Strategic R&D cooperatives

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Long Abstract

Although firms have many reasons for investing in R&D, still market forces are believed to be inadequate for directing an optimal amount of funds towards R&D investments. An important tool for diminishing this failure on markets for R&D is to sustain R&D cooperatives, a policy instrument recently (re)discovered by public authorities. For quite some time the formal economics literature did not pay substantial attention to this policy, but with the appearance of the seminal analysis of d'Aspremont and Jacquemin [1988] this silence was abruptly disturbed.

The objective of the present paper is to develop a general version of the d'Aspremont and Jacquemin [1988] model which still allows for the calculation of specific equilibrium and therefore enables a comparison between cooperative and noncooperative R&D. While pursuing this objective an analysis is presented which encompasses several recent contributions to the literature.

Having established this general characterisation of a market with possible strategic R&D cooperatives the arguments against and in favour of this industrial policy are evaluated. It appears that there are circumstances when these strategic alliances could indeed be socially beneficial. However there remains always the threat of firms increasing their market power by extending the cooperative agreement the product market.

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Strategic R&D Cooperatives

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Abstract

Allowing firms to cooperate in their R&D is an industrial policy which has received much attention in recent economics literature. Many of these contributions are based on the seminal analysis of d'Aspremont and Jacquemin [1988]. We provide a general version of their model which encompasses several recent contributions in the literature. With this general model we then examine the main arguments against and in favour of sustaining R&D cooperatives.

Keywords: differentiated oligopoly, Cournot competition, Bertrand competiton, spillovers.

JEL-codes: D43, L13, L41.

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1. INTRODUCTION.

Although firms have many reasons for investing in R&D, still market forces are believed to be inadequate for directing an optimal amount of funds towards R&D investments. First, private rates of return to R&D investments are lower than social return rates (for recent empirical evidence see Jones and Williams [1997]). This difference in rates of return is firstly due to bargaining problems. To the extent that innovative products or processes contain complementary technologies, incremental rents from an innovation may accrue to downstream suppliers. These benefits are not (fully) counted by an upstream firm when deciding on its R&D investment. In addition, a horizontal bargaining problem arises if innovative firms are not able to price discriminate perfectly in the market where they try to sell (or license) their innovation. For instance, it is difficult for possible buyers to value an innovation without the inventor giving away some information, diminishing the latter's bargaining power due to difficulties in reclaiming 'loaned' information.

Involuntary leakage of innovative information, technological spillovers, is a second source for divergence between social and private rates of return to R&D investment. This free flow of information is not counted as a benefit by the innovator, whereas a social planner takes into account all proceeds of the R&D process. Indeed, as observed by Arrow [1962], authorities are confronted with a trade-off. On the one hand, the diffusion of technological knowledge should be kept to a minimum in order to preserve private incentives to conduct R&D, but on the other hand, it is in society's interest to disseminate innovative knowledge as much as possible.

A second reason why the market for innovation fails is due to the pecuniary externality effect of technological spillovers. That is, each innovator's search for new knowledge may strengthen, through spillovers, its rival's competitive position, a socially desirable strengthening of competition which, however, induces the innovator to devote less resources to R&D.

Uncertainty surrounding the markets for innovations is a third reason for under-investment. Many research projects involve a great deal of trial and error, thus making it difficult to predict accurately whether or not some technology being developed will perform properly. In addition to this *technological uncertainty* is *market uncertainty*. That is, there is no perfect foresight as to the existence and size of a market for some product yet to materialize. Thirdly, *if* R&D leads to successful new processes or products, for which there is a market, it could be that some innovator's competitor has entered this market before, rewarding it with the possibility of creating entry barriers such as patenting preemptively. Indeed, any firm can lose a patent race, despite the success of its research unit, leading to *competitive uncertainty*. All in all, uncertainty in the markets for innovations restricts firms' research horizons, thereby excluding possible socially beneficial research avenues.

An important tool within the policy spectrum for diminishing the failure on markets for R&D is to sustain R&D cooperatives, an instrument recently discovered by policy makers. National and supra-national authorities actively encourage the formation of strategic alliances in R&D, expecting them to gear private incentives to invest in R&D towards the socially desirable level.[1] For quite some time the formal economics literature did not pay substantial attention to this policy (see Tirole [1988, p. 413-414]). This silence was abruptly disturbed however with the appearance of the seminal analysis of d'Aspremont and Jacquemin [1988] on strategic R&D cooperatives. Indeed, the majority of the flood of papers considering strategic R&D cooperatives that followed, is rooted in one way or another in the contribution of

[1] In Europe, the European Commission granted in its Regulation 418/85 a thirteen-year block exemption un-der Article 85 para.3 to collusion in R&D. In the United States some cooperation between innovating firms is al-lowed under the National Cooperative Research Act of 1984. Japanese corporate law also allows firms to cooper-ate in their research. For a comparison between Europe, the U.S. and Japan on this issue see Martin [1997].

d'Aspremont and Jacquemin [1988] (including Kamien et al. [1992], Suzumura [1992], Choi [1993], Vonortas [1994], Steurs [1995], Poyago-Theotoky [1995, 1998], Hinloopen [1997b], Brod and Shivakumar [1997], and Qiu [1997]).

Many of these studies have confirmed the main conclusion of d'Aspremont and Jacquemin [1988], being that joint R&D efforts exceed competitive research activity if the extent to which information flows freely among competitors in absence of a cooperative agreement (technological spillovers) is relatively 'high'. For relatively 'small' spillovers the opposite holds. The explanation for this general finding lies in the interaction between two externalities associated with strategic R&D investments (see Kamien et al. [1992] and Hinloopen [1997]). On the one hand, devoting resources to R&D increases the innovator's efficiency of production and thus rewards it with a larger market share at the expense of its competitors. That is, any firms' R&D investment has an impact on *all* firms' profits. On the other hand, there is the free flow of novel information from an innovator to its competitors, thereby increasing the latter's production efficiency. The first of these effects, labelled by Kamien et al. [1992] as the *combined-profits* externality, can either be positive or negative with respect to the incentive to invest in R&D. The second, identified as the *competitive-advantage* externality by Kamien et al. [1992], is unambiguously negative. In deciding how much to invest in R&D individual firms always take the competitive-advantage externality into account. R&D cooperatives, in addition, internalize the combined-profits externality. The fact that cooperative R&D exceeds noncooperative R&D when technological spillovers are relatively large thus means that in that case the combined-profits externality is positive, *and* that it outweighs the free-rider effect (i.e. the competitive-advantage externality).

The objective of the present paper is to develop a general version of the d'Aspremont and Jacquemin [1998] model which still allows for the calculation of specific equilibria and therefore enables a comparison between cooperative and noncooperative R&D. In particular we consider an oligopoly where each firm produces one variety of a differentiated product. As in d'Aspremont and Jacquemin [1988] a two-stage game is considered in which firms first simultaneously determine their investment in R&D, followed by a stage in which production is set simultaneously. Competition in the second stage of the game can either be over quantities or over price.[2] Within this general framework three scenarios are considered: (i) competition in both the first and the second stage; (ii) cooperation in R&D, competition in production; and (iii) cooperation in both the first and the second stage.

Having established this general characterization of a market with possible strategic R&D cooperatives the arguments against and in favour of this industrial policy can be evaluated. It appears that there are circumstances when these strategic alliances could be socially beneficial. However, there is always the threat of firms increasing their market power by extending the cooperative agreement to the production stage. The model also allows for an assessment of the claim that cooperative R&D exceeds noncooperative R&D when technological spilovers are substantial, a theoretical stylized fact which has not been considered within a context as general as presented here. As will be shown below, the comparison between cooperative and noncooperative R&D not only depends on the intensity of technological spillover but also on the extent to which products are differentiated and on the number of firms in the industry.

The paper evolves as follows. In Section 2 the most prominent potential benefits and drawbacks of sustaining R&D cooperatives are reviewed, followed by a description of the model in Section 3. In Section 4 the market equilibria are characterized as they emerge under the three different scenarios considered. Section 5 contains a detailed analyzes of cooperative R&D versus noncooperative R&D. In particular the considerations provided in Section 2 are

[2] Recal that d'Aspremont and Jacquemin [1988] consider a homogeneous duopoly where second-stage competition is over quantities only.

confronted with the analytical results of Section 4. Section 6 concludes.

2. SOME PRELIMINARY THOUGHTS ON COOPERATIVE R&D.

Before the main arguments against and in favour of the permissive antitrust treatment of cooperatives in R&D can be reviewed some different types of R&D cooperatives have to be recognized and formally defined, since an implicit assumption in the seminal analysis of d‘Aspremont and Jacquemin [1988] (being that an agreement to cooperate in R&D does not affect the extent to which information flows among members of the cooperative), has prompted the subsequent literature to label chaotically different types of R&D cooperatives.[3] Kamien et al. [1992] order the lexicographic jungle as to the names of R&D cooperatives by making explicit the difference between ventures in which participants agree to share information concerning their individual research outcomes, and agreements according to which firms jointly set their R&D investments without exchanging innovative information.[4]

In particular, *R&D cartels* are agreements to coordinate R&D activities so as to maximize the sum of overall profits. This contract does not imply that participating firms share the outcomes of their R&D efforts. Rather, firms form a strategic alliance and set individual R&D investments such that joint profits are maximized (it is this type of R&D cooperative d’Aspremont and Jacquemin [1988] analyze). *Research Joint Ventures* (RJVs) on the other hand refer to agreements according to which firms decide unilaterally on their R&D investments but the results of their R&D are fully shared. Note that RJVs do not entail cooperation in R&D to the extent that R&D investments are coordinated, but encompas only the sharing of results of

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[3] Two years later though the same authors do indicate that cooperation in R&D will lead to higher spillover rates (see d’Aspremont and Jacquemin [1990]). Moreover, the results reported by d’Aspremont and Jacquemin [1988] do not change qualitatively if the fixed-spillover assumption is relaxed (see Choi [1993]).

[4] Kamien et al. [1992] do not state exactly the same definitions as those presented in the text. However, they can be unequivocally deduced from their descriptions of the different types of R&D cooperatives.

independent R&D efforts. Indeed, within RJVs duplication of research is diminished and possibly eliminated.[5] Finally, *RJV cartels* are agreements to fully share the results of R&D *and* to coordinate R&D activities in order to maximize the sum of overall profits. Observe that both in an RJV and RJV cartel firms could be seen as licensing their innovations at zero price.

2.1 THE CASE FOR COOPERATIVE R&D.

The first main argument in favour of cooperative R&D emerges from the existence of technological spillovers. As observed in the introduction, the mere existence of these externalities creates a wedge between social and private incentives towards R&D investments. However, technological spillovers do not diminish the incentives to invest in R&D if partners agree to share the research cost before the R&D investment is actually realized. Firms understand that there will be no free-riding on their investment, at least not by the members of the cooperative. Moreover, if future partners also agree to fully share the results generated by their cooperative R&D, the trade-off identified by Arrow [1962] disappears. That is, *ex ante* agreements to fully share the fruits and cost of research (that is, to form RJV cartels) preserve the private incentives to undertake R&D while diffusing all information within the cooperating group. In addition, full sharing of information eliminates wasteful duplication within the R&D cooperative and thus increases the efficiency of research, that is, fewer resources are needed to obtain a given level of effective R&D. Hence, a fall in resources devoted to R&D because of cooperation does not necessarily mean a drop in effective research.

