} - \sqrt{(x_j+\beta x_i)/\gamma}\right]^2 - x_i. \quad (6)$$

If firms behave noncooperatively in the R&D stage, each firm sets R&D levels so as to maximize (6). This results in (symmetric) effective equilibrium levels of R&D given by[10,11]

$$f\left(X^{NC}\right) = \sqrt{[(1+\beta)x^{NC}]/\gamma} = \frac{(a-A)(2-\beta)}{9b\gamma - (2-\beta)}, \quad (7)$$

where NC stands for 'noncooperative'.[12]

On the other hand, if both firms cooperate in setting their R&D investment, in the R&D stage they consider joint profits, which are

$$\widetilde{\Pi}(x_i, x_j) = \frac{1}{9b}\sum_{\substack{i,j=1,2\\ i\neq j}}^{2}\left\{\left[(a-A) + 2\sqrt{(x_i+\theta x_j)/\gamma} - \sqrt{(x_j+\theta x_i)/\gamma}\right]^2\right\} - \sum_{i=1}^{2} x_i, \quad (8)$$

where θ is the rate of technological input spillover if firms cooperate in R&D, that is, the *post-cooperative* technological input spillover. It is thus assumed that $0 \leq \beta \leq \theta \leq \overline{\beta} < 1$, indicating that the technological spillover between firms cooperating in R&D is at least as intense as that between firms competing in the R&D stage. Maximizing joint profits over R&D efforts yields a symmetric equilibrium level of effective cooperative R&D given by[13]

$$f\left(X^{C}\right) = \sqrt{[(1+\theta)x^{C}]/\gamma} = \frac{(a-A)(1+\theta)}{9b\gamma - (1+\theta)}, \quad (9)$$

where C stands for 'cooperative'.[14] We are now in a position to address the main issue of the paper.

[10] The second-order condition requires that $b\gamma > (2-\beta)^3/9(2-\beta^2)$.

[11] The Routh-Hurwitz stability condition is that $\frac{\partial^2\pi_1}{\partial x_1^2}\frac{\partial^2\pi_2}{\partial x_2^2} - \frac{\partial^2\pi_1}{\partial x_2 x_1}\frac{\partial^2\pi_2}{\partial x_1\partial x_2} > 0$. For R&D being a strategic substitute ($\frac{\partial^2\pi_1}{\partial x_2 x_1} < 0$; see Bulow *et al.* [1985]) this translates into $b\gamma > (2-\beta)^2/3(2+\beta)$. For R&D being a strategic complement ($\frac{\partial^2\pi_1}{\partial x_2 x_1} > 0$; see Bulow *et al.* [1985]) this translates into $b\gamma > (2-\beta)/9$.

[12] For post-innovation marginal cost to be positive it must be that $A - f(X^{NC}) > 0$, or $1 > A/a > (2-\beta)/9b\gamma$, which coincides with the stability condition for strategically substitutable R&D.

[13] The second-order condition requires that $b\gamma > (1+\theta)(5-8\theta+5\theta^2)/9(1+\theta^2)$.

[14] Positive post-innovation marginal cost prevail if $1 > A/a > (1+\theta)/9b\gamma$, a condition that is less strict than the related second-order condition (see footnote 13).

4 Cooperative versus noncooperative R&D

Comparing equilibrium levels of effective cooperative R&D with equilibrium levels of effective noncooperative R&D leads to the following proposition.

Proposition 1 *Let $\beta \in [0, \overline{\beta})$, $0 < \overline{\beta} < 1$, be the pre-cooperative technological spillover rate, and let $\theta \in [0, \overline{\beta})$ be the post-cooperative technological spillover rate such that $\theta \geq \beta$. In a two-stage linear duopoly with process-innovating R&D, input spillovers, diminishing returns to R&D investments and second-stage Cournot competition, (i) if $\overline{\beta} \in [0, \frac{1}{2})$ then $X^C < X^{NC}$, and (ii) if $\overline{\beta} \in (\frac{1}{2}, 1)$ then $\forall\ \beta \in [0, 1 - \overline{\beta})$ we have that $X^C < X^{NC}$, and $\forall\ \beta \in (1 - \overline{\beta}, \overline{\beta})$ we have that $X^C > X^{NC}$ if, and only if,*

$$\theta - \beta \geq \max\{0, 1 - 2\beta\}.$$

Proof. *First observe that for the comparison between effective R&D efforts we can restrict ourselves to comparing effective R&D outputs, due to the monotonicity of f. That is*

$$X^C \geq X^{NC} \Leftrightarrow f\left(X^C\right) \geq f\left(X^{NC}\right).$$

Comparing then (7) with (9) leads to

$$f\left(X^C\right) \geq f\left(X^{NC}\right) \Leftrightarrow (1 + \theta) \geq (2 - \beta). \tag{10}$$

From (10) follows that the necessary increase in β to θ to induce $X^C \geq X^{NC}$ equals $1 - 2\beta$. For $\overline{\beta} > \frac{1}{2}$ this is feasible as long as $\beta + 1 - 2\beta \leq \overline{\beta}$, or $\beta \geq 1 - \overline{\beta}$. For $\overline{\beta} < \frac{1}{2}$ (10) can never hold. ■

Proposition 1 is illustrated in Figure 1 for $\overline{\beta} > \frac{1}{2}$. Observe that if the pre-cooperative spillover rate is relatively high (that is, above 50%) an R&D cooperative always generates more effective R&D efforts than would a competitive R&D market. However, also if the pre-cooperative technological spillover rate is relatively small (that is, below 50%) it could very well be that an R&D cooperative agreement leads to more effective R&D. Indeed, what matters for the comparison between effective levels of cooperative and noncooperative R&D when technological spillovers are relatively small is *not the size* of the pre-cooperative technological spillover, but the *increase* in technological spillover due to cooperation. In particular, if technological spillovers increase by $1 - 2\beta$ due to cooperation, cooperative R&D efforts exceed noncooperative R&D activity.

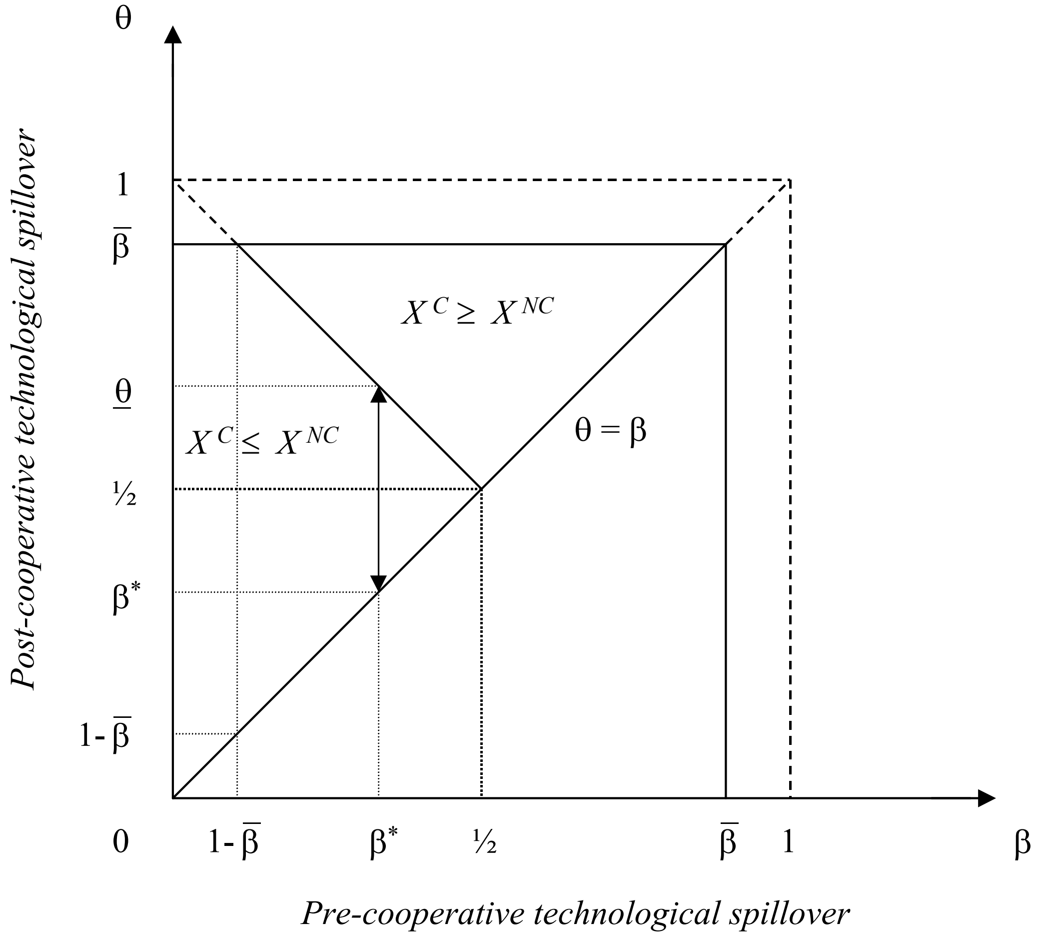

Figure 1: The θ-β-space divided in case $\overline{\beta} > \frac{1}{2}$ according to the level of effective cooperative R&D activites, X^C, being below or above the level of effective noncooperative R&D efforts, X^{NC}, that is, $\theta \lesseqgtr \max\{\beta, 1-\beta\}$.

In Figure 1 this mechanism is illustrated for pre-cooperative spillover level β^* (note that β^* is below 50% and above $1 - \overline{\beta}$). If the cooperative agreement would not affect this spillover we have that $X^C \leq X^{NC}$. However, if, due to cooperation in R&D, the rate of spillover increases from β^* to (at least) $\underline{\theta}$, R&D efforts of the cooperative would exceed those of a competitive R&D market. Put differently, $\underline{\theta}$ is the minimum level of post-cooperative technological spillover that would induce cooperating firms to undertake more R&D than would noncooperating firms facing a pre-cooperative technological spillover of β^*.

Observe that this necessary increase is larger the smaller are pre-cooperative spillovers. This is because both the competitive-advantage externality and the combined-profits externality are smaller the smaller are technological spillovers. Hence, the R&D-diminishing effect of the competitive-advantage externality is mild. At the same time the combined-profits externality is only weakly positive or even negative for small enough spillovers (in that case the R&D cooperative would decide to cut R&D expenses provided that the spillover rate is not affected by the cooperative agreement). Accordingly, a substantial increase of the pre-cooperative technological spillover is necessary for the combined-profits externality to be strong enough to induce the R&D cooperative to do more R&D than would a competitive R&D market. And the smaller is β, the more this reasoning applies, the higher is $\underline{\theta}$.

If $\overline{\beta}$ is less than 50%, the post-cooperative technological spillover can never be such that cooperative R&D efforts exceed those of a competitive R&D market. Indeed, if pre-cooperative technological spillovers are an indication as to the alignment of potential partner's research efforts, it is questionable that in these cases cooperation would enhance the productivity of individual firm's R&D (see also Link and Bauer [1987]).

Finally, as mentioned before, observe that the result in Proposition 1 is the continuous analogue of that reported by Kamien *et al.* [1992] who consider only two polar cases: (i) $\theta, \beta \in [0, 1]$ with $\theta = \beta$ and (ii) $\beta \in [0, 1]$ and $\theta = 1$. In the first situation the technological spillover is not affected by the cooperative agreement while in the second case cooperation induces technological spillover to be maximal ($\overline{\beta}$ in our case). Indeed, all remaining intermediate cases, in which θ is neither equal to β nor equal to $\overline{\beta}$, are also dealt with in Proposition 1.

5 Policy implications

To allow for the formation of an R&D cooperative three questions have to be answered. First, are the cooperating firms inclined to increase the technological spillover such that the agreement yields an increase in R&D activity? Second, is the potentially necessary increase in technological spillover feasible? And third, what will be the effect of the cooperative agreement on total surplus?

Inserting (9) into (8) yields

$$\pi^C = \frac{1}{2}\Pi^C = \frac{\gamma(a-A)^2}{9b\gamma - (1+\theta)}. \tag{11}$$

From (11) it is immediate that firms always try to increase the technological spillover as much as possible if they form an R&D cooperative. As alluded to in the Introduction, cooperating firms realize that enhancing the combined-profits externality (that is, increasing θ) yields an increase in profits because of the efficiency gain of a single firm's R&D efforts.[15] Indeed, if $\underline{\theta} \leq \overline{\beta}$ (which is equivalent to $\beta \geq \underline{\beta}$; see Proposition 1) an R&D cooperative will not only seek to increase the level of technological spillover, it will do so to a level that induces an increase in R&D activity. On the other hand if $\underline{\theta} > \overline{\beta}$, cooperatives will also try to enhance the technological spillover as much as possible, but this will *not* lead to an increase in R&D activity because the necessary level of post-cooperative technological spillover, $\underline{\theta}$, can not be established.

To assess the social desirability of an R&D cooperative first note that

Proposition 2 *In a two-stage linear duopoly with process-innovating R&D, input spillovers, diminishing returns to R&D investments and second-stage Cournot competition, $\exists\ X^* > 0$ such that $\forall\ X < X^*$ total surplus is increasing in X.*

Proof. The sum of consumers' surplus ($b\left[Q^C\right]^2/2$) and producers' surplus as a function of x equals

$$\widetilde{TS}(x) = \frac{4}{9b}\left[(a-A) + f(X)\right]^2 - 2x. \tag{12}$$

For (12) to be increasing in $X(= (1+\eta)x;\ \eta \in [0, \overline{\beta}))$, $\partial\widetilde{TS}(x)/\partial x$ must be positive, which translates into

$$f(X) < \frac{4(a-A)(1+\eta)}{9b\gamma - 4(1+\eta)} = f(X^*). \tag{13}$$

Because of the monotonicity of f, this holds $\forall\ X < X^*$. ■

[15] See e.g. Link and Bauer [1987], who report a statistically significant correlation between participation in an R&D cooperative and the productivity of partner's own R&D.

The right-hand-side of (13) is a 'second-best' level of effective R&D efforts in the sense that it maximizes (12).[16] It is straightforward to check that $f(X^*)$ exceeds both $f(X^{NC})$ for $\eta = \beta$, and $f(X^C)$ for $\eta = \theta$. Accordingly, *whenever the R&D cooperative agreement yields in increase in effective R&D efforts, total surplus increases.*

The implications for policy are now obvious. Whenever the formation of an R&D cooperative yields in increase in effective R&D efforts it should be sustained, all else equal. Contrary to conventional wisdom, this does not exclusively translate into 'pre-cooperative technological spillovers being large enough'. Also if these spillovers are small an R&D cooperative could enhance total surplus. What matters in this case is whether or not the cooperative agreement yields an *increase* in technological spillover that is 'large enough', as defined in Proposition 1. Indeed, conventional wisdom holds it that in this case proposed cooperatives diminish total surplus and should thus not be allowed. According to Propositions 1 and 2, quite the opposite is possible.

In practise this means that in order to reach a balanced judgement as to the desirability of a proposed R&D cooperative, policy makers not only must acquire an adequate approximation of the size of pre-cooperative technological spillovers (see e.g. Bernstein [1988]), they should also assess the likely increase in spillover brought about by the proposed cooperative agreement. From Propositions 1 and 2 follows that for this assessment an adequate approximation of either $\underline{\beta}$ or $\overline{\beta}$ (in addition to that of β) is enough information. One way to proceed would be to carefully examine existing R&D cooperatives, approximate $\overline{\beta}$ (and hence $\underline{\beta} = 1 - \overline{\beta}$), and then to compare it with approximations of β. Indeed, whenever β is thought to be above $\underline{\beta}$ the R&D cooperative would raise the technological spillover such that effective R&D efforts increase and thereby total surplus (provided of course that $\overline{\beta} > \frac{1}{2}$).

6 Conclusion

More than a decade ago, Katz [1986] observed that the free flow of information between competing firms will increase if these firms enter into a cooperative agreement regarding their R&D efforts. The seminal analysis of AJ on the economics of cooperative and noncooperative R&D has overlooked this point. This has prompted many subsequent contributions within the same sphere of economic analysis not to distinguish between pre-cooperative and post-cooperative technological spillovers.

Realizing this distinction reveals that in case of relatively small pre-cooperative technological spillovers it is *not their size* that dictates the com-

[16] The associated second-order condition is that $b\gamma > 4(1 + \eta)/9$.

parison of cooperative and noncooperative R&D levels, *but their increase* due to cooperation. In particular, even if the pre-cooperative technological spillovers are small, an agreement to cooperate in R&D raises effective R&D efforts if the post-cooperative technological spillover rate is high enough.

Total surplus is increasing in R&D efforts up to some level, an upper bound-that is not attained in either a noncooperative or cooperative setting. Accordingly, *whenever the R&D cooperative agreement yields in increase in effective R&D efforts, total surplus increases.* Indeed, contrary to conventional wisdom R&D cooperatives can also be socially desirable if pre-cooperative spillovers are small, provided that the cooperative induces an increase in technological spillover that is 'large enough'. And because joint profits are always increasing in the rate of technological spillover, policy makers have to assess whether or not the potentially necessary increase is possible through a proposed R&D cooperative. This assessment would not only involve an approximation of pre-cooperative spillovers, but also of the maximum level of spillover that can emerge between firms if they cooperate in R&D

The present paper employs a simple model. Accordingly, there is ample scope for generalizations of the main result presented here. We conjecture however that the essence of our finding will be robust to many of these generalizations. For example, employing a general R&D cost reduction f rather than the functional form of (4) qualitatively would not affect our results since f would be monotonic in its argument. Alternatively, the number of firms is extended to an arbitrary number n. This would affect the absolute size of both the combined-profits externality and the competitive-advantage externality, and hence the magnitude of the forces that drive our results. Qualitatively however the analysis would still apply. Indeed, the powers identified in this paper that are responsible for the comparison between cooperative and noncooperative R&D levels with varying degrees of technological spillover would also prevail in a general framework such as that of Suzumura [1992].[17] In any case, as an example of a small robustness check consider the analysis in the Appendix. There the results of Sections 3 and 4 are replicated for the seminal AJ model. Qualitatively the results appear to be identical.

[17] For an analysis of R&D subsidies this is shown to hold in particular; Hinloopen [2000c] generalizes some of the results in Hinloopen [2001], the latter being based on d'Aspremont and Jacquemin [1988] and the former taking off from Suzumura [1992].

7 Appendix Cooperative and noncooperative R&D in duopoly with increasing spillovers

In this appendix we replicate the analysis of Section 3 for the model of AJ. Firm i's second-stage profits are

$$\pi_i(q_i, q_j; x_i, x_j) = (a - bQ)q_i - (A - x_i - \beta x_j)q_i - \gamma x_i^2/2. \tag{14}$$

Following AJ it is assumed that $0 < A < a$, $x_i + \beta x_j \leq A$ (positive post-innovation marginal cost), and $Q \leq a/b$. Note that the R&D mapping now is of the form:

$$f(X_i) = X_i \tag{15}$$

Maximizing (14) over quantities leads to first-stage equilibrium profits given by

$$\pi_i(x_i, x_j) = \left[(a - A) + (2 - \beta)x_i + (2\beta - 1)x_j\right]^2 /9b - \gamma x_i^2/2. \tag{16}$$

If firms behave noncooperatively in the R&D stage, each firm sets R&D levels so as to maximize (16). This results in (symmetric) equilibrium levels of R&D given by[18]

$$x^{NC} = \frac{(a - A)(2 - \beta)}{4.5b\gamma - (2 - \beta)(1 + \beta)}. \tag{17}$$

The effective equilibrium level of noncooperative R&D then equals

$$f\left(X^{NC}\right) = (1 + \beta)x^{NC} = \frac{(a - A)(1 + \beta)(2 - \beta)}{4.5b\gamma - (2 - \beta)(1 + \beta)}. \tag{18}$$

On the other hand, if both firms cooperate in setting their R&D investment, in the R&D stage they consider joint profits, which are

$$\Pi(x_i, x_j) = \frac{1}{9b}\sum_{i=1}^{2}\left\{\left[(a - A) + (2 - \theta)x_i + (2\theta - 1)x_j\right]^2 - \gamma x_i^2/2\right\}. \tag{19}$$

Maximizing these joint profits over R&D efforts yields an equilibrium level of cooperative R&D given by[19]

$$x^C = \frac{(a - A)(1 + \theta)}{4.5b\gamma - (1 + \theta)^2}. \tag{20}$$

[18] The accompanying second-order condition reads as $4.5b\gamma > (2 - \beta)^2$, while the concomitant stability condition implies that (see Henriques [1990]; see also Hinloopen [1997]) $3(2 - \beta)(1 - \beta) < 4.5b\gamma, \beta \in [0, 1/2) \vee (2 - \beta)(1 + \beta) < 4.5b\gamma, \beta \in (1/2, 1]$.

[19] The concomitant associated second-order condition is $4.5b\gamma > 2(1 + \beta)^2$.

Each firm's effective level of cooperative R&D then equals

$$f\left(X^C\right) = (1+\theta)x^C = \frac{(a-A)(1+\theta)^2}{4.5b\gamma - (1+\theta)^2}. \tag{21}$$

The equivalent of Proposition 1 then reads as

Proposition 3 *Let $\beta \in [0, \overline{\beta})$, $0 < \overline{\beta} < 1$, be the pre-cooperative technological spillover rate, and let $\theta \in [0, \overline{\beta})$ be the post-cooperative technological spillover rate such that $\theta \geq \beta$. Let $g(\beta) = \sqrt{1+\beta}\left(\sqrt{2-\beta} - \sqrt{1+\beta}\right)$. In a two-stage linear duopoly with process-innovating R&D, output spillovers, diminishing returns to R&D investments, and second-stage Cournot competition, (i) if $\overline{\beta} \in [0, \sqrt{2}-1)$, then $X^C < X^{NC}$, and (ii) if $\overline{\beta} \in (\sqrt{2}-1, 1)$, then $\forall\ \beta \in (g^{-1}(\overline{\beta}), \overline{\beta})$ we have that $X^C < X^{NC}$, and $\forall\ \beta \in (0, g^{-1}(\overline{\beta}))$ we have that $X^C > X^{NC}$ if, and only if,*

$$\theta - \beta \geq \max\left\{0, \sqrt{1+\beta}\left(\sqrt{2-\beta} - \sqrt{1+\beta}\right)\right\}.$$

Proof. Comparing (18) with (21) leads to

$$f\left(X^C\right) \geq f\left(X^{NC}\right) \Leftrightarrow (1+\theta)^2 \geq (1+\beta)(2-\beta). \tag{22}$$

Solving this inequality and considering the positive root yields $g(\beta)$. It follows that the necessary increase in β to θ to induce $X^C \geq X^{NC}$ equals $g(\beta) - \beta$. For $\overline{\beta} > \sqrt{2} - 1$ this is feasible as long as $\beta + g(\beta) - \beta \leq \overline{\beta}$, or $\beta \leq g^{-1}(\beta)$. For $\overline{\beta} < \sqrt{2} - 1$ (22) can never hold. ■

Proposition 3 is illustrated in Figure 2 for $\overline{\beta} \in (\sqrt{2}-1, 1)$. The equivalent of Proposition 2 follows directly from Hinloopen [2000c]. Accordingly, both (18) and (21) are below the level of effective R&D that maximizes total surplus. Indeed, also in the AJ model an increase in effective R&D efforts always yields an increase in total surplus. For 'small' spillovers this can happen if an R&D cooperative is sustained that induces the technological spillover to be 'large enough'.

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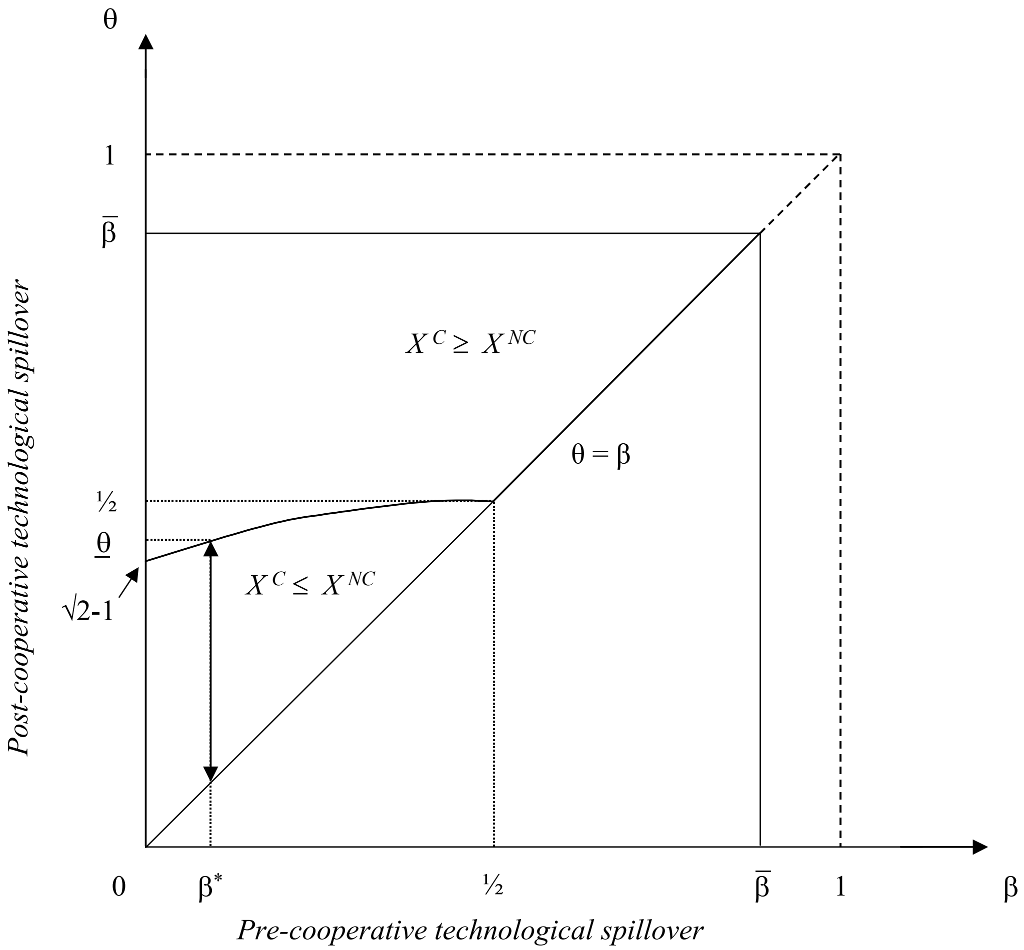

Figure 2: The θ-β-space divided according to the level of effective cooperative R&D activites, X^C, being below or above the level of effective noncooperative R&D efforts, X^{NC} ; $\overline{\beta} > \sqrt{2} - 1$.

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