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Roberto Cellini and Luca Lambertini
Editors

The Economics of Innovation

Incentives, Cooperation, and R&D Policy

THE ECONOMICS OF INNOVATION:
INCENTIVES, COOPERATION, AND R&D POLICY

CONTRIBUTIONS TO ECONOMIC ANALYSIS

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United Kingdom – North America – Japan
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THE ECONOMICS OF INNOVATION: INCENTIVES, COOPERATION, AND R&D POLICY

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The Editors' Preface

R&D activities and incentives, together with the pace of the resulting technical progress, have been core issues ever since the pioneering work of Schumpeter (1942) and the consequent debate about the so-called Schumpeterian hypothesis, according to which the higher is the degree of market power enjoyed by a firm, the higher is her incentive to invest in innovation. This debate has received a crucial impulse by Arrow (1962), putting forward convincing argument against the Schumpeterian claim, by pointing out that a firm operating initially under perfect competition should indeed be endowed with the highest possible incentive to strive for an innovation whereby, if successful, she could throw her rivals out of the market and acquire monopoly power over the latter.

The existing literature on R&D, either for process or for product innovation, is way too large to be exhaustively summarized here, but surely its dimensions, a casual look at the contents of the main textbooks in industrial organization theory (say, Tirole, 1988; Shy, 1995, and Martin, 2001), and the mere observation that technical progress is in fact a manifold issue with extremely relevant implications for industrial policy, economic growth, international trade and globalization, confirms its cross-sectional relevance in modern economics. Here, we shall confine ourselves to briefly recollect the main lines of research in order to set up a reference framework for the present book.

One of the most widely analyzed aspects, which stems directly from the debate between Schumpeter and Arrow, is that of evaluating R&D incentives in connection with either industry structure (Kamien and Schwartz, 1976; Dasgupta and Stiglitz, 1980a; Futia, 1980; Gilbert and Newbery, 1982; Reinganum, 1983) or the type of market competition, i.e., Bertrand versus Cournot (Loury, 1979; Lee and Wilde, 1980; Brander and Spencer, 1983; Delbono and Denicolò, 1991; Qiu, 1997). Clearly, R&D incentives are conditional upon the appropriability of the profit flows generated by innovations. Hence, the need arises for a well specified patent law, taking into account the different *dimensions* of an innovation (Nordhaus, 1969; Kamien and Schwartz, 1974; Gilbert and Shapiro, 1990; Klemperer, 1990; Gallini, 1992; Denicolò, 1996). R&D activities are intrinsically uncertain. Accordingly, a major effort has been carried out to investigate the features of R&D races (Loury, 1979; Dasgupta and Stiglitz, 1980b; Reinganum, 1981, 1982; Harris and Vickers, 1985, 1987). A fourth theme that frequently attracts the attention of researchers in this field is the possibility of resorting to some form of cooperation (either R&D cartels or research joint ventures) to reduce the undesirable duplication of efforts and, at the same time, better exploit information sharing and technological spillovers (d'Aspremont and Jacquemin, 1988; Kamien et al., 1992; Suzumura, 1992). A complete list would be much longer, with almost uncountable relevant contributions, and a thorough view of the general picture is hunting the dreams of many of us.

The comparatively modest aim of the present volume is to offer some advances in three directions, namely, (i) the role and optimal design of patents, (ii) cost sharing and technological externalities, and (iii) the relationship between firms' organization and R&D incentives. Accordingly, the book consists of three parts.

Part I is devoted to the role of patents. In Chapter 1, Ulrich Doraszelski investigates the link between patent protection and rent dissipation. The literature on R&D races suggests that non-colluding firms carry out excess investment in R&D. Doraszelski shows that this result depends critically on the winner-take-all assumption. Although rents continue to be dissipated once the winner-take-all assumption is relaxed because firms in general fail to provide the optimal R&D effort, the mechanisms behind this rent dissipation change with the degree of patent protection. He then illustrates how the patent system can be used to elicit the optimal R&D effort. In Chapter 2, Vincenzo Denicolò and Luigi Franzoni examine the alternative between patents and trade secrets. They investigate the possibility of adjusting patent protection in such a way that the innovator is indifferent between disclosing the innovation (by patenting it) and keeping it secret. Their main findings are that (i) patents is socially efficient as compared to secrets if there's duplication; (ii) secrecy is socially preferable only if the threat of duplication induces pre-emptive licensing. In Chapter 3, Poddar and Sinha propose a survey of the main results produced by the literature on licensing and some original insights, with a particular focus on globalization, North–South models of technology transfer, the issue of how the intellectual property rights influences international licensing, and asymmetric information.

Part II sets out with Chapter 4, where Hauenschild and Sander analyze the stability and welfare properties of cooperative R&D projects in an oligopoly market. The authors show that the sizes of stable coalitions varies significantly with the kind and level of spillovers, the institutional R&D arrangement and the underlying stability concept. An additional result is that the welfare maximizing coalition is rarely a stable equilibrium outcome: accordingly, there's scope for a policy intervention. However, the informational requirements on the part of the policy makers are high, and they are at risk to adopt inappropriate measures that are detrimental to social welfare. In Chapter 5, Hinloopen illustrates a model where the outcome of R&D activities is uncertain, and the rate of success can be increased by exploiting scope economies generated by cooperation. The presence of scope economies yields the result that the range of spillover levels wherein cooperation is socially desirable increases, to such an extent that, if scope economies are above a critical threshold, then cooperation is socially beneficial for any level of technological externalities. In Chapter 6, Kamien and Zang explore the possibility of an established firm repelling a newcomer's cost reducing technical advances by providing the newcomer access to its currently superior technology. The oldtimer is supposed to offer his technology in return for the newcomer either ceasing R&D or sharing her findings. The authors find that newcomers with the R&D potential to drive the oldtimer out of business cannot be coopted, but that less potent newcomers can. Whenever newcomers are deterred, the product price is higher and technical advance lower than it would be in the absence of a deal. In Chapter 7, Lambertini, Poddar and Sasaki take a close look at the strategic incentives arising in a situation where firms share the costs and profits in a multi-firm project, and bargain for their respective (precommitted) cost- and profit-shares. They establish that, when each firm's effort contribution to the joint undertaking is mutually observable (which is often the case in closely collaborative operations) and hence can form basis of the contingent cost- and profit-sharing scheme, it is not the gross economic efficiency but the super-/sub-additivity of the net returns from effort that directly affects the sustainability of a profile of firms' effort contributions. The (in)efficiency result obtained in this paper is of different nature from so-called "free riding" or "team competition" problems: the set of sustainable outcomes with bargaining over precommitted cost- and profit-shares is generally neither a superset nor a subset of the sustainable set without bargaining. In Chapter 8, Lin points out that research joint ventures (RJVs) avoid undesirable effort duplications and facilitate the diffusion of knowledge. Yet, sharing R&D output intensifies post-innovation market competition and hence hampers firms' incentive to join an RJV. He models the RJV formation game as a non-cooperative sequential game. R&D is certain, and it is design to yield a given process innovation. The issues addressed Lin can be summarized as follows: how many RJVs will be formed in equilibrium? And what are their sizes? How does the equilibrium pattern of RJVs compare with the social optimum? Can RJV formation be used as a means to drive rival firms out of the market? He also considers firms with different pre-innovation costs and looks at how their incentives to form RJVs differ. Moreover, he also investigates whether a firm prefers to invite a large (low-cost) firm or small (high-cost) firm to join an RJV. Policy implications are discussed as well.