A second argument in favour of R&D cooperatives is one of scale economies. As early as 1952, John Kenneth Galbraith observes (Galbraith [1952, p.86])

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[5] The extent to which duplication is avoided depends on the frequency with which members of an RJV ex-change their research results, whether or not partners fully disclose their R&D records, and the type of research firms cooperate in (generic research being more transparent and easy to diffuse than development research).

> There is no more pleasant fiction than that technological change is the product of the matchless ingenuity of the small man forced by competition to employ his wits to better his neighbor. Unhappily, it is a fiction. Technological development has long since become the preserve of the scientist and the engineer. Most of the cheap and simple inventions have, to put it bluntly and unpersuasively, been made. Not only is development now sophisticated and costly but it must be on a sufficient scale so that success and failures will in some measure average out.

He consequently concludes (Galbraith [1952, p.87])

> Because development is costly, it follows that it can be carried on only by a firm that has the resources which are associated with considerable size.

Due to the ever increasing complexity of innovations and the concomitant rise in development costs, many claim that today even large firms do not have the necessary assets for developing new technologies. R&D cooperatives are then a natural means for participants to provide the necessary capital by pooling members' financial resources, given that capital markets are imperfect (that is, credit is rationed because of asymmetric information and different attitudes between banks and firms towards risk, the former being relatively risk averse). Moreover, to obtain financial credit the bargaining power of a consortium of firms is likely to be stronger than that of a single firm, implying that an R&D cooperative can undertake larger projects than the sum of its members' individual capital stocks would permit. Further, what often matters for innovations to be commercially successful is the timely introduction of new products or technologies, which requires R&D capital to be readily available. Providing these assets by pooling financial resources is then the preferred alternative for the elaborate bargaining process between firms and financial institutions will take much more time than financing the project directly out of the R&D cooperative's capital stock. In short, cooperatives can conduct larger R&D projects than any of the participants could pursue on its own, while also being able to introduce new innovations more quickly because of better access to the necessary financial resources.

Finally, the scope of feasible R&D projects is enlarged if firms conduct R&D cooperatively. By pooling resources more avenues of research are within reach because of possible synergies and complementarities among cooperating firms. Moreover, by sharing the risk of research through cooperation, members of the R&D cooperative might contemplate more risky projects, thereby also widening the potential research horizon.

2.2 THE CASE AGAINST COOPERATIVE R&D.

Against the potential benefits of R&D cooperatives inevitably lurk some drawbacks, the most important among these being that members of an R&D cooperative could use the agreement as a forum to discuss and to set prizes prevailing in the product market, practices which are likely to yield a harmful reduction of competition. Indeed, not only are side-payments more easily made if firms meet on a regular (and legal) basis, the fact that some firm is cooperating in the pre-competitive stage of the production process might signal its cooperative nature and it could thus be identified as a possible colluding partner in the competitive stage. On the other hand, as argued by Geroski [1992], for an innovation to be commercially successful there have to be strong links between those conducting the research and those marketing the concomitant innovative product, since it is the feedback from output markets that directs research towards profitable avenues.[6] Given then the necessity of strong links between pre-competitive R&D and final competition, firms' incentives to conduct joint research might be diluted if not at least some form of joint exploitation of cooperative research is allowed for in the product market. In sum, if firms are allowed to cooperate in their research they have ample opportunity to extend the cooperative agreement to output markets (see Martin [1995] for an illustration of this point). Moreover, in order not to undermine the incentives for cooperation in R&D some market power has to be given to the cooperating firms. Indeed, as aptly observed by

[6] For this reason, Geroski [1992] argues further that the stimulation of vertical links within innovative industries is likely to be more effective in bringing research to a success than allowing for horizontal links.

Jacquemin [1988], in deciding whether or not firms are allowed to form R&D cooperatives, authorities are faced with a Schumpeterian trade-off between static and dynamic efficiency.

Another objection to R&D cooperatives is that they might actually lower the incentives to conduct research. This is likely to happen when negative pecuniary externalities prevail. For instance, if joint research lowers only the cost of some of the participants, thereby reducing final profits of all other members of the cooperative, it could be in the interest of the whole group to diminish the overall research intensity. Another such situation arises when partners realize that products embodying new technologies will only replace existing ones. Indeed, a large dominant incumbent firm could engage in cooperative research with a small entrant in order to hamper the latter's research agenda. Also, if competition in output markets is strong, firms can jointly decide to cut on R&D expenses, since in this case severe product market competition is likely to direct all surplus towards final consumers. Finally, if future research will be such that only the first successful innovator will make a profit ('the winner takes it all'), thereby driving all other firms out of the industry, existing firms may decide collectively not to engage in this 'patent race'. What this all adds up to is that cooperatives in R&D internalizing negative pecuniary externalities are likely to collectively decide to cut on R&D activities. This then will lead to the introduction of fewer new (and possibly superior) products, not only because any cooperative agreement diminishes competition (see Martin [1995]), but those engaged in research will devote fewer resources to it.

The final main argument against R&D cooperatives is that they can act as a barrier to entry. Excessively accelerating R&D programmes in order to patent preemptively (see Gilbert and Newberry [1982]) might very well require the amount of capital only a cooperative can come up with. Moreover, cooperating firms could collectively decide on standards of future products, effectively blocking non-participants' and future entrants' ability to compete in the post-innovation market. Industry-wide adoption of a standard set by an R&D cooperative is, of course, more probable the more firms join the R&D cooperative. Indeed, the threat of increased entry barriers through cooperation in R&D cautions the approval of industry-wide R&D cooperatives.

3. A MODEL TO ANALYZE STRATEGIC R&D COOPERATIVES.

To examine the relative strength of the different arguments presented in the previous section we proceed with constructing a model that allows us to analyze the mechanisms associated with cooperative R&D. The model is a general version of the seminal analysis of d'Aspremont and Jacquemin [1988] and encompasses several recent contributions rooted in this analysis, including Brod and Shivakumar [1997], Qiu [1997] and Poyago-Theotoky [1998].

3.1 DEMAND.

The demand-side of the economy hosts a continuum of consumers of the same type, all represented by a single consumer. This consumer's utility is linear and separable in a numeraire good, q_0. The representative consumer maximizes a standard quadratic utility function

$$U(q_o,\dots,q_n) = q_0 + a\sum_{i=1}^{n} q_i - \frac{b}{2}\left[\sum_{i=1}^{n} q_i^{\,2} + \theta \sum_{i=1}^{n} q_i Q_{-i}\right], \qquad \textbf{(1)}$$

where q_i is the production of commodity *i*, p_i the concomitant price, $Q_{-i} = \sum_{j=1,j\neq i}^{n} q_j$ total production less that of firm *i*, and *a* and *b* some positive constants. The parameter $\theta \in [0,1]$ captures the extent to which products are differentiated; $\theta = 1$ indicates that all goods are completely homogeneous, while $\theta = 0$ implies that commodities are independent. Observe that it is assumed that all goods are differentiated to the same extent, that is, θ does not vary accross commodities.

Given that the representative consumer's budget is equal to $\sum_{i=0}^{n} p_i q_i$, the functional form of utility proposed in (1) leads to the following system of inverse demands

$$p_i(q_i, Q_{-i}) = a - b(q_i + \theta Q_{-i}), \tag{2}$$

or in direct rather than indirect form

$$q_i(p_i, P_{-i}) = \frac{1}{b(1-\theta)[1+\theta(n-1)]}\left\{(1-\theta)a + \theta P_{-i} - [1+\theta(n-2)]p_i\right\}, \tag{3}$$

where $P_{-i} = \sum_{j=1, j \neq i}^{n} p_j$.[7]

3.2 SUPPLY.

The industry considered consists of a competitive sector, which produces the numeraire good q_0, and a monopolistic sector. In the latter each firm *i* produces one variety of the differentiated commodity, q_i, $i = 1, \dots, n$. Fixed costs of production are assumed to be the same for all firms and set equal to zero. The marginal costs of production, *A*, are also constant, but each firm *i* can lower these by devoting resources to R&D (being denoted by x_i). That is, firms which are active in the monopolistic sector can invest in process-innovating R&D (for cooperative R&D in product-innovating industries see Motta [1992] and Rosenkranz [1995]).

We assume that the returns to R&D investments are diminishing to scale (see Patel and Pavit [1995] for empirical evidence concerning returns to scale in R&D). Hence, firm *i*'s net benifit of conducting R&D is given by (remember that R&D lowers marginal cost)

$$\left(x_i + \beta X_{-i}\right) q_i - \gamma \frac{x_i^2}{2}, \tag{4}$$

where $X_{-i} = \sum_{j=1, j \neq i}^{n} x_j$ are total R&D efforts less that of firm *i*. In (4) the parameter $\beta \in [0, 1]$

[7] For (3) to be well-defined, products cannot be completely homogeneous. Hence, whenever we refer to homogeneous products we implicitly assume products to be differentiated to an infinitesimal extent, that is, $\theta = 1 - \epsilon$ where $\epsilon \downarrow 0$.

captures the technological spillover. If $\beta = 0$ there is no leakage of information among competitors, whereas $\beta = 1$ indicates that there is full dissemination of knowledge among firms. Observe that (4) implies that the amount of technological knowledge that leaks between firms is the same among all firms.[8] A single firm's profit can now be computed to be

$$\pi_i(p_i, q_i, x_i, X_{-i}) = p_i q_i - (A - x_i - \beta X_{-i}) q_i - \gamma \frac{x_i^2}{2}. \quad \textbf{(5)}$$

To examine strategic R&D cooperatives a two-stage game is now defined. In the first stage firms decide on their investment in R&D. In the subsequent stage they compete, either over price or quantities, given the first-stage R&D investment. Within this framework several scenarios are considered in Section 4. First however we identify within the model presented here the different types of R&D cooperatives as distinguished in Section 2. An RJV implies that firms do not cooperate in either stage of the production process. Rather, only β is set equal to one. On the other hand, an R&D cartel refers to maximization of joint profits over R&D investments without, however, affecting the size of β. An RJV cartel then is an R&D cartel with $\beta = 1$.

4. MARKET EQUILIBRIA.[9]

We proceed with the computation of different market equilibria. In Section 4.1 the full competitive regime, both under second-stage Cournot and Bertrand competition, is described,

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[8] Amir [1995] questions (4) as an adequate way of modeling technological spillovers, stressing that it is not at the output end of the R&D-stage where spillovers occur, but at the input end (as modelled by Kamien et al. [1992]). However, given the abundance of studies using d'Aspremont and Jacquemin's analysis and considering the survey-nature of the present paper we confine ourselves to the formulation of d'Aspremont and Jacquemin [1988]. Moreover, it is questionable whether the critique of Amir [1995] leads to fundamentally different results. (see e.g. Hinloopen [1998]).

[9] GAUSS-programs were written to check numerically all analytical expressions presented in the paper, and are available upon request.

followed by an analysis of cooperative R&D (that is, an R&D cartel) in Section 4.2, again both under second-stage competition over price and quantities. In Section 4.3 the behaviour of a monopoly is characterized.

4.1 NO COOPERATION IN EITHER R&D OR PRODUCTION.

In the second stage of the game firms compete over price or quantities. In the latter case each firm i maximizes (5) over q_i, which results in the equilibrium quantity conditional on R&D efforts (observe that conditional equilibrium prices follow from (2))[10]

$$\hat{q}_i^C(x_i, X_{-i}) = \frac{1}{b(2-\theta)[2+\theta(n-1)]} \times \left\{(a-A)(2-\theta) + [2+\theta(n-2) - \theta\beta(n-1)]x_i + (2\beta-\theta)X_{-i}\right\}. \quad \textbf{(6)}$$

On the other hand, in case of second-stage Bertrand competition, each firm i maximizes (5) with respect to p_i. Conditional equilibrium prices thus derived equal (with concomitant conditional equilibrium quantities implicitely defined by (3))

$$\hat{p}_i^B(x_i, X_{-i}) = \frac{1}{b[2+\theta(n-3)][2+\theta(2n-3)]} \times \left\{\alpha_1^B - [1+\theta(n-2)]\left[\{2+\theta(n-2)+\theta\beta(n-1)\}x_i + \{\theta + 2\beta[1+\theta(n-2)]\}X_{-i}\right]\right\}, \quad \textbf{(7)}$$

where $\alpha_1^B = [2+\theta(2n-3)]\{A[1+\theta(n-2)] + a(1-\theta)\}$.

In the preceeding stage, when firms determine their R&D investments, profits in case of second-stage Cournot or Bertrand competition can be written respectively as

$$\hat{\pi}_i^C(x_i, X_{-i}) = \frac{\left[\alpha_2^C\right]^2}{b(2-\theta)^2[2+\theta(n-1)]^2} - \gamma\frac{x_i^2}{2}, \quad \textbf{(8a)}$$

[10] A hat refers to a conditional equilibrium expression. Second-stage Cournot competition is denoted by *C*, whereas second-stage Bertrand competition is indicated by *B*.

with $\alpha_2^C = (a-A)(2-\theta)+\{2+\theta(n-2)-\theta\beta(n-1)\}x_i+(2\beta-\theta)X_{-i}$, and

$$\hat{\pi}_i^B(x_i,X_{-i}) = \frac{\left\{\hat{p}_i^{\,B}(x_i,X_{-i})-(A-x_i-\beta X_{-i})\right\}\alpha_2^B}{b(1-\theta)[1+\theta(n-1)]}-\gamma\frac{x_i^2}{2}, \tag{8b}$$

with $\alpha_2^B = (1-\theta)a-[1+\theta(n-2)]\hat{p}_i^{\,B}(x_i,X_{-i})+\theta\hat{P}_{-i}^{\,B}(x_i,X_{-i})$. Maximizing (8) with respect to the R&D efforts result in the following reaction functions[11]

$$x_i^{\,C}(x_j^{\,C}) = \frac{\alpha_3^C+2(n-1)(2\beta-\theta)\{2+\theta(n-2)-\theta\beta(n-1)\}x_j^{\,C}}{b\gamma(2-\theta)^2[2+\theta(n-1)]^2-2\{2+\theta(n-2)-\theta\beta(n-1)\}^2}, \tag{9a}$$

where $\alpha_3^C = 2(a-A)(2-\theta)\{2+\theta[(n-2)-\beta(n-1)]\}$, and

$$x_i^{\,B}(x_j^{\,B}) = \frac{2\Delta[1+\theta(n-2)]\left\{\alpha_3^B+\left[(2\beta-\theta)[1+\theta(n-2)]-\theta^2\beta(n-1)\right](n-1)x_j^{\,B}\right\}}{b\gamma(1-\theta)[1+\theta(n-1)][2+\theta(n-3)]^2[2+\theta(2n-3)]^2-2\Delta^2[1+\theta(n-2)]}, \tag{9b}$$

where $\Delta = 2+3\theta(n-2)+\theta^2[(n-1)(n-2)-(2n-3)]-\theta\beta(n-1)[1+\theta(n-2)]$,[12] and where $\alpha_3^B = (a-A)(1-\theta)[2+\theta(2n-3)]$. From (9) we derive the following stability conditions (see Henriques[1990] for the case with $n=2$, whith homogeneous goods and second-stage Cournot competition)

$$b\gamma(2-\theta)[2+\theta(n-1)]^2 > 2\{2+\theta[(n-2)-\beta(n-1)][1+\beta(n-1)]\}, \tag{10a}$$

and

$$b\gamma[1+\theta(n-1)][2+\theta(2n-3)][2+\theta(n-3)]^2 > 2\Delta[1+\theta(n-2)][1+\beta(n-1)]. \tag{10a}$$

Equating the R&D reaction functions leads to the equilibrium R&D efforts given by[13]

$$x_{IC}^* = \frac{2(a-A)\{2+\theta[(n-2)-\beta(n-1)]\}}{b\gamma(2-\theta)[2+\theta(n-1)]^2-2\{2+\theta[(n-2)-\beta(n-1)]\}[1+\beta(n-1)]}, \tag{11a}$$

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[11] The second-order condition for a global maximum under second-stage Cournot competition is $b\gamma(2-\theta)^2[2+\theta(n-1)]^2 > 2\{2+\theta[\theta(n-2)-\beta(n-1)]\}^2$, whereas under Bertrand competition in the product market it is $b\gamma(1-\theta)[1+\theta(n-1)][2+\theta(n-3)]^2[2+\theta(2n-3)]^2 > 2\Delta^2[1+\theta(n-2)]$.

[12] Observe that $\Delta > 0,\ \forall n,\beta,\theta$.

[13] A star refers to an unconditional equilibrium expression.

and

$$x_{IB}^{*} = \frac{2\Delta(a-A)[1+\theta(n-2)]}{b\gamma[1+\theta(n-1)][2+\theta(2n-3)][2+\theta(n-3)]^2-2\Delta[1+\theta(n-2)][1+\beta(n-1)]}, \qquad \textbf{(11a)}$$

where I refers to the fully noncooperative nature of the game considered.

The analytical expressions for all relevant variables for the fully noncooperative game are summarized in Tables A1 and A3 of Appendix A.

4.2 COOPERATION IN R&D (R&D CARTEL), COMPETITION IN PRODUCTION.

In this section we consider an R&D cartel without cooperation in the product market. Observe that in this case the second stage of the game, conditional on R&D efforts, is not different from that under the fully competitive regime. Hence, if firms compete over quantities their optimal response is still given by (6), whereas (7) is the optimal price to quote if firms face second-stage price competition.

In an R&D cartel firms maximize *joint* profits in the first stage. These are

$$\hat{\Pi}^{C}(\boldsymbol{x}) = \frac{1}{b(2-\theta)^2[2+\theta(n-1)]^2} \times \sum_{i=1}^{n}\left\{\left[(a-A)(2-\theta)+\{2+\theta[(n-2)-\beta(n-1)]\}x_i+(2\beta-\theta)X_{-i}\right]^2-\gamma\frac{x_i^2}{2}\right\}, \qquad \textbf{(12a)}$$

and

$$\hat{\Pi}^{B}(\boldsymbol{x}) = \frac{1}{b(1-\theta)[1+\theta(n-1)]} \times \sum_{i=1}^{n}\left\{\left[\hat{p}_i^{B}(x_i,X_{-i})-(A-x_i-\beta X_{-i})\right]\left[(1-\theta)a-[1+\theta(n-2)]\hat{p}_i^{B}(x_i,X_{-i})+\theta\hat{P}_{-i}^{B}(x_i,X_{-i})\right]-\gamma\frac{x_i^2}{2}\right\}, \qquad \textbf{(12b)}$$

under second-stage Cournot and Bertrand competition respectively, where $\boldsymbol{x}=\{x_1,\dots,x_n\}$.

The R&D efforts of an R&D cartel follow from maximizing (12) over x_i, and are given by[14]

$$x^*_{IIC} = \frac{2(a-A)[1+\beta(n-1)]}{b\gamma[2+\theta(n-1)]^2 - 2[1+\beta(n-1)]^2}, \qquad \textbf{(13a)}$$

and

$$x^*_{IIB} = \frac{2(a-A)(1-\theta)[1+\theta(n-2)][1+\beta(n-1)]}{b\gamma[1+\theta(n-1)][2+\theta(n-3)]^2 - 2(1-\theta)[1+\theta(n-2)][1+\beta(n-1)]^2}, \qquad \textbf{(13b)}$$

where *II* indicates that the game is partially cooperative.

In Tables A2 and A4 of Appendix A all analytical expressions of relevant variables for the game considered in this section are presented.

4.3 COOPERATION IN R&D (R&D CARTEL) AND PRODUCTION.

If all firms cooperate in determining their production as well as in setting their R&D efforts, they collectively act as a monopolist. In that case there is no difference in the type of market competition considered since there is no competitive production stage. That is, if production is jointly set the conditional equilibrium price follows immediately from (2). Likewise, conditional equilibrium quantities are defined by (3) if price is the second-stage decission variable. In what follows we treat the cooperative as determining the optimal quantity in the second stage.

Joint second-stage profits are

$$\Pi(q_i, Q_{-i}; x_i, X_{-i}) = \sum_{i=1}^{n}\left\{(a - b[q_i - \theta Q_{-i}])q_i - (A - x_i - \beta X_{-i})q_i - \gamma\frac{x_i^2}{2}\right\}. \qquad \textbf{(14)}$$

Equilibrium quantities, conditional on the monopoly R&D effort, are obtained by maximizing

[14] The second-order condition is $b\gamma[2+\theta(n-1)]^2 > 2[1+\beta(n-1)]^2$ under Cournot competition, while under Bertrand competition it reads as $b\gamma[1+\theta(n-1)][2+\theta(n-3)]^2 > 2(1-\theta)[1+\theta(n-2)][1+\beta(n-1)]^2$.

(14) over q_i. This results in

$$\hat{q}(x) = \frac{(a-A)+[1+\beta(n-1)]x}{2b[1+\theta(n-1)]}. \qquad \textbf{(15)}$$

Joint first-stage profits are then given by

$$\hat{\Pi}(x) = n\left\{\frac{1}{4b[1+\theta(n-1)]}\{(a-A)+[1+\beta(n-1)]x\}^2-\gamma\frac{x^2}{2}\right\}. \qquad \textbf{(16)}$$

In the first stage the monopoly maximizes (16) to obtain its optimal R&D effort. This effort is given by[15]

$$x^*_{III} = \frac{(a-A)[1+\beta(n-1)]}{2b\gamma[1+\theta(n-1)]-[1+\beta(n-1)]^2}, \qquad \textbf{(17)}$$

where *III* refers to the game being fully cooperative.

Analytical equilibrium expressions for all relevant variables in case of a monopoly are given in Table A5 of Appendix A.

5. COOPERATION VERSUS COMPETITION

Having computed the three equilibria as they arise under the three regimes considered, the effects on market performance of firms cooperating in one or two stages of the production process can be evaluated.

5.1 COMPETITIVE R&D AND R&D CARTELS

In ranking the different levels of R&D activity we follow the definitions given in Section 2. For fixed technological spillovers the complete ranking of private R&D efforts is given in Proposition 1 (the proof of which is in Appendix B.1; there it is also shown that the regions

[15] The second-order condition reads as $2b\gamma[1+\theta(n-1)]>[1+\beta(n-1)]^2$.

defined in Proposition 1 in terms of technological spillovers are well-defined).

PROPOSITION 1

For $n \geq 2$, $\beta \in [0,1]$ and $\theta \in [0,1]$ the following holds

$$x_{IC}^{*} > x_{III}^{*} > x_{IIC}^{*} \quad \Leftrightarrow \quad \beta \in [0, C_1),$$

$$x_{III}^{*} > x_{IC}^{*} > x_{IIC}^{*} \quad \Leftrightarrow \quad \beta \in (C_1, C_2),$$

$$x_{III}^{*} > x_{IIC}^{*} > x_{IC}^{*} \quad \Leftrightarrow \quad \beta \in (C_2, 1],$$

with $C_1 = \theta[4 + 2\theta(n-1) + \theta^2(n-1)] \big/ [8 + 8\theta(n-1) + 2\theta^2(n-1)^2 - \theta^3(n-1)^2]$ and $C_2 = \theta/2$, and

$$x_{IB}^{*} > x_{III}^{*} > x_{IIB}^{*} \quad \Leftrightarrow \quad \beta \in [0, B_1),$$

$$x_{III}^{*} > x_{IB}^{*} > x_{IIB}^{*} \quad \Leftrightarrow \quad \beta \in (B_1, B_2),$$

$$x_{III}^{*} > x_{IIB}^{*} > x_{IB}^{*} \quad \Leftrightarrow \quad \beta \in (B_2, 1],$$

with $B_1 = \theta[4 + 2\theta(3n-7) + \theta^2(2n^2 - 11n + 13)] \big/ [8 + 16\theta(n-2) + 2\theta^2[5n^2 - 20n + 19] + \theta^3(n-1)(2n^2 - 9n + 11)]$,

and $B_2 = \theta[1 + \theta(n-2)] \big/ [2 + 2\theta(n-2) - \theta^2(n-1)]$.

Proposition 1 is illustrated in Figures 1a and 1b for two different industry sizes. The regions in the figures are labeled according to the value of the spillover parameter. In particular, β_1^C refers to $\beta \in [0, C_1)$, β_2^C implies that $\beta \in (C_1, C_2)$, and β_3^C points to $\beta \in (C_2, 1]$. A similar notation applies for Bertrand competition.

INSERT FIGURES 1a AND 1b ABOUT HERE

According to Proposition 1 R&D cooperatives devote more resources to R&D than would a competitive research market only when technological spillovers are relatively large (areas β_3^C and β_3^B in Figure 1). This implies two things. First, if there are no spillovers (and hence, no competitive-advantage externality), the combined-profits externality is negative. If in this case firms form an R&D cooperative (in the sence of cartelization) total R&D spending will be reduced. Second, if spillovers increase, the combined-profits externality gradually becomes positive. For large enough spillovers it outweighs the negative competitive-advantage externality (although the latter's absolute size increases with expanding spillovers), inducing cooperating firms to spend more on R&D viz-à-viz noncooperating firms.

Proposition 1 reveals however that the conditions on the size of technological spillover indicating when cartelized R&D exceeds competitive R&D, C_2 and B_2, are influenced by the extent to which products are differentiated. This follows from the influence of product differentiation on the two externalities identified above. In particular, the more disctinct products are, the weaker the competitive-advantage externality will be. On the other hand, the effect of increased product differentiation on the combined-profits externality can be either positive or negative. But the overall effect on the size of technological spillover for which the level of cooperative R&D exceeds the noncooperative R&D level is unambiguously negative since both C_2 and B_2 are increasing in θ.[16] That is, an increase in the extent to which products are differentiated (that is, a *lower* value of θ) induces the range of spillovers for which cartelized R&D exceeds noncooperative R&D to increase (see also Figure 1). Note in passing that qualitatively the influence of product differentiation is the same under second-stage Cournot and Bertrand competition.

Another parameter important for the comparison between levels of cartelized and competitive R&D is the size of the industry. In this case however, the comparative statics *do* depend on the type of product-market competition. In particular, under second-stage Cournot competition the critical technical spillover is independent of the number of firms in the industry, whereas under second-stage Bertrand competition it is increasing in the number of firms forming an industry-wide R&D cooperative.[17] Indeed, under second-stage Bertrand

[16] $\partial C_2/\partial\theta = 1/2 > 0$, $\partial B_2/\partial\theta = [2+4\theta(n-2)+\theta^2\{(n-1)+2(n-2)^2\}]\big/[2+2\theta(n-2)-\theta^2(n-1)]^2 > 0$.

[17] $\partial B_2/\partial n = \theta^3(1-\theta)\big/[2+2\theta(n-2)-\theta^2(n-1)]^2 > 0$.

competition more of the surplus generated by a single firms' R&D efforts is directed towards consumers. Accordingly, any firms' R&D efforts are more likely to reduce joint profits viz-à-viz the situation with product-market competition over quantities. It is therefore that B_2 is increasing in *n*.

Another way of comparing cooperative R&D with noncooperative R&D is by distinguishing complementary from substitutable research (see Geroski [1993]). As shown by Bulow et al. [1985], R&D is complementary if, and only if, $\partial^2 \pi_i^*(x_i, X_{-i})/\partial x_i \partial x_j$ is positive, and substitutable if this second derivative is negative. For the model of Section 3 it is straightforward to derive that

$$\frac{\partial^2 \pi_i^C(x_i, X_{-i})}{\partial x_i \partial x_j} < 0 \quad \Leftrightarrow \quad \beta < C_2, \tag{18a}$$

and

$$\frac{\partial^2 \pi_i^B(x_i, X_{-i})}{\partial x_i \partial x_j} < 0 \quad \Leftrightarrow \quad \beta < B_2, \tag{18b}$$

where C_2 and B_2 are defined in Proposition 1. Hence, competitive research levels exceed levels of cartelized R&D whenever R&D is substitutable, while the reverse holds for complementary research (which holds for all models based on d'Aspremont and Jacquemin [1988]).

Finally, as shown in Proposition 1, when the number of firms in the industry increases, the parameter-space for which a monopolist invests most in R&D also increases (see also Figure 1). Indeed, for *n* going to infinity the R&D efforts of a monopolist are always the highest.[18] As observed by d'Aspremont and Jacquemin [1988], this is due to firms cooperating in the

[18] Using l'Hôspital's rule it follows that $\lim_{n\to\infty} C_1 = \lim_{n\to\infty} \theta(2+\theta)/[8+2\theta(2-\theta)(n-1)] = 0$, and $\lim_{n\to\infty} B_1 = \lim_{n\to\infty} 2\theta/[10+\theta(6n-11)] = 0$.

product market being more able to capture the surplus generated by their research, compared to either the partially or fully competitive regime. The larger the number of firms in the industry, the lower profits are because of more intense competition. Hence, the more significant the surplus-capturing effect, due to product-market cooperation, will be.

5.2 RJVS AND RJV CARTELS.

We continue with the examination of R&D levels induced by cooperative agreements which can also influence the technological spillover. The following proposition, proved in Appendix B.2, completes the ranking of R&D efforts for the different types of R&D cooperatives considered.

PROPOSITION 2

part (i)

$\forall n, \beta, \theta$, the following holds

$x^*_{IIC}|_{\beta=1} > x^*_{IC}, x^*_{IIC},$

$x^*_{IIB}|_{\beta=1} > x^*_{IIB}.$

If $\theta < 2/3$, $\forall n, \beta$ the following holds

$x^*_{IIB}|_{\beta=1} > x^*_{IB}.$

part (ii)

$\forall n, \beta, \theta$, the following holds

$x^*_{III}|_{\beta=1} > x^*_{IIC}, x^*_{IIB}, x^*_{III}.$

For a model similar to that of Section 3, Kamien et al. [1992] show that under second-stage Cournot competition a RJV cartel results in the highest R&D investments of all R&D cooperatives considered. In addition, Proposition 2 shows that the incentives to invest in R&D

are even more enhanced through the rent- capturing effect of cooperation in the product market.[19]

Under second-stage Bertrand competition, a sufficient condition for an RJV cartel to devote more resources to R&D compared to the competitive alternative is that products are differentiated at least to a modest extent. In that case, the increased force of the combined-profits externality due to full information sharing outweighs the increased diluting effect on R&D investments of the competitive-advantage externality. On the other hand, there are situations when competitive R&D efforts exceed those of an RJV cartel. This could only happen if products are quasi-homogenous and pre-cooperative spillovers small. Under these circumstances any firm's R&D efforts considerably reduce all other firms' profits because of the similarity of products and the intense product-market competition. Hence, the combined-profits externality is more likely to be negative or only mildly positive. In addition, full exchange of information has a relatively large effect on each firm's incentive to invest in R&D since pre-cooperative spillovers are small. Together this means that competitive R&D efforts could exceed those of an RJV cartel. Observe however, that $\theta > 2/3$ is only a *sufficient* condition. That is, also under second-stage Bertrand competition, in most cases an RJV cartel (without collusion in the product market) will yield the highest investment in R&D.

5.3 PRIVATE INCENTIVES TOWARDS R&D COOPERATIVES

The phrase 'allowing firms to cooperate in R&D' does not make sense if firms do not want to set R&D investments cooperatively. Indeed, any R&D cooperative can settle for the noncooperative solution if this is more profitable. The private incentives towards R&D cartelization are summarized in the following proposition (proved in Appendix B.3).

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[19] This result is also mentioned by Kamien et. al [1992].

PROPOSITION 3

$\forall\, n, \beta, \theta$, the following holds

$$\pi^*_{III} > \pi^*_{IIC} > \pi^*_{IC} \quad \Leftrightarrow \quad \beta \in [0, C_2) \cup (C_2, 1],$$

$$\pi^*_{III} > \pi^*_{IIC} = \pi^*_{IC} \quad \Leftrightarrow \quad \beta = C_2,$$

and

$$\pi^*_{III} > \pi^*_{IIB} > \pi^*_{IB} \quad \Leftrightarrow \quad \beta \in [0, B_2) \cup (B_2, 0],$$

$$\pi^*_{III} > \pi^*_{IIB} = \pi^*_{IB} \quad \Leftrightarrow \quad \beta = B_2,$$

where C_2 and B_2 are defined in Proposition 1.

Under both second-stage Cournot and Bertrand competition, and irrespective of the size of the industry, the intensity of technological spillover and the extent to which products are differentiated, firms always want to collude in as many stages of the production process as allowed. Hence, the endogenous market outcome will be a monopoly.

Considering then the incentives to (fully) share information first leads to the next proposition (the proof of which can be found in Appendix B.4).

PROPOSITION 4

$\forall\, n, \beta, \theta$, the following holds

$$\frac{\partial \pi^*_{IIC}}{\partial \beta}, \frac{\partial \pi^*_{IIB}}{\partial \beta}, \frac{\partial \pi^*_{III}}{\partial \beta} > 0.$$

If firms form an R&D cartel, they always want to exchange innovative information as much as possible (under second-stage Cournot competition, Katz [1986] reports similar findings for an R&D cartel without product market collusion). According to Proposition 4 this information-sharing incentive is independent of the type of product market competition, and whether or not firms cooperate in the second stage of the production process.

Second, private incentives to form an RJV are less clear cut. Simulation results presented in Hinloopen [1997a, Chapter 2] show that competing firms' profits are increasing in the spillover rate if both the number of firms in the industry and pre-cooperative spillovers are not too high. In that case, each firm benefits more from all information it receives from its competitors than the price it has to pay: disseminating all its innovative information within the industry. On the other hand, if the number of firms benefiting from any firms' innovative information is large, and if there are substantial pre-cooperative technological spillovers, full information sharing will lower individual firms' profits.

Together Propositions 2, 3, and 4 imply that market forces generate the highest amount of R&D investments possible. That is, if firms are allowed to cooperate in as many stages as desired, an industry-wide monopoly will arise in which innovative information is fully shared, a market structure which yields the highest R&D investments.

5.4 SOCIAL INCENTIVES TOWARDS COOPERATION IN R&D

The consequences for net total surplus of allowing firms to engage in either of the R&D cooperatives considered, are revealed through two propositions and a numerical excercise. The first proposition summarizes the effect of an R&D cartel (and follows immediately from the definition of net total surplus; see also Suzumura [1992]).

PROPOSITION 5

$\forall n, \beta, \theta$, the following holds

$$W_{IB}^{*} > W_{IIB}^{*} \iff \beta \in [0, B_2),$$

$$W_{IB}^{*} = W_{IIB}^{*} \iff \beta = B_2,$$

$$W_{IB}^{*} < W_{IIB}^{*} \iff \beta \in (B_2, 1],$$

where B_2 is defined in Propositon 1.

If $n = 2$, or if $n \geq 3 \wedge \beta > 1/12$, $\forall \theta$ the following holds

$$W^*_{IC} > W^*_{IIC} \Leftrightarrow \beta \in [0, C_2],$$

$$W^*_{IC} = W^*_{IIC} \Leftrightarrow \beta = C_2,$$

$$W^*_{IC} < W^*_{IIC} \Leftrightarrow \beta \in (C_2, 1],$$

where C_2 is defined in Proposition 1.

According to Proposition 5, in most cases allowing firms to form an R&D cartel is only desired if this leads to an increase in total R&D efforts. In particular, R&D cartels enhance net total surplus if participants of the R&D cooperative are engaged in mutually complementary research. Cooperative agreements between firms conducting substitutable research will yield a reduction in total R&D spending, and with it a reduction in total net surplus.

Observe that under second-stage Cournot competition the pre-cooperative spillover rate has to be above a threshold of $1/12$ for the ranking to go through (given that the number of firms in the industry is at least 3). For values of β below $1/12$ the effect of an R&D cartel on net total surplus depends on specific parameter values.

As observed by Arrow [1962], full sharing of information is socially beneficial given that the cost of transmitting knowledge is often close to zero. Hence, an industry-wide RJV is likely to be socially desirable. However, the social benefits of an industry-wide RJV depend on both the change in consumers' and producers' surplus a full dissemination of innovative knowledge induces. From the discussion in Section 5.1 it is clear that forcing technological spillovers to be maximal has a diluting effect on firms' incentives to invest in R&D, which possibly leads to a reduction in profits. As a result, private and social incentives to form an industry-wide RJV could be in conflict.

Examining then the effects of full information sharing on net total surplus reveals that in most cases this leads to a net gain (see Hinloopen [1997, Chapter 2]). Only if the industry is large and pre-cooperative spillovers are substantial would full information sharing be socially damaging. Under these circumstances any single firm's innovative knowledge would be disseminated among many competitors, inducing it to cut R&D expenses. And because pre-cooperative spillovers are already large, society's additional gain from full information sharing does not sufficiently compensate this drop in innovative activity. On the other hand, if products are independent, or if pre-cooperative technological spillovers are modest, an industry-wide RJV is always desired. In the former situation any firm is a local monopolist, making it immune to allegedly increased competition through full dissemination of knowledge, while in the latter case social gains associated with a substantially increased spillover rate outweigh the concomitant reduction in R&D activity.

Finally, if firms cooperate in their R&D, social and private incentives to share innovative information are in agreement, as shown in Proposition 6 (see Appendix B.5 for the proof).

PROPOSITION 6

$\forall n, \beta, \theta,$ the following holds

$$\frac{\partial W^*_{IIC}}{\partial \beta}, \frac{\partial W^*_{IIB}}{\partial \beta}, \frac{\partial W^*_{III}}{\partial \beta} > 0.$$

Proposition 4 and Proposition 6 together imply that if firms are allowed to cooperate in their R&D (but remain competitors in the production stage), they always will engage in that type of R&D cooperative which enhances net total surplus most. That is, if firms cooperate in R&D, they settle for an RJV cartel, a type of R&D cooperative governments also prefer to an R&D cartel. Observe that this consistency between social and private incentives is independent of the type of product market competition.

Allowing firms to cooperate in their research thus seems an elegant way out of Arrow's [1962] trade off. Not only will firms fully exchange innovative information once they are allowed to jointly set their R&D investments, the concomitant level of R&D activity also exceeds that under a full competitive regime, as shown in Proposition 2. However, according to Proposition 3, an R&D cooperative also wants to determine collectively prices prevailing in the subsequent product market. But this reduces net total surplus, since[20]

$$\min_{n,\beta,\theta} \{ W^*_{IIC} - W^*_{III} \} > 0.78,$$
$$\min_{n,\beta,\theta} \{ W^*_{IIB} - W^*_{III} \} > 0.79. \qquad \textbf{(19)}$$

That is, extending the R&D-cooperative agreement to the production stage always leads to a loss in net total surplus. Observe that this holds for any size of technological spillover. Extending therefore an RJV cartel to a production cartel is also socially harmful.

Given then this contradiction between social and private incentives to collusion in production, the fundamental question arises as to the desirability of any R&D cooperative. Comparing social welfare under the full competitive regime with that arising under an RJV cartel with product market collusion reveals that in general the former exceeds the latter (see the simulation results in Hinloopen [1997c, Chapter 2]). In particular, only if products are independent *and* the number of firms in the industry is small, or if pre-cooperative spillovers are absent *and* the industry is large, is the endogenous market outcome preferred to the full competitive regime. In all other cases it leads to a reduction in social welfare.

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[20] The numerical procedure underlying (19) considers all possible values any parameter of the model is al-lowed to take on, given the second-order and stability conditions.

6 CONCLUSIONS

As discussed in Section 2, there are three main reasons why allowing for R&D cooperatives could lead to increased R&D activity. The analytical excercise presented in Sections 3 through 5 shows that R&D cartels are indeed likely to invest more in R&D compared to the competitive alternative if research is complementary. And this increase in R&D activity also leads to an increase in total surplus. On the other hand, there are also three objections against sustaining R&D cooperatives. The first, that cooperatives collectively decide to cut on R&D expenses, applies when research is substitutable. In this case net total surplus reduces due to the (collective) cut in R&D spending. The second, that members of the R&D cooperative are tempted to extend the cooperative agreement to the production stage, is always at hand. In most cases, an industry-wide monopoly leads to a reduction in total surplus compared to the fully competitive alternative. The main conclusion of the analytical excercise presented here is that allowing for an R&D cooperative is likely to yield an increase in total surplus provided that collusion in the product market is effectively banned. In that case an RJV cartel would emerge, which is also most desired from society's point of view.

The literature on cooperative R&D has grown fast over the last decade. Most of these contributions are based on the seminal analysis of d'Aspremont and Jacquemin [1988]. The conclusions presented here encompass several of these recent contributions. Yet, many important aspects of R&D cooperatives are still to be considered. In particular, the endogenous formation of RJV cartels deserves more attention. Also, the analysis of partial R&D cooperatives (in which firms carried out only part of their research within the cooperative) is to be presented. Finally, proper treatment of uncertainty in models of strategic R&D is still lacking.

8. REFERENCES

Amir, R., 1995, “Modelling imperfectly appropriable R&D via spillovers”, *Discussion Paper* FS IV 95-33, Berlin: Wissenschaftszentrum Berlin.

Arrow, K.J., 1962, “Economic welfare and the allocation of resources for invention”, in Nelson, R.R., (ed.), *The rate and direction of inventive activity: economic and social factors*, Princeton: Princeton University Press, 609-26.

Brod, A. and Shivakumar, R., 1997, “R&D cooperation and the joint exploitation of R&D , *Canadian Journal of Economics*, **XXX**, No.3, 673-84.

Bulow, J., Geanakoplos, J. and Klemperer, P., 1985, “Multimarket oligopoly: strategic substitutes and complements”, *Journal of Political Economy*, **93**, 488-511.

Choi, J.P., 1993, “Cooperative R&D with product market competition”, *International Journal of Industrial Organization*, **11**, 553-71.

D’Aspremont, C., and Jacquemin, A., 1988, “Cooperative and noncooperative R&D in duopoly with spillovers”, *American Economic Review*, **78**, No.5, December, 1133-7.

D’Aspremont, C., and Jacquemin, A., 1990, “Cooperative and noncooperative R&D in duopoly with spillovers: erratum”, *American Economic Review*, **80**, No.3, June, 641-2.

Galbraith, J.K., 1952, *American capitalism, the concept of countervailing power*, 2nd edition, Oxford (UK) and Cambridge (USA): Blackwell (use is made of the reprinted version from 1980).

Geroski, P.A., 1992, “Vertical relations between firms and industrial policy”, *Economic Journal*, **102**, January, 138-47.

Geroski, P.A., 1993, “Antitrust policy towards co-operative R&D ventures”, *Oxford Review of Economic Policy*, **9**, No.2, 58-71.

Gilbert, R.J. and Newbery, D.M.G., 1982, "Preemptive patenting and the persistence of monopoly", *American Economic Review*, **72**, No.3, June, 514-26.

Henriques, I., 1990, "Cooperative and noncooperative R&D in duopoly with spillovers: comment", *American Economic Review*, **80**, No.3, June, 638-40.

Hinloopen, J., 1997a, *Research and development, product differentiation and robust estimation*, Ph.D.-thesis, Florence: European University Institute.

Hinloopen, J., 1997b, "Subsidizing cooperative and noncooperative R&D in duopoly with spillovers", *Journal of Economics*, **66**, No.2, 151-75.

Hinloopen, J., 1998, "Subsidizing cooperative and noncooperative R&D in duopoly with spillovers: a confirmation", mimeo, Delft: Technische Universiteit Delft.

Jacquemin, A., 1988, "Cooperative agreement in R&D and European antitrust policy", *European Economic Review*, **32**, 551-60.

Jones, C.I. and Williams, J.C., 1997, "Measuring the social return to R&D", *Finance and Economics Discussion Series*, Staff Working Paper 1997-12, Washington, D.C.: Federal Reserve Board.

Kamien, M.I., Muller, E. and Zang, I., 1992, "Research joint ventures and R&D cartels", *American Economic Review*, **82**, No.5, December, 1293-1306.

Katz, M.L., 1986, "An analysis of cooperative research and development", *RAND Journal of Economics*, **17**, No.4, Winter, 527-43.

Martin, S., 1995, "R&D joint ventures and tacit product market collusion", *European Journal of Political Economy*, **11**, No.4, April, 733-41.

Martin, S., 1997, "Public Policies towards cooperation in research and development: the European Union, Japan, the United States", in Comanor, W., Goto, A. and Waverman, L., (eds.), *Competition in a global economy*, London and New York: Routledge.

Motta, M., 1992, "Cooperative R&D and vertical product differentiation", *International Journal of Industrial Organization*, **10**, 643-661.

Patel, P. and Pavitt, K., 1995, "Patterns of technological activity: their measurement and inter-pretation", in Stoneman, P. (ed.), *Handbook of the economics of innovation and technological change*, Oxford (UK) and Cambridge (USA): Blackwell, 14-51.

Poyago-Theotoky, J., 1995, "Equilibrium and optimal size of a research joint venture in an oligopoly with spillovers", *Journal of Industrial Economics*, **XLIII**, No.2, June, 209-26.

Poyago-Theotoky, J., 1998, "A note on endogenous spillovers in a non-tournament R&D duopoly", *Review of Industrial Organization*, forthcoming.

Qiu, L.D., 1997, "On the dynamic efficiency of Bertrand and Cournot equilibria , *Journal of Economic Theory*, **75**, 213-29.

Rosenkranz, S., 1995, "Innovation and cooperation under vertical product differentiation", *International Journal of Industrial Organization*, **13**, 1-22.

Steurs, G., 1995, "Inter-industry spillovers: what difference do they make?", *International Journal of Industrial Organization*, **13**, 249-76.

Suzumura, K., 1992, "Cooperative and noncooperative R&D in an oligopoly with spillovers", *American Economic Review*, **82**, 1307-1320.

Tirole, J.,1988, *The theory of industrial organization*, London (UK) and Cambridge (USA): The MIT Press.

Vonortas, N.S., 1994, "Inter-Firm cooperation with imperfectly appropriable research", *International Journal of Industrial Organization*, **12**, 413-35.

APPENDIX A MARKET EQUILIBRIA

Table A.1 Equilibrium under second-stage Cournot competition; No cooperation in R&D, no cooperation in output.[a]

x^*_{IC}	$\dfrac{2(a-A)[2+\theta\{(n-2)-\beta(n-1)\}]}{b\gamma(2-\theta)[2+\theta(n-1)]^2-2[2+\theta\{(n-2)-\beta(n-1)\}][1+\beta(n-1)]}$
p^*_{IC}	$a - \dfrac{b\gamma(a-A)(2-\theta)[2+\theta(n-1)][1+\theta(n-1)]}{b\gamma(2-\theta)[2+\theta(n-1)]^2-2[2+\theta\{(n-2)-\beta(n-1)\}][1+\beta(n-1)]}$
Q^*_{IC}	$\dfrac{\gamma n(a-A)(2-\theta)[2+\theta(n-1)]}{b\gamma(2-\theta)[2+\theta(n-1)]^2-2[2+\theta\{(n-2)-\beta(n-1)\}][1+\beta(n-1)]}$
π^*_{IC}	$\dfrac{\gamma(a-A)^2\{b\gamma(2-\theta)^2[2+\theta(n-1)]^2-2[2+\theta\{(n-2)-\beta(n-1)\}]^2\}}{\{b\gamma(2-\theta)[2+\theta(n-1)]^2-2[2+\theta\{(n-2)-\beta(n-1)\}][1+\beta(n-1)]\}^2}$
W^*_{IC}	$\dfrac{n\gamma(a-A)^2\{b\gamma(2-\theta)^2[3+\theta(n-1)][2+\theta(n-1)]^2-4[2+\theta\{(n-2)-\beta(n-1)\}]^2\}}{2\{b\gamma(2-\theta)[2+\theta(n-1)]^2-2[2+\theta\{(n-2)-\beta(n-1)\}][1+\beta(n-1)]\}^2}$

[a] R&D levels and profits concern a single firm.

Table A.2 Equilibrium under second-stage Cournot competition; Cooperation in R&D, no cooperation in output.[a]

x^*_{IIC}	$\dfrac{2(a-A)[1+\beta(n-1)]}{b\gamma[2+\theta(n-1)]^2-2[1+\beta(n-1)]^2}$
p^*_{IIC}	$a - \dfrac{b\gamma(a-A)[2+\theta(n-1)][1+\theta(n-1)]}{b\gamma[2+\theta(n-1)]^2-2[1+\beta(n-1)]^2}$
Q^*_{IIC}	$\dfrac{\gamma n(a-A)[2+\theta(n-1)]}{b\gamma[2+\theta(n-1)]^2-2[1+\beta(n-1)]^2}$
π^*_{IIC}	$\dfrac{\gamma(a-A)^2}{b\gamma[2+\theta(n-1)]^2-2[1+\beta(n-1)]^2}$
W^*_{IIC}	$\dfrac{n\gamma(a-A)^2\{b\gamma[3+\theta(n-1)][2+\theta(n-1)]^2-4[1+\beta(n-1)]^2\}}{2\{b\gamma[2+\theta(n-1)]^2-2[1+\beta(n-1)]^2\}^2}$

[a] R&D levels and profits concern a single firm.

Table A.3 **Equilibrium under second-stage Bertrand competition; No cooperation in R&D, no cooperation in output.**[a,b]

x^*_{IB}	$\dfrac{2\Delta(a-A)[1+\theta(n-2)]}{b\gamma[1+\theta(n-1)][2+\theta(2n-3)][2+\theta(n-3)]^2-2\Delta[1+\theta(n-2)][1+\beta(n-1)]}$
p^*_{IB}	$a - \dfrac{b\gamma(a-A)[1+\theta(n-1)][1+\theta(n-2)][2+\theta(2n-3)][2+\theta(n-3)]}{b\gamma[1+\theta(n-1)][2+\theta(2n-3)][2+\theta(n-3)]^2-2\Delta[1+\theta(n-2)][1+\beta(n-1)]}$
Q^*_{IB}	$\dfrac{\gamma n(a-A)[1+\theta(n-2)][2+\theta(2n-3)][2+\theta(n-3)]}{b\gamma[1+\theta(n-1)][2+\theta(2n-3)][2+\theta(n-3)]^2-2\Delta[1+\theta(n-2)][1+\beta(n-1)]}$
π^*_{IB}	$\dfrac{\gamma(a-A)^2[1+\theta(n-2)]\{b\gamma(1-\theta)[1+\theta(n-1)][2+\theta(2n-3]^2[2+\theta(n-3)]^2-2\Delta^2[1+\theta(n-2)]\}}{\{b\gamma[1+\theta(n-1)][2+\theta(2n-3)][2+\theta(n-3)]^2-2\Delta[1+\theta(n-2)][1+\beta(n-1)]\}^2}$
W^*_{IB}	$\gamma n(a-A)^2[1+\theta(n-2)] \times \dfrac{b\gamma[3+\theta(n-4)][1+\theta(n-1)][2+\theta(2n-3)]^2[2+\theta(n-3)]^2-4\Delta^2[1+\theta(n-2)]}{2\{b\gamma[1+\theta(n-1)][2+\theta(2n-3)][2+\theta(n-3)]^2-2\Delta[1+\theta(n-2)][1+\beta(n-1)]\}^2}$

[a] R&D levels and profits concern a single firm.
[b] $\Delta = 2+3\theta(n-2)+\theta^2[(n-1)(n-2)-(2n-3)]-\theta\beta(n-1)[1+\theta(n-2)]$.

Table A.4 **Equilibrium under second-stage Bertrand competition; Cooperation in R&D, no cooperation in output.**[a]

x^*_{IIB}	$\dfrac{2(a-A)(1-\theta)[1+\theta(n-2)][1+\beta(n-1)]}{b\gamma[1+\theta(n-1)][2+\theta(n-3)]^2-2(1-\theta)[1+\theta(n-2)][1+\beta(n-1)]^2}$
p^*_{IIB}	$a - \dfrac{b\gamma(a-A)[1+\theta(n-1)][1+\theta(n-2)][2+\theta(n-3)]}{b\gamma[1+\theta(n-1)][2+\theta(n-3)]^2-2(1-\theta)[1+\theta(n-2)][1+\beta(n-1)]^2}$
Q^*_{IIB}	$\dfrac{n\gamma(a-A)[1+\theta(n-2)][2+\theta(n-3)]}{b\gamma[1+\theta(n-1)][2+\theta(n-3)]^2-2(1-\theta)[1+\theta(n-2)][1+\beta(n-1)]^2}$
π^*_{IIB}	$\dfrac{\gamma(a-A)^2(1-\theta)[1+\theta(n-2)]}{b\gamma[1+\theta(n-1)][2+\theta(n-3)]^2-2(1-\theta)[1+\theta(n-2)][1+\beta(n-1)]^2}$
W^*_{IIB}	$n\gamma(a-A)^2[1+\theta(n-2)] \times \dfrac{b\gamma[1+\theta(n-1)][3+\theta(n-4)][2+\theta(n-3)]^2-4(1-\theta)^2[1+\theta(n-2)][1+\beta(n-1)]^2}{2\{b\gamma[1+\theta(n-1)][2+\theta(n-3)]^2-2(1-\theta)[1+\theta(n-2)][1+\beta(n-1)]^2\}^2}$

[a] R&D levels and profits concern a single firm.

Table A.5 Equilibrium under both second-stage Cournot and Bertrand competition; Cooperation in R&D, cooperation in output.[a]

x^*_{III}	$\dfrac{(a-A)[1+\beta(n-1)]}{2b\gamma[1+\theta(n-1)]-[1+\beta(n-1)]^2}$
p^*_{III}	$a - \dfrac{b\gamma(a-A)[1+\theta(n-1)]}{2b\gamma[1+\theta(n-1)]-[1+\beta(n-1)]^2}$
Q^*_{III}	$\dfrac{\gamma n(a-A)}{2b\gamma[1+\theta(n-1)]-[1+\beta(n-1)]^2}$
π^*_{III}	$\dfrac{\gamma(a-A)^2}{2\{2b\gamma[1+\theta(n-1)]-[1+\beta(n-1)]^2\}}$
W^*_{III}	$\dfrac{n\gamma(a-A)^2\{3b\gamma[1+\theta(n-1)]-[1+\beta(n-1)]^2\}}{2\{2b\gamma[1+\theta(n-1)]-[1+\beta(n-1)]^2\}^2}$

[a] R&D levels and profits concern a single firm.

APPENDIX B PROOFS OF PROPOSITIONS

B.1 PROOF OF PROPOSITION 1

Comparing the different levels of R&D leads to

$$x_{IC}^{*}-x_{IIC}^{*} = \frac{2b\gamma(a-A)(n-1)[2+\theta(n-1)]^{2}}{b\gamma(2-\theta)[2+\theta(n-1)]^{2}-2\{[2+\theta(n-2)]-\theta\beta(n-1)\}[1+\beta(n-1)]} \times \frac{\theta-2\beta}{b\gamma[2+\theta(n-1)]^{2}-2[1+\beta(n-1)]^{2}},$$

$$x_{IC}^{*}-x_{III}^{*} = \frac{b\gamma(a-A)(n-1)}{2b\gamma[1+\theta(n-1)]-[1+\beta(n-1)]^{2}} \times \frac{\beta[8+8\theta(n-1)+2\theta^{2}(n-1)^{2}-\theta^{3}(n-1)^{3}]-\theta[4+2\theta(n-1)+\theta^{2}(n-1)]}{b\gamma(2-\theta)[2+\theta(n-1)]^{2}-2\{[2+\theta(n-2)]-\theta\beta(n-1)\}[1+\beta(n-1)]},$$

$$x_{IIC}^{*}-x_{III}^{*} = \frac{b\gamma(a-A)(n-1)^{2}\theta^{2}[1+\beta(n-1)]}{\{b\gamma[2+\theta(n-1)]^{2}-2[1+\beta(n-1)]^{2}\}\{2b\gamma[1+\theta(n-1)]-[1+\beta(n-1)]^{2}\}},$$

and

$$x_{IB}^{*}-x_{IIB}^{*} = \frac{2b\gamma(a-A)(n-1)[1+\theta(n-1)][1+\theta(n-2)][2+\theta(n-3)]^{2}}{b\gamma[1+\theta(n-1)][2+\theta(2n-3)][2+\theta(n-3)]^{2}-2\Delta[1+\theta(n-2)][1+\beta(n-1)]} \times \frac{\theta[1+\theta(n-2)]-\beta[2+2\theta(n-2)-\theta^{2}(n-1)]}{b\gamma[1+\theta(n-1)][2+\theta(n-3)]^{2}-2(1-\theta)[1+\theta(n-2)][1+\beta(n-1)]^{2}},$$

$$x_{IB}^{*}-x_{III}^{*} = \frac{b\gamma(a-A)(n-1)[1+\theta(n-1)]}{2b\gamma[1+\theta(n-1)]-[1+\beta(n-1)]^{2}} \times \frac{\beta[8+16\theta(n-2)+2\theta^{2}[5n^{2}-20n+19]+\theta^{3}(n-1)(2n^{2}-9n+11)]-\theta[4+2\theta(3n-7)+\theta^{2}(2n^{2}-11n+13)]}{b\gamma[1+\theta(n-1)][2+\theta(2n-3)][2+\theta(n-3)]^{2}-2\Delta[1+\theta(n-2)][1+\beta(n-1)]},$$

$$x_{III}^{*}-x_{IIB}^{*} = \frac{b\gamma(a-A)\theta^{2}(n-1)^{2}}{b\gamma[1+\theta(n-1)][2+\theta(n-3)]^{2}-2(1-\theta)[1+\theta(n-2)][1+\beta(n-1)]^{2}} \times \frac{[1+\theta(n-1)][1+\beta(n-1)]}{2b\gamma[1+\theta(n-1)]-[1+\beta(n-1)]^{2}}.$$

Then observe that

$$x_{IC}^{*} - x_{IIC}^{*} > 0 \quad \Leftrightarrow \quad \beta < C_2,$$

$$x_{IC}^{*} - x_{III}^{*} > 0 \quad \Leftrightarrow \quad \beta < C_1,$$

$$x_{III}^{*} - x_{IIC}^{*} > 0 \quad \Leftrightarrow \quad \forall \beta \in [0,1],$$

and

$$x_{IB}^{*} - x_{IIB}^{*} > 0 \quad \Leftrightarrow \quad \beta < B_2,$$

$$x_{IB}^{*} - x_{III}^{*} > 0 \quad \Leftrightarrow \quad \beta < B_1,$$

$$x_{III}^{*} - x_{IIB}^{*} > 0 \quad \Leftrightarrow \quad \forall \beta \in [0,1].$$

Finally, it is to be examined whether or not the boundaries on β, for which the inequalities stated in Proposition 1 hold, do not cross. Observe that under second stage Cournot competition

$$C_2 - C_1 = \frac{\theta^2 (n-1)\{4 + 2\theta(n-2) - \theta^2(n-1)\}}{2\{8[1+\theta(n-1)] + \theta^2(n-1)(2-\theta)\}},$$

the denominator of which is clearly positive. The numerator is positive *iff* $-2/(n-1) < \theta < 2$, and $\theta \neq 0$, conditions which are all satisfied under the parameter space considered in the analysis. Further, under second-stage Bertrand competition

$$B_2 - B_1 = \frac{\theta^2 (n-1)\{4 + 2\theta(5n-8) + \theta^2[8n^2 - 27n + 21] + \theta^3[2n^3 - 11n^2 + 18n - 9]\}}{\{2(1-\theta) + \theta(n-1)(2-\theta)\}\{16\theta(n-2) + 2\{4 + \theta^2[5n^2 - 20n + 19]\} + \theta^3(n-1)[2n^2 - 9n + 11]\}},$$

the denominator of which also is obviously positive. The same holds for the numerator if it is observed that it is increasing in n and positive for $n = 2$. Hence, both under second stage Cournot and Bertrand competition the regions in terms of β as stated in Proposition 1 are well defined.

Q.E.D.

B.2 PROOF OF PROPOSITION 2

Part (i)

First observe that $\forall n, \beta, \theta$,

$$x^*_{IIC}|_{\beta=1} - x^*_{IC} = \frac{2(a-A)(n-1)}{b\gamma[2+\theta(n-1)]^2 - 2n^2}$$

$$\times \frac{b\gamma[2+\theta(n-1)]^2[2-2\theta+\theta\beta] + 2n(1-\beta)[2+\theta\{(n-2)-\beta(n-1)\}]}{b\gamma(2-\theta)[2+\theta(n-1)]^2 - 2[2+\theta\{(n-2)-\beta(n-1)\}[1+\beta(n-1)]} > 0,$$

and

$$x^*_{IIB}|_{\beta=1} - x^*_{IB} = \frac{2(a-A)(n-1)[1+\theta(n-2)]}{b\gamma[1+\theta(n-1)][2+\theta(n-3)]^2 - 2(1-\theta)n^2[1+\theta(n-2)]}$$

$$\times \frac{b\gamma[1+\theta(n-1)][2+\theta(n-3)]^2\{2+2\theta(n-3)-\theta^2(3n-5)+\theta\beta[1+\theta(n-2)]\}}{b\gamma[1+\theta(n-1)][2+\theta(2n-3)][2+\theta(n-3)]^2 - 2\Delta[1+\theta(n-2)][1+\beta(n-1)]}.$$

For the second of these to be positive, it suffice that

$$2+\theta\{2(n-3)-\theta(3n-5)\}+\theta\beta[1+\theta(n-2)]$$

or

$$2+\theta\{2(n-3)-\theta(3n-5)\}$$

is positive. The latter expression has two roots in θ, one positive and one negative. For θ below the positive root, that is, for

$$\theta < \frac{n-3+\sqrt{(n-1)(n+1)}}{3n-5},$$

it is true that $x^*_{IIB}|_{\beta=1} - x^*_{IB} > 0$. Observe that the positive root is decreasing in *n* and that

$$\lim_{n\to\infty}\left\{\frac{n-3+\sqrt{(n-1)(n+1)}}{3n-5}\right\} = \frac{2}{3}.$$

The proof of the first part of the lemma is complete if it is realized that $\forall n, \beta, \theta$,

$$\frac{\partial x^*_{IIC}}{\partial \beta} = \frac{2(n-1)(a-A)\{b\gamma[2+\theta(n-1)]^2 + 2[1+\beta(n-1)]^2\}}{\{b\gamma[2+\theta(n-1)]^2 - 2[1+\beta(n-1)]^2\}^2} > 0,$$

$$\frac{\partial x^*_{IIB}}{\partial \beta} = 2(n-1)(a-A)(1-\theta)[1+\theta(n-2)]$$

$$\times \frac{b\gamma[1+\theta(n-1)][2+\theta(n-3)]^2 + 2(1-\theta)[1+\theta(n-2)][1+\beta(n-1)]^2}{\{b\gamma[1+\theta(n-1)][2+\theta(n-3)]^2 - 2(1-\theta)[1+\theta(n-2)][1+\beta(n-1)]^2\}^2} > 0.$$

Part (ii)

First observe that $\forall n, \beta, \theta$,

$$x^*_{III}|_{\beta=1} - x^*_{IIC}|_{\beta=1} = \frac{n(n-1)^2 b\gamma\theta^2(a-A)}{\{2b\gamma[1+\theta(n-1)] - n^2\}\{b\gamma[2+\theta(n-1)]^2 - 2n^2\}} > 0,$$

and

$$x^*_{III}|_{\beta=1} - x^*_{IIB}|_{\beta=1} = \frac{n(n-1)^2 b\gamma\theta^2(a-A)}{b\gamma[1+\theta(n-1)][2+\theta(n-3)]^2 - 2n^2(1-\theta)[1+\theta(n-2)]}$$

$$\times \frac{[1+\theta(n-1)]}{2b\gamma[1+\theta(n-1)] - n^2} > 0.$$

From the proof of part (i) it then readily follows that also $\forall n, \beta, \theta$,

$$x^*_{III}|_{\beta=1} > x^*_{IC},\ x^*_{IIB},\ x^*_{IIC}.$$

However, as shown above, under second stage Bertrand competition, competitive R&D efforts do not always fall below those of a RJV cartel. To be considered in addition therefore is

$$x^*_{III}|_{\beta=1} - x^*_{IB} = \frac{(a-A)}{2b\gamma[1+\theta(n-1)] - n^2}$$

$$\times \frac{b\gamma[1+\theta(n-1)]\{4(n-1)\theta\beta[1+\theta(n-2)]^2 + 2\Delta n(n-1)(1-\beta)[1+\theta(n-2)] + \alpha^B_{71} + \alpha^B_{72}\}}{b\gamma[1+\theta(n-1)][2+\theta(2n-3)][2+\theta(n-3)]^2 - 2\Delta[1+\theta(n-2)][1+\beta(n-1)]},$$

$\alpha^B_{71} = [2+\theta(2n-3)][2+\theta(n-3)]^2 - 4[1+\theta(n-2)]\{2+3\theta(n-2)+\theta^2[(n-1)(n-2)-(2n-3)]\}$, and $\alpha^B_{72} = (n-1)[2+\theta(2n-3)][2+\theta(n-3)]^2$. A sufficient condition for $x^*_{III}|_{\beta=1} - x^*_{IB}$ to be positive is that $\alpha^B_{71} + \alpha^B_{72}$ is greater than zero. Then observe that $\forall n, \theta, \beta$,

$$\alpha^B_{71} + \alpha^B_{72} > 2[1+\theta(n-2)]\{4(n-1)+2\theta[2n^2-9n+6]+\theta^2[n^3-8n^2+19n-10]\} > 0.$$

The proof of the second part of the lemma is complete if it is realized that $\forall n, \beta, \theta,$

$$\frac{\partial x^*_{III}}{\partial \beta} = \frac{(n-1)(a-A)\{2b\gamma[1+\theta(n-1)]+[1+\beta(n-1)]^2\}}{\{2b\gamma[1+\theta(n-1)]-[1+\beta(n-1)]^2\}^2} > 0.$$

Q.E.D.

B.3 PROOF OF PROPOSITION 3

Comparing the levels profits leads to

$$\pi^*_{III} - \pi^*_{IIC} = \frac{\gamma(n-1)^2(a-A)^2 b\gamma\theta^2}{2\{2b\gamma[1+\theta(n-1)]-[1+\beta(n-1)]^2\}\{b\gamma[2+\theta(n-1)]^2-2[1+\beta(n-1)]^2\}},$$

$$\pi^*_{IIC} - \pi^*_{IC} = \frac{2n\gamma(a-A)^2 b\gamma}{b\gamma[2+\theta(n-1)]^2-2[1+\beta(n-1)]^2} \times \frac{(n-1)^2[2+\theta(n-1)]^2[2\beta-\theta]^2}{\{b\gamma(2-\theta)[2+\theta(n-1)]^2-2\{[2+\theta(n-2)]-\theta\beta(n-1)\}[1+\beta(n-1)]\}^2},$$

and

$$\pi^*_{III} - \pi^*_{IIB} = \frac{\gamma(n-1)^2(a-A)^2}{2\{2b\gamma[1+\theta(n-1)]-[1+\beta(n-1)]^2\}} \times \frac{b\gamma\theta^2[1+\theta(n-1)]}{b\gamma[1+\theta(n-1)][2+\theta(n-3)]^2-2(1-\theta)[1+\theta(n-2)][1+\beta(n-1)]^2},$$

$$\pi^*_{IIB} - \pi^*_{IB} = \frac{2\gamma(n-1)^2(a-A)^2}{b\gamma[1+\theta(n-1)][2+\theta(n-3)]^2-2(1-\theta)[1+\theta(n-2)][1+\beta(n-1)]^2}$$
$$\times \frac{b\gamma[1+\theta(n-1)][1+\theta(n-2)]^2[2+\theta(n-3)]^2\{\beta[2+2\theta(n-2)-\theta^2(n-1)]-\theta[1+\theta(n-2)]\}^2}{\{b\gamma[1+\theta(n-1)][2+\theta(2n-3)][2+\theta(n-3)]^2-2\Delta[1+\theta(n-2)][1+\beta(n-1)]\}^2},$$

from which the Proposition follows immediately.

Q.E.D.

B.4 PROOF OF PROPOSITION 4

The appropriate partial derivatives equal

$$\frac{\partial \pi^*_{IIC}}{\partial \beta} = \frac{4\gamma(n-1)(a-A)^2[1+\beta(n-1)]}{\{b\gamma[2+\theta(n-1)]^2-2[1+\beta(n-1)]^2\}^2} > 0,$$

$$\frac{\partial \pi^*_{IIB}}{\partial \beta} = \frac{4\gamma(n-1)(a-A)^2(1-\theta)^2[1+\theta(n-2)]^2[1+\beta(n-1)]}{\{b\gamma[1+\theta(n-1)][2+\theta(n-3)]^2-2(1-\theta)[1+\theta(n-2)][1+\beta(n-1)]^2\}^2} > 0,$$

$$\frac{\partial \pi^*_{III}}{\partial \beta} = \frac{4\gamma(n-1)(a-A)^2[1+\beta(n-1)]}{4\{2b\gamma[1+\theta(n-1)]-[1+\beta(n-1)]^2\}^2} > 0.$$

Q.E.D.

B.5 PROOF OF PROPOSITION 6.

The appropriate partial derivatives equal

$$\frac{\partial W^*_{IIC}}{\partial \beta} = \frac{4\gamma n(n-1)(a-A)^2[1+\beta(n-1)]\{b\gamma[2+\theta(n-1)]^3-2[1+\beta(n-1)]^2\}}{\{b\gamma[2+\theta(n-1)]^2-2[1+\beta(n-1)]^2\}^3} > 0,$$

$$\frac{\partial W^*_{IIB}}{\partial \beta} = 4\gamma n(n-1)(a-A)^2(1-\theta)[1+\theta(n-2)]^2[1+\beta(n-1)]$$

$$\times \frac{b\gamma[1+\theta(n-1)][2+\theta(n-3)]^3-2(1-\theta)^2[1+\theta(n-2)][1+\beta(n-1)]^2}{\{b\gamma[1+\theta(n-1)][2+\theta(n-3)]^2-2(1-\theta)[1+\theta(n-2)][1+\beta(n-1)]^2\}^3} > 0,$$

$$\frac{\partial W^*_{III}}{\partial \beta} = \frac{\gamma n(n-1)(a-A)^2[1+\beta(n-1)]\{4b\gamma[1+\theta(n-1)]-[1+\beta(n-1)]^2\}}{\{2b\gamma[1+\theta(n-1)]-[1+\beta(n-1)]^2\}^3} > 0.$$

Q.E.D.

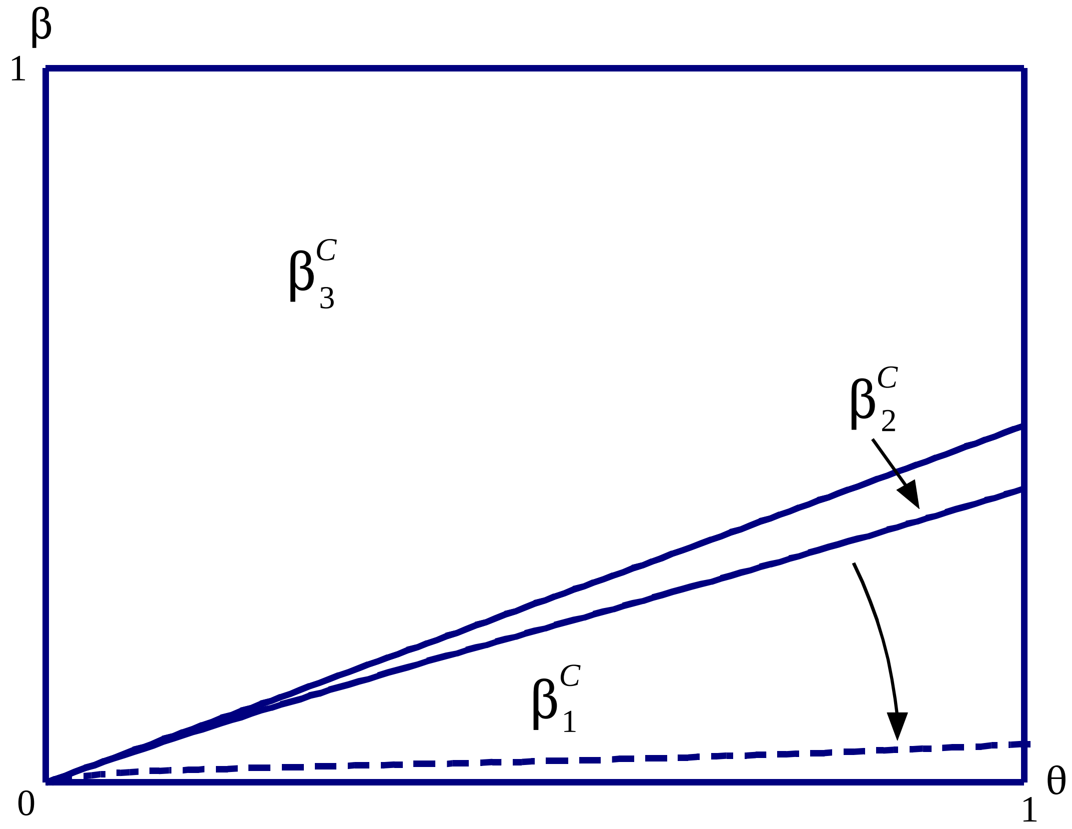

Figure 1a Regions dividing R&D investments for different regimes; Cournot competition; Effect of increasing the number of firms from n=2 to n=50.

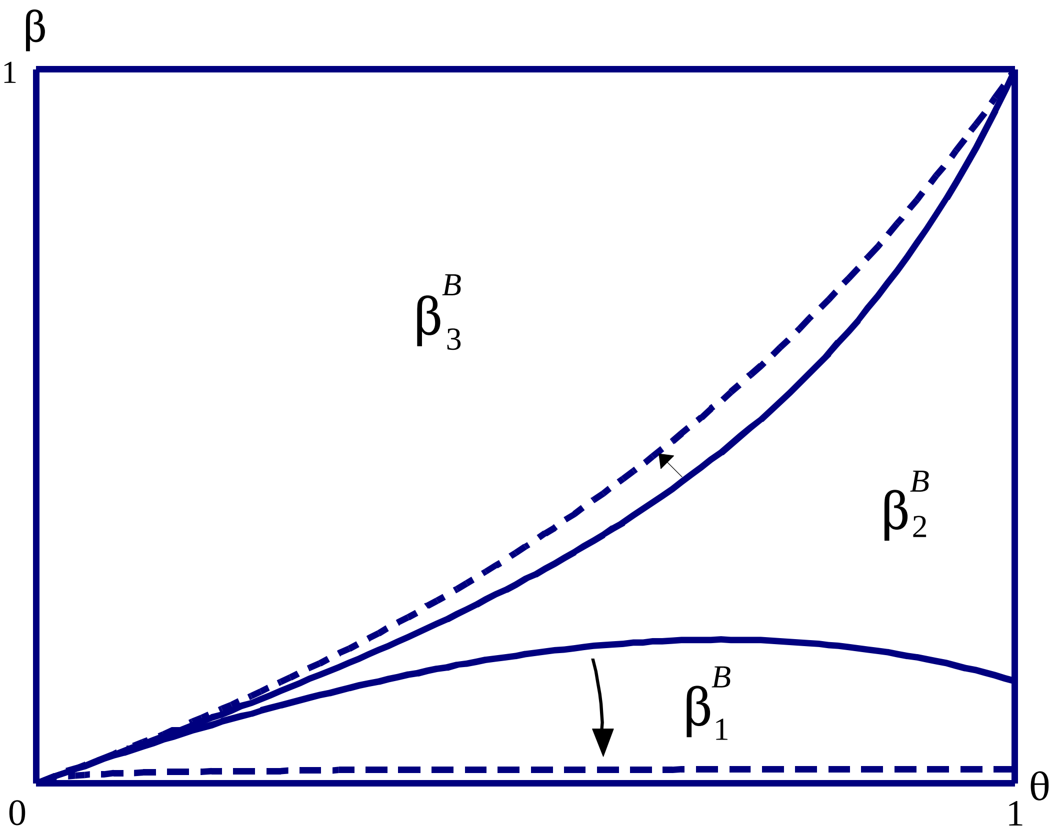

Figure 1b Regions dividing R&D investments for different regimes; Bertrand competition; Effect of increasing the number of firms from n=2 to n=50.