The existing literature on R&D for either process or product innovation focuses mainly upon the innovative incentives of entrepreneurial (i.e., profit-seeking) firms. However, the separation between ownership and control and the shape of managerial incentive contracts may indeed matter in determining the size of R&D efforts. Indeed, Part III collects two essays focusing on this issue, that is, the interplay between strategic delegation of control to managers who are not strictly interested in maximizing their respective firms' profits, and R&D incentives. In Chapter 9, Cellini and Lambertini propose a dynamic view of this issue, modeling both process and product innovation in a differential game framework where managerial firms are involved. They show that firms run by managers who exhibit a taste for output expansion outperform strict profit-seeking units in terms of process innovation, but not in terms of product innovation. In Chapter 10, Kopel and Riegler consider a strategic delegation setting with R&D spillovers in a Cournot duopoly. The game has four stages. First, each owners have the option to hire managers. If the owners delegate, then in the contracting stage they have to determine the optimal incentives for the managers. In the R&D stage, the levels of investments in cost-reducing R&D are chosen. Finally, in the production stage quantities are set. The authors characterize the subgame perfect outcomes of this game depending on the level of R&D spillovers, and derive the following main insights. First, if no spillovers exist, both owners have an incentive to delegate R&D and production decisions to managers. This leads to higher outputs, higher R&D activities, but lower profits in comparison with an entrepreneurial (owner-managed) firm. These results still hold if the unit production costs are high, irrespective of the existence of spillovers. In these cases delegation leads to an increase in social welfare. Second, when spillovers exist and production costs are low, then there are situations where owners delegate but discourage managers from being aggressive. This "reverse" commitment leads to lower outputs, lower R&D, but higher profits for the firms in comparison with an entrepreneurial one. Here, however, delegation results in lower welfare.

This book is itself a research joint venture. We would like to thank all contributors for having accepted our invitation to join the venture and for their patience while the final product was slowly taking a definite, and then final, shape. In the latter phase, we have benefited from the editorial experience and advice of Rachel Strachan and Mark Newson at Elsevier.

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PART I

Patents

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CHAPTER 1

Rent Dissipation in R&D Races

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Abstract

The literature on R&D races suggests that noncolluding firms invest excessively in R&D. We show that this result depends critically on the winner-take-all assumption. Although rents continue to be dissipated once the winner-take-all assumption is relaxed because firms in general fail to provide the optimal R&D effort, the mechanisms behind this rent dissipation change with the degree of patent protection. We then illustrate how the patent system can be used to elicit the optimal R&D effort.

1. Introduction

Do firms invest too little or too much in R&D? The literature on R&D races suggests that noncolluding firms invest excessively in R&D (see Reinganum, 1989, for a survey). In this paper, we show that this result depends critically on the so-called winner-take-all assumption that is typically made to facilitate the welfare comparisons (e.g., Reinganum, 1981). According to this assumption, the firm that wins the race is awarded a patent, whereas the others receive nothing. The empirical evidence, however, suggests that patent protection is far from perfect and that there are benefits to imitation (losing the R&D race) as well as innovation (winning the R&D race) (e.g., Cohen et al., 2000). This casts serious doubts on the winner-take-all assumption.

We show that once the winner-take-all assumption is relaxed, it no longer can be ascertained that noncolluding firms invest excessively in R&D. In this more realistic setting, rents continue to be dissipated because firms in general fail to provide the optimal R&D effort. However, the mechanisms behind this rent dissipation change with the degree of patent protection.

We use this insight to show how the patent system can be used to elicit the optimal R&D effort. In particular, we show that, whether firms invest too much or too little in R&D, it is always possible to replicate the planner's solution by offering the appropriate rewards to the participating firms.

The literature has long recognized that the degree of patent protection is a crucial determinant of competitive behavior (e.g., Reinganum, 1982). Beath et

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al. (1989) show that whether a firm's reaction function in an R&D race is upward or downward sloping depends on the values of the firm's reaction function at zero ("profit incentive") and at infinity ("competitive threat"). Our results complement theirs in that we provide an alternative characterization of strategic complements and substitutes in terms of the relative magnitude of the value of continued play and the benefit to imitation. Going beyond Beath et al. (1989), we also draw the comparison between noncooperative equilibrium and collusive outcome.

The remainder of this paper is organized as follows. Section 2 develops a standard R&D race model (Lee and Wilde, 1980; Reinganum, 1981; Reinganum, 1982). Section 3 characterizes the noncooperative equilibrium, Section 4 the collusive outcome. Section 5 discusses the driving forces underlying rent dissipation. The policy implications are discussed in Section 6. Section 7 concludes. All proofs are relegated to the Appendix.

2. Model

Consider an R&D race in which two identical firms are simultaneously seeking a particular innovation. Firms compete to be the first to make the discovery. The date of a successful innovation is assumed to be random and influenced by firms' R&D efforts. Time is continuous and the horizon is infinite.

Let τ_i be the random date of a successful innovation by firm i. Following the literature, we assume that the distribution of τ_i is

$$\Pr(\tau_i \leqslant t) = 1 - e^{-\lambda u_i t}, \quad \lambda \geqslant 0.$$

It follows that firm i's hazard rate of successful innovation is $h_i = \lambda u_i$.[1]

The firm which makes the innovation first is awarded a patent of positive value $\overline{P} > 0$, whereas its rival receives nothing if patent protection is assumed to be perfect. This is the winner-take-all assumption that is typically made by the existing literature. On the other hand, if patent protection is imperfect as the empirical evidence suggests (e.g., Cohen et al., 2000), the loser receives a positive payoff $\underline{P}$, where $\overline{P} > \underline{P} > 0$. $\overline{P}$ is understood to be the expected net present value of all future revenues from marketing the innovation net of any costs the firm incurs in doing so. Similarly $\underline{P}$ is the expected net present value of the all future cash flows including costs of imitation. Hence, $\overline{P}$ and $\underline{P}$ implicitly depend on the length and breadth of patent protection and the particulars of product market competition (as modeled in Denicolo, 1996, see also Klemperer, 1990; Gallini, 1992, and Matutes et al., 1996).

To simplify the notation, we focus on firm 1 in what follows. The derivations for firm 2 are analogous. Let V_1 denote the expected value of the race to firm 1.

[1] Doraszelski (2003) considers alternative distributions of success times.

It is implicitly given by

$$rV_1 = \max_{u_1 \geqslant 0} h_1(\overline{P} - V_1) + h_2(\underline{P} - V_1) - c(u_1),$$

where $r > 0$ is the interest rate and the cost incurred to exert R&D effort u_1 is $c(u_1) = \frac{1}{\eta} u_1^\eta$. The parameter $\eta > 1$ measures the elasticity of the cost function. The expected value V_1 can be interpreted as the asset or option value to firm 1 of participating in the race. This option is priced by requiring that the opportunity cost of holding it, rV_1, equals the current cash flow, $-c(u_1)$, plus the expected capital gain or loss flow. The latter is composed of two parts, namely the capital gain from winning the race, $\overline{P} - V_1$, times the likelihood of doing so, h_1, and the capital loss from losing the race, $\underline{P} - V_1$, times the likelihood of doing so, h_2.

Differentiating the above equation yields the FOC for an interior solution $u_1^* > 0$. Solving gives

$$u_1^* = \left(\lambda(\overline{P} - V_1)\right)^{\frac{1}{\eta - 1}}.$$

Since the objective function is strictly concave due to $\eta > 1$, the FOC is also sufficient for an interior solution.

3. Noncooperative equilibrium

Since firms are identical, we focus on symmetric Nash equilibria. Hence, $V_1 = V_2 = V$ and $u_1^* = u_2^* = u^*$. The following proposition establishes the existence of a unique symmetric Nash equilibrium.

PROPOSITION 1. *There exists a unique symmetric Nash equilibrium with* $0 < V < \overline{P}$ *characterized by*

$$0 = \lambda u^*(\overline{P} + \underline{P}) - \frac{1}{\eta}(u^*)^\eta - (r + 2\lambda u^*)V, \tag{1}$$

where

$$u^* = \left(\lambda(\overline{P} - V)\right)^{\frac{1}{\eta - 1}}. \tag{2}$$

There is a slight difference between our model and the one analyzed by Reinganum (1981, 1982). In her model, equilibrium strategies depend on time for two reasons. First, there is an exogenously given terminal date at which all competition ceases. Second, the costs of knowledge acquisition are discounted over time whereas the benefits accruing from innovation are not. Proposition 1 shows that if Reinganum's (1981, 1982) model is modified by discounting the benefits as well as the costs and if it is given an infinite horizon to eliminate end effects, then firms do not alter their R&D efforts over time (similar to Lee and Wilde's, 1980 model). Eliminating this somewhat artificial time dependency simplifies the characterization of the equilibrium and, in effect, enables us to obtain novel insights into the welfare properties of R&D races.

4. Collusive outcome

We study the welfare implications of our R&D race model by comparing the outcome of the noncooperative game to the collusive solution. The colluding firms strive to maximize the expected value W of making the discovery and receiving $Q = \overline{P} + \underline{P}$, which is implicitly given by

$$rW = \max_{u_1 \geqslant 0, u_2 \geqslant 0} (h_1 + h_2)(Q - W) - c(u_1) - c(u_2).$$

Carrying out the indicated maximization yields

$$u_1^{**} = u_2^{**} = u^{**} = \big(\lambda(Q - W)\big)^{\frac{1}{\eta - 1}}.$$

As in the case of the noncooperative game, we establish the existence of a unique solution.

PROPOSITION 2. *There exists a unique solution with* $0 < W < Q$ *characterized by*

$$0 = 2\lambda u^{**} Q - \frac{2}{\eta}(u^{**})^{\eta} - (r + 2\lambda u^{**})W, \tag{3}$$

where

$$u^{**} = \big(\lambda(Q - W)\big)^{\frac{1}{\eta - 1}}. \tag{4}$$

The collusive solution is a special case of the planner's solution in which a planning authority strives to maximize the benefits of the innovation to society. The difference is that in the planner's solution the social benefits Q need not be equal to the private benefits $\overline{P} + \underline{P}$.

It has long been argued that, from society's point of view, $Q > \overline{P} + \underline{P}$ for several reasons. First, an important part of the value of an innovation are the benefits accruing to consumers. Second, R&D generates knowledge. This knowledge is valuable to the extent that it leads to spillovers across time or firms. For example, a firm's current R&D efforts may help it in making other discoveries in the future, or they may benefit firms in other industries that are engaged in similar R&D projects. Both consumer surplus and spillovers are neglected in $\overline{P} + \underline{P}$. Indeed, based on case studies of 17 industrial innovations, Mansfield et al. (1977) estimate a median social rate of return of 56% compared to a median private rate of return of 25%.

More recent evidence suggests that patent races reflect excessive patenting from a social perspective. In particular, the building of patent fences around some core innovation and the amassing of large patent portfolios are indicative of socially wasteful investment in R&D. Patent fences may not only preclude innovations that substitute for the core innovation but also innovations that improve upon it (see Scotchmer, 1991, for evidence and Scotchmer, 1996, and Denicolo, 2000, for models along this line). Similarly, the amassing of large patent portfolios may impede entry into the industry and the spur to innovative activity that usually accompanies it (Cohen et al., 2000). This suggests that $Q < \overline{P} + \underline{P}$.

In the next section, we focus on the special case where social and private benefits are equal ($Q = \overline{P} + \underline{P}$), and study the welfare implications of our R&D race model. In Section 6 we turn to the general case ($Q \neq \overline{P} + \underline{P}$).

5. Rent dissipation

If firms behave noncooperatively, then there is in general a misallocation of resources. In particular, since the colluding firms maximize the sum of the individual payoffs and are free to replicate the noncooperative outcome, the value of the race to the colluding firms must be at least as big as the combined value of the race to firms 1 and 2, i.e., $2V \leqslant W$. The reason for this rent dissipation, however, depends critically on the degree of patent protection.

To illustrate this, we provide two numerical examples. Our first example illustrates a winner-take-all situation in which the winning firm is awarded a patent of positive value whereas the losing firm receives nothing, $\overline{P} = 0.23$ and $\underline{P} = 0$. The remaining parameter values are $\lambda = 1$, $r = 0.05$, and $\eta = 2$. This ensures that the expected duration of the race is three years. Using Propositions 1 and 2 we obtain $2V = 0.1282 < 0.1455 = W$. The reason for this rent dissipation is that $u^* = 0.1667 > 0.0853 = u^{**}$, i.e., each firm invests excessively in R&D. Since the two firms compete for the same discovery, each additional dollar invested in R&D brings a firm closer to winning the race and, at the same time, brings its rival closer to losing the race. Hence, its R&D efforts impose a *negative externality* on its rival, and the firm consequently invests excessively in R&D.

Our second example illustrates the polar case in which the loser can costlessly and immediately imitate the winner and thus both firms receive the same payoff, $\overline{P} = \underline{P} = 0.23$. There is again rent dissipation ($2V = 0.3163 < 0.3326 = W$), but the reason is now that firms invest too little in R&D: $u^* = 0.0726 < 0.1290 = u^{**}$. In contrast to a winner-take-all situation, each additional dollar invested in R&D brings both firms closer to the finish line. Hence, a firm's R&D efforts impose a *positive externality* on its rivals, which causes the firm to underinvest in R&D.

To clarify the distinction between the two scenarios, let u^* denote firm 1's equilibrium strategy and let u denote an arbitrary strategy for firm 2. Then Equations (1) and (2) can be rewritten as

$$0 = \lambda u^* \overline{P} + \lambda u \underline{P} - \frac{1}{\eta}(u^*)^\eta - (r + \lambda u^* + \lambda u)V,$$

$$0 = \lambda(\overline{P} - V) - (u^*)^{\eta-1}.$$

Total differentiation yields

$$\frac{dV}{du} = \frac{\lambda(\underline{P} - V)}{r + \lambda u^* + \lambda u},$$

$$\frac{du^*}{du} = \frac{-\lambda^2(\underline{P} - V)}{(\eta - 1)(u^*)^{\eta-2}(r + \lambda u^* + \lambda u)}.$$

Hence, $\underline{P} < V$ if and only if $\frac{dV}{du} < 0$ if and only if $\frac{du^*}{du} > 0$. That is, if $\underline{P} < V$, then reaction functions are upward sloping and firms' R&D efforts are strategic complements. On the other hand, if $\underline{P} > V$, then reaction functions are downward sloping and firms' R&D efforts are strategic substitutes. It follows that a firm's R&D efforts impose a negative externality on its rival whenever $\underline{P} < V$ and a positive externality whenever $\underline{P} > V$. In other words, depending on whether or not the benefit to imitation $\underline{P}$ is less than the value of continued play V, the character of the R&D race changes from a *preemption game* into a *waiting game*. If patent protection is perfect and thus $\underline{P} = 0$, then the R&D race always has the character of a preemption game, whereas if imitation is costless and immediate and thus $\underline{P} = \overline{P}$, then the R&D race always has the character of a waiting game. Finally, if $0 < \underline{P} < \overline{P}$, then the preemption as well as the waiting incentive is operative.

The following proposition formally shows that there is indeed overinvestment (underinvestment) in R&D if and only if a firm's R&D efforts impose a negative externality (positive externality) on its rival.

PROPOSITION 3. *Let $Q = \overline{P} + \underline{P}$. Then $u^* \gtrless u^{**}$ if and only if $V \gtrless \underline{P}$.*

It follows that $\underline{P} = 0$ ($\underline{P} = \overline{P}$) implies $u^* > u^{**}$ ($u^* < u^{**}$). Hence, a sufficient condition for overinvestment (underinvestment) is that patent protection is perfect (imitation is costless and immediate).

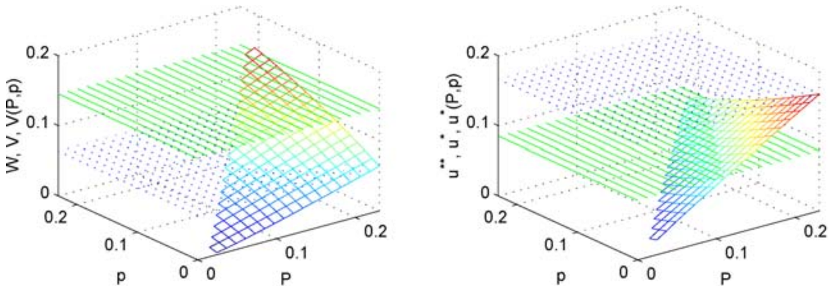
6. Policy implications

In this section, we study the policy implications of our R&D race model. Proposition 4 shows that a planning authority can always redistribute (part of) the social benefits of an innovation Q to replicate the planner's solution. That is, the planning authority can always choose rewards $\overline{P}$ and $\underline{P}$ with $\overline{P} + \underline{P} < Q$ that elicit the optimal R&D effort. Note that while we think of $\overline{P}$ and $\underline{P}$ as being implicitly determined by the patent system, choosing rewards is clearly tantamount to assigning property rights (as analyzed in Mortensen, 1982). To emphasize the dependence of the value and policy functions on the offered rewards, we write $V(\overline{P}, \underline{P})$ and $u^*(\overline{P}, \underline{P})$ in what follows.

PROPOSITION 4. *Given Q there exist $\overline{P}$ and $\underline{P}$ with $\overline{P} + \underline{P} < Q$ such that $u^*(\overline{P}, \underline{P}) = u^{**}$.*

In the remainder of this section, we provide a numerical example to show that there is in general more than one combination of $\overline{P}$ and $\underline{P}$ that leads to the optimal R&D effort. This enables the social planner to influence the firms' valuation of participating in the R&D race. We set $Q = 0.23$ and, for purposes

Figure 1. Replicating the planner's solution.



W and u^{**} refer to the planner's solution (dashed line), V and u^* to the noncooperative game in the absence of a social planner (dotted line). $V(P, p)$ and $u^*(P, p)$ are as defined in the text with $P = \overline{P}$ and $p = \underline{P}$ (solid line).

of comparison, $\overline{P} = Q$ and $\underline{P} = 0$. By Proposition 3 this leads to overinvestment in R&D. As the right panel of Figure 1 shows we can achieve $u^*(\overline{P}, \underline{P}) = u^{**}$ for any $\overline{P}$ and $\underline{P}$ such that $\overline{P} = 0.1122 + 0.6304\underline{P}$. As the left panel shows $V(\overline{P}, \underline{P})$ ranges from 0.0269 at (0.1122, 0) over 0.0727 at (0.1580, 0.0727) to 0.1455 at (0.23, 0.1881). Consequently, the social planner is free to choose the rewards to make firms either worse or better off than in the absence of a planning authority ($V = 0.0641$).

7. *Conclusions*

The literature on R&D races suggests that noncolluding firms invest excessively in R&D. We show that this result depends critically on the winner-take-all assumption. Once the winner-take-all assumption is relaxed, it no longer can be ascertained that noncolluding firms always invest excessively in R&D. On the contrary, firms sometimes invest too little in R&D. We show that although rents continue to be dissipated because firms in general fail to provide the optimal R&D effort, the mechanisms behind this rent dissipation change with the degree of patent protection: As patent protection becomes less effective, the character of the R&D race changes from a preemption game with overinvestment into a waiting game with underinvestment in R&D.

Our results allow us to illustrate how the patent system can be used to elicit the optimal R&D effort. Starting from perfect patent protection in which the winner-take-all assumption is warranted, the misallocation of resources in the noncooperative game can be reduced by reducing the asymmetry in the rewards to winning and losing the R&D race. One way to accomplish this is to partially insure the participating firms against losing the R&D race, e.g., by making patent protection less than perfect. Another way is to "throw money" at all participating firms. In either case reducing the asymmetry in the rewards reduces the negative externality stemming from firms' R&D efforts. This in turn moves the R&D race away from a preemption game and overinvestment towards a waiting game and underinvestment in R&D.

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Appendix

PROOF OF PROPOSITION 1. Equations (1) and (2) follow from symmetry. Substitute Equation (2) into (1) to define

$$\Delta(V) = \big(\lambda(\overline{P} - V)\big)^{\frac{\eta}{\eta-1}}\left(1 - \frac{1}{\eta}\right) + \lambda\big(\lambda(\overline{P} - V)\big)^{\frac{1}{\eta-1}}(\underline{P} - V) - rV.$$

At $V = \overline{P}$, we have

$$\Delta(\overline{P}) = -r\overline{P} < 0.$$

At $V = 0$, we have

$$\Delta(0) = (\lambda\overline{P})^{\frac{\eta}{\eta-1}}\left(1 - \frac{1}{\eta}\right) + \lambda(\lambda\overline{P})^{\frac{1}{\eta-1}}\underline{P} > 0$$

since $\eta > 1$. Since $\Delta(V)$ is continuous in V, there exists a solution to $\Delta(V) = 0$ by the intermediate value theorem.

It remains to establish uniqueness of the solution. We have

$$\Delta'(V) = -2\lambda\big(\lambda(\overline{P} - V)\big)^{\frac{1}{\eta-1}} - \frac{\lambda^2}{\eta - 1}\big(\lambda(\overline{P} - V)\big)^{\frac{2-\eta}{\eta-1}}(\underline{P} - V) - r,$$

$$\Delta''(V) = \frac{3\lambda^2}{\eta - 1}\big(\lambda(\overline{P} - V)\big)^{\frac{2-\eta}{\eta-1}} + \frac{\lambda^3(2-\eta)}{(\eta-1)^2}\big(\lambda(\overline{P} - V)\big)^{\frac{3-2\eta}{\eta-1}}(\underline{P} - V).$$

Rearranging yields

$$\Delta''(V) = \frac{\lambda^2}{\eta - 1}\big(\lambda(\overline{P} - V)\big)^{\frac{2-\eta}{\eta-1}}\left(3 + \frac{2-\eta}{\eta-1}\frac{\underline{P} - V}{\overline{P} - V}\right).$$

Note that the term in parenthesis governs the sign of $\Delta''(V)$. Differentiating it yields

$$-\frac{2-\eta}{\eta-1}\frac{\overline{P} - \underline{P}}{(\overline{P} - V)^2},$$

which is nonnegative if $\eta \geqslant 2$ and nonpositive if $1 < \eta < 2$. Consider the case of $\eta \geqslant 2$ first. Then the term in parenthesis is nondecreasing in V and achieves its minimum of

$$3 + \frac{2-\eta}{\eta-1}\frac{\underline{P}}{\overline{P}} \geqslant 2$$

at $V = 0$, where the last inequality uses the facts that $0 \leqslant \frac{\underline{P}}{\overline{P}} \leqslant 1$ and $-1 \leqslant \frac{2-\eta}{\eta-1} \leqslant 0$ whenever $\eta \geqslant 2$. Hence, $\Delta''(V) \geqslant 0$ and the claim follows. Consider the case of $1 < \eta < 2$ next. Then the term in parenthesis is nonincreasing in V, achieves its maximum of

$$3 + \frac{2-\eta}{\eta-1}\frac{\underline{P}}{\overline{P}} \geqslant 3$$

at $V = 0$, and approaches $-\infty$ as V approaches $\overline{P}$. By continuity it follows that $\Delta''(V) \geqslant 0$ around $V = 0$ and $\Delta''(V) \leqslant 0$ around $V = \overline{P}$. Since the term in parenthesis changes sign at most once, so does $\Delta''(V)$, and the claim follows. □

PROOF OF PROPOSITION 2. Equations (3) and (4) follow from symmetry. Define

$$\Delta(W) = 2\big(\lambda(Q - W)\big)^{\frac{\eta}{\eta-1}}\left(1 - \frac{1}{\eta}\right) - rW.$$

At $W = Q$, we have

$$\Delta(Q) = -rQ < 0.$$

At $W = 0$, we have

$$\Delta(0) = 2(\lambda Q)^{\frac{\eta}{\eta-1}}\left(1 - \frac{1}{\eta}\right) > 0$$

since $\eta > 1$. Since $\Delta(W)$ is continuous in W, there exists a solution to $\Delta(W) = 0$ by the intermediate value theorem. Uniqueness of the solution follows from noting that $\Delta(W)$ is decreasing in W. □

PROOF OF PROPOSITION 3. We have $u^* = (\lambda(\overline{P} - V))^{\frac{1}{\eta-1}} \gtrless (\lambda(\overline{P} + \underline{P} - W))^{\frac{1}{\eta-1}} = u^{**}$ if and only if $W \gtrless V + \underline{P}$. From the proofs of Propositions 1 and 2, we know that the solution to the noncooperative game and to the planner's problem are characterized by the zeros of

$$\Delta^V(V) = \big(\lambda(\overline{P} - V)\big)^{\frac{\eta}{\eta-1}}\left(1 - \frac{1}{\eta}\right) + \lambda\big(\lambda(\overline{P} - V)\big)^{\frac{1}{\eta-1}}(\underline{P} - V) - rV$$

and

$$\Delta^W(W) = 2\big(\lambda\big((\overline{P} + \underline{P}) - W\big)\big)^{\frac{\eta}{\eta-1}}\left(1 - \frac{1}{\eta}\right) - rW,$$

respectively. Let V solve $\Delta^V(V) = 0$ and consider $W = V + \underline{P}$ as a candidate solution to $\Delta^W(W) = 0$. Rewriting yields

$$\Delta^W(V + \underline{P}) = 2\Delta^V(V) + \left(r + 2\lambda\left(\lambda(\overline{P} - V)\right)^{\frac{1}{\eta-1}}\right)(V - \underline{P}).$$

Since $\Delta^V(V) = 0$, $\Delta^W(V + \underline{P}) \gtrless 0$ if and only if $V \gtrless \underline{P}$. Since $\Delta^W(W)$ is decreasing, this implies that the actual solution to $\Delta^W(W) = 0$ satisfies $W \gtrless V + \underline{P}$ if and only if $V \gtrless \underline{P}$. □

Proof of Proposition 4. Set $\underline{P} = 0$. Hence, $0 \leqslant \overline{P} \leqslant Q$. We have $V(0, 0) = 0$ and $u^*(0, 0) = 0 \leqslant u^{**}$. Since the value of the race to the planner exceeds the combined value of the race to firms 1 and 2 whenever $Q = \overline{P} + \underline{P}$, we have $2V(Q, 0) \leqslant W$ which, in conjunction with $0 < V(Q, 0)$, gives $V(Q, 0) < W$. We therefore have $Q - V(Q, 0) > Q - W$ and $u^*(Q, 0) = (\lambda(Q - V(Q, 0)))^{\frac{1}{\eta-1}} > (\lambda(Q - W))^{\frac{1}{\eta-1}} = u^{**}$. Since $u^*(\overline{P}, 0)$ is continuous in $\overline{P}$, there exists a solution to $u^*(\overline{P}, 0) = u^{**}$ by the intermediate value theorem. □

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CHAPTER 2

Innovation, Duplication, and the Contract Theory of Patents

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Abstract

In this paper we look at patents as alternative to trade secrets. We disentangle the disclosure *motive for patent protection from the traditional* reward *motive by adjusting the level of patent protection so as to make the innovator just indifferent between patenting and keeping the innovation secret. Thus, we keep the reward (expected profits) to the innovator fixed and focus on* ex post *efficiency. When duplication is not feasible and secrecy only entails the risk of public disclosure (a leakage), patents and secrets are perfect substitutes. Yet, a distinctive features of trade secret protection is that it allows for independent creation. The duplicative efforts to reproduce a concealed innovation make patents and secrets imperfect substitutes. If such duplicative efforts are actually exerted under secrecy, patents provide the pre-specified incentive to innovate at least social cost. If, however, the threat of duplication induces the innovator to preemptively license her trade secret, and such licensing agreements allow the innovator to appropriate all the saved duplication costs, then secrets can reward innovative activity more efficiently than patents. Thus, the issue of whether patents are socially preferable to secrets boils down to an assessment of the prevalence and the efficiency of trade secret licensing. The available empirical evidence suggests that licensing of trade secret information is limited and so hints at the superiority of patents.*

1. Introduction

Various empirical studies have found that secrecy and lead time are more highly ranked than patents as a protection mechanism for both product and process innovations and have increased in importance over the last decade.[1] Analyzing the results of the 1994 Carnegie Mellon survey of over 1400 US R&D firms,

[1] See the surveys of US firms reported in Levin et al. (1987) and Cohen et al. (2000).

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Cohen et al. (2000) report that for process innovations, only 23% of all respondents consider patents as an effective appropriability mechanism as compared to 50% and 38% of respondents for secrecy and lead time, respectively. For product innovations, patents are considered relatively more effective (41%), but still less effective than either secrecy (51%) or lead time (50%).

These empirical findings suggest that firms may have a substantial incentive to innovate even in the absence of patent protection. However, this fact does not necessarily imply that letting firms rely on secrecy or lead time[2] is socially preferable to granting patents. Secrecy or lead time can only reward innovative activity to the extent that they allow innovators to price above marginal cost, temporarily at least; therefore, they entail deadweight losses similar in nature to those associated with patents. This means that society must inevitably bear a welfare loss to provide an incentive to innovate, and raises the question of whether such a loss is lower under patents or secrets.[3]

In this paper, we set up a simple analytical framework to address this question. In the model, an innovator must decide how to protect an innovation—by patenting or keeping it secret. We assume that the level of protection provided by secrecy depends on the probability of leakage and the risk of successful duplication by others and cannot be influenced by the policymaker. By way of contrast, the policymaker controls the level of protection provided by patents and adjusts it so as to make the innovator just indifferent between patenting and keeping the innovation secret. One interpretation is that the policymaker chooses the level of patent protection *ex post*, i.e., after the innovation is achieved. From such an *ex post* viewpoint, it would be pointless to provide more patent protection than is just necessary to induce the innovator to disclose and patent the innovation. A more general interpretation is that when the innovator is just indifferent between patenting (disclosing) and keeping the innovation secret, these two tools provide exactly the same incentive to innovate and so a comparison of the welfare losses tells us which form of protection is more efficient.

Three main results emerge. In the benchmark case in which innovators relying on secrecy face only the risk of inadvertent disclosure of the secret to the public, patents and secrets are perfect substitutes as a mean to reward innovators (Proposition 1). However, secrecy does not preclude independent creation by others, so invites investments to duplicate the innovation. The duplicative efforts to re-produce a concealed innovation make patents and secrets imperfect

[2] Lead time differs from secrecy in that innovative technical knowledge is not intentionally hidden by the inventor. However, the mechanism through which lead time protects the innovator is similar to secrecy, namely, the mere fact that the inventor practices her innovation does not disclose enough information to allow instant and costless replication by others.

[3] We focus on patents because typically the kind of innovative knowledge that is protected by copyrights cannot be kept secret, and thus only rarely are copyrights a feasible alternative to secrecy. (Software is one important exception, and is also peculiar since source-code secrecy complements copyright or patent protection rather than being a substitute for it.) In addition, copyrights are similar to secrets in that they do not prevent independent creators from marketing their works.

substitutes. If such duplicative efforts are actually exerted, patents provide the pre-specified incentive to innovate at the least social cost (Proposition 2). If, however, the threat of duplication induces the innovator to preemptively license her trade secret, and such licensing agreements allow the innovator to appropriate all the saved duplication costs, then secrets can reward innovative activity more efficiently than patents (Proposition 3). Thus, the issue of whether patents are socially preferable to secrets boils down to an assessment of the feasibility and the costs of trade secret licensing. What empirical evidence is available suggests that the licensing of trade secret information is limited and therefore hints at the superiority of patents.

The paper is organized as follows. Section 2 introduces the model and Section 3 describes the benchmark case where patents and secrets are perfect substitutes. Next, we consider duplication, either actual (Section 4) or threatened (Section 5). We assume that there is free entry of potential duplicators. In Section 4, duplication occurs until a zero-profit condition is satisfied. In Section 5, the innovator engages in preemptive licensing such that no duplication occurs. In Section 6 we discuss intermediate cases and we try to assess to what extent trade secret licensing occurs in practice. Section 7 offers some concluding remarks.

2. *The model*

To fix ideas, let us consider a product innovation.[4] Let the demand for the new product be given by $X(p)$, where p is price, X is output, and $X(.)$ is a strictly decreasing and differentiable function on $[0, \bar{p}]$ and is zero on $[\bar{p}, \infty)$. It follows that inverse demand, $p(X)$, is decreasing and differentiable on $[0, X(0)]$. Let the post-innovation marginal cost be constant at c.[5] We assume that either demand is finite at $p = c$, in which case we denote by X_c the competitive output, or $\lim_{X\to\infty} p(X) = c$.

The innovator must decide whether to patent the innovation or keep it secret. By patenting, the innovator reaps monopoly profits π_m[6] for the duration of the patent, T[7]; when the patent expires, the innovator's profits are driven to

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[4] A product innovation is equivalent to a drastic cost-reducing innovation. (An innovation is drastic if the innovator is unconstrained by outside competition and can therefore engage in monopoly pricing.) The analysis can be readily extended to the case of non-drastic innovation, as we shall show in footnotes. Our main results hold *a fortiori* with non-drastic innovations.

[5] The post-innovation equilibrium does not depend on the pre-innovation cost as long as the innovation is drastic. With non-drastic innovation, let c_0 be the pre-innovation cost. For the innovation to be non-drastic, it must be $c_0 < p_M(c)$, where $p_M(c)$ is the (finite) monopoly price associated with the new cost $c < c_0$.

[6] With non-drastic innovation, the innovator engages in limit pricing and so the innovator's profit is $(c_0 - c)X(c_0)$.

[7] We assume that it is impossible to imitate a patented innovation without infringing the patent. As a consequence, the strength of patent protection is fully captured by the patent's life. Explicit analysis of the breadth-length trade-off (see Denicolò, 1996, and the literature cited therein) would complicate matters and add little to the issues that we focus on in this paper.

zero. Alternatively, the innovator can rely on secrecy.[8] Here the risk is accidental disclosure (a "leak") or successful duplication by followers. We assume that leakage of the secret has the same effects as expiry of the patent, i.e., the innovation becomes public and profits are driven to zero. The random event of a leak occurs with an exogenous probability γ.[9] The innovator also loses her monopoly if the innovation is duplicated. Initially we assume that if the innovation is not patented there is free entry by duplicators, upon payment of a fixed duplication cost k. (Later we shall also consider alternative scenarios with a fixed number of potential duplicators.)

Let s denote the number of active firms, other than the original innovator. We denote by $\pi(s)$ the individual flow of profit with $s+1$ active firms (i.e., the original innovator and s duplicators); $\pi(0) \equiv \pi_m$ is the monopoly profit. For a variety of reasons, the social returns from the innovation typically exceed the private returns. In our simplified framework, the social returns include at least any gain that accrues to consumers before the patent expires. Such gains depend on equilibrium price and output, so they depend on the number of active firms. Let $S(s)$ and S_c denote the instantaneous social returns from the innovation with $s+1$ active firms and under perfect competition, respectively, and let $S_c - S(s) = D(s)$ denote the deadweight loss with $s+1$ active firms; $D(0) \equiv D_m$ is the monopoly deadweight loss. We assume that individual profits and the deadweight loss decrease with s: that is, treating the number of active firms as a continuous variable and assuming differentiability of the functions involved, $\pi'(s) < 0$ as long as $\pi(s) > 0$,[10] and $D'(s) < 0$. All future profits are discounted at the common discount rate r. It is convenient to define

"normalized" patent length: $z \equiv \left(1 - e^{-rT}\right)$.

z can be interpreted as a "discounting-adjusted" patent life; it equals the fraction of overall discounted monopoly profits, $\frac{\pi_m}{r}$, that accrue to the patentee. Because there is a one-to-one relationship between z and T, we can focus on z with no loss of generality. As T goes from 0 to ∞, z ranges from 0 to 1.

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[8] While patents and secrets are deemed equally legitimate under the law, in principle innovators cannot benefit from both. If they choose to patent, they have to disclose the innovation fully in the patent specification, so as to enable any person expert in the art to practice it. This prevents them from extending the monopoly beyond the term of the patent. Alternatively, if they decide to rely on secrecy, they forfeit the right to patent after a one-year grace period (not even this grace period is granted in Europe): this prevents inventors from keeping the innovation secret and applying for a patent only under the threat of impending duplication. These provisions of patent law justify our assumption that innovator can rely on either patents or secrets, but not both. However, if a complex innovation can be split into various complementary components, the innovator can try to patent some and keep the others secret. In the concluding section, we discuss this strategy more fully.

[9] In general, the probability of a leak depends both on the technical difficulty of concealing the innovation and the strength of trade secret protection, so it can be a matter of policy. However, it is taken as exogenous in our analysis.

[10] When $\pi(s) = 0$ it must obviously be $\pi'(s) = 0$.

Summarizing, the timing of events is as follows. First, the innovator decides whether or not to patent. Second, if the innovator has not patented, uncertainty concerning leakage is resolved. If the innovation is kept secret by the inventor, and the secret does not leak out, duplicators decide whether or not to enter the market. Finally, profits are realized. All parameter values and actions are common knowledge.

3. *Benchmark: no duplication*

In this section we develop a useful benchmark by assuming that the duplication cost k is infinite, so that there can be no duplication. In this simplified framework, we compare the welfare loss associated with patents and secrecy, assuming that the level of patent protection is adjusted so as to make the innovator just indifferent between patenting and keeping the innovation secret.

To begin with, let us consider the innovator's problem. The innovator, who already owns the innovation, must decide whether or not to patent. If the innovator patents, she earns monopoly profits until the patent expires; therefore, her payoff is:

$$\int_0^T e^{-rt}\pi_m\,dt = z\frac{\pi_m}{r}.$$

If the innovator does not patent, her payoff is $(1-\gamma)\frac{\pi_m}{r}$: the discounted value of a constant flow of a monopoly profit, multiplied by the probability that the secret does not leak out. Clearly, the innovator patents if and only if $z \geqslant (1-\gamma)$.[11]

Next consider social welfare. As compared to the first best solution, in which the market is perfectly competitive and there are no deadweight losses, the welfare loss society bears if the innovator chooses to patent is

$$L_{\text{patents}} = \int_0^T D_m e^{-rt}\,dt = z\frac{D_m}{r}$$

i.e., the present value of the monopoly deadweight loss for the duration of the patent. If instead the innovation is kept secret, society bears the monopoly deadweight loss forever, conditional on the secret not leaking out. Therefore, the expected welfare loss is

$$L_{\text{secrets}} = (1-\gamma)\frac{D_m}{r}.$$

Ex post, it would be pointless to provide more patent protection than is just necessary to induce the innovator to patent, so a benevolent policymaker would set $z = (1-\gamma)$. More generally, comparing the welfare losses at $z = (1-\gamma)$

[11] To fix ideas, we assume that the innovator patents when she is indifferent between patenting and not, but our results are independent of this tie-breaking rule.

allows us to determine which instrument, patents or secrets, provides the pre-specified incentive to innovate more efficiently. Inspection of the formulas for L_{patents} and L_{secrets} reveals that

PROPOSITION 1. *If patent length is just long enough as to induce the innovator to patent, in the absence of duplication the welfare loss under patents equals the welfare loss under secrecy.*[12]

This equivalence result brings us to a popular critique of the so-called *contract* (or *exchange*) *theory of patents*. The contract theory maintains that patents do not serve to reward innovative activity. Rather, they can be viewed as a "contract" between innovators and society whereby a temporary property right is granted in exchange for disclosure. This legal theory has a long tradition and is still respected by the courts, but is discredited among economists. Stressing the well known *one-size-fits-all* problem, critics of the contract theory argue that the patent system will inevitably over-reward certain innovations. Thus, an equivalence result like Proposition 1 implies that secrets are better than patents after all. As pointed out long ago by a vocal opponent of the patent system, Oxford economist J.E.T. Rogers (1863),[13]

> ...the bargain of the inventor with the public, is thoroughly one-sided. If it be his interest to keep his secret, he infallibly does so, not so much from the cause that a patent is expensive, as because it is his interest. [...] It is perfectly true, indeed it is insisted on by the advocates of the rights of invention, that nothing can compel him to disclose his discovery. Does he ever do so except on the ground that the profits of the monopoly would be more valuable than the profits of the secret? (Rogers, 1863, p. 127)

In a similar vein, more recently Boldrin and Levine (2004, p. 129) note that

> Granting a legal monopoly in exchange for revealing the "secret" of the innovation is one, apparently clean, way to make innovations more widely available in the long run. However, this argument has not been subject to much scrutiny by economists, and indeed, in the simplest case it fails. Suppose that each innovation can be kept secret for some period of time, with the actual length varying from innovation to innovation, and that the length of legal patent protection is 20 years. Then the innovator will choose secrecy in those cases where it is possible to keep the secret for longer than 20 years, and choose patent protection in those cases where the secret can be kept only for less than 20 years. In this case, patent protection has a socially damaging effect. Secrets that can be kept for more than 20 years are still kept for the maximum length of time, while those that without patent would have been kept for a shorter time, are now maintained for at least 20 years.

This argument is based upon the result that the welfare loss associated with the *marginal innovation* (i.e., an innovation for which the innovator is just indifferent between patenting and not) is independent of the mode of protection, i.e.,

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[12] With non-drastic innovation, π_m must be replaced by $(c_0 - c)X(c_0)$ and the deadweight loss associated with the equilibrium price $p = c_0$ is $\int_{X(c_0)}^{X(c)} [p(\varphi) - c]\, d\varphi$. The comparison of patents and secrets, however, is unaffected by these changes since they impact both cases symmetrically.

[13] See Machlup and Penrose (1950) for an account of the patent debate in the XIX century.

Proposition 1. In the remainder of the chapter we shall show that the possibility that others duplicate the original innovation alters the comparison between patents and secrets, making patents and secrets imperfect substitutes for society when they are equally good for innovators. In other words, when duplication is possible, it is no longer a matter of indifference for society whether marginal innovations are protected by patents or by secrets. If for marginal innovations secrets dominate patents, the case against the contract theory is reinforced. But if society prefers that marginal innovations are protected by patents, the contract theory is vindicated.

4. Duplication with no licensing

In this section we analyze the effects of duplicative activity conducted with the goal of re-producing a concealed innovation. Such duplicative activity has two direct effects on social welfare. On the negative side, the duplicative efforts exerted for the independent rediscovery of the innovation are socially wasteful. On the positive side, competition by successful duplicators lowers the equilibrium price and hence reduces the static deadweight loss. In general it is hard to tell which effect dominates.

However, competition by duplicators also lowers the profitability of secrecy. This means that when duplication is possible, patent protection becomes relatively more attractive, enhancing the innovator's propensity to patent. For marginal innovations, the possibility of duplication has therefore a third, indirect effect; namely, a shorter patent life now suffices to make the innovator just indifferent between patenting and not. Keeping this indirect effect into account, in this section we show that under a weak condition, the overall effect of duplication is that patents are better than secrets for marginal innovations. More precisely, adapting Gallini's (1992) analysis of optimal patent breadth, we prove that the existence of a business stealing effect makes patents better than secrets.

To proceed, assume that the duplication cost k is finite and small enough that some duplication occurs at equilibrium: $k < (1-\gamma)\frac{\pi_d}{r}$, where $\pi_d \equiv \pi(1)$ is duopoly profit. With free entry of duplicators, the equilibrium number of entrants, s^*, is the largest integer s such that $\frac{\pi(s)}{r} \geqslant k$. Treating s as a continuous variable, the free entry condition then becomes

$$\frac{\pi(s)}{r} = k, \tag{1}$$

which determines s^* uniquely.

The innovator's expected profit, in case she relies on secrecy, is now

$$(1-\gamma)\frac{\pi(s^*)}{r} = (1-\gamma)k$$

because with probability γ the secret leaks out and the innovator gets nothing, and with the complementary probability $(1-\gamma)$ the secret does not leak out but s^* duplicators enter the market. Consequently, the innovator will prefer to patent if and only if

$$z \geqslant (1-\gamma)\frac{rk}{\pi_m}.$$

Assuming again that this condition holds as an equality, the welfare loss under patents is

$$L_{\text{patents}} = (1-\gamma)k\frac{D_m}{\pi_m}. \tag{2}$$

Our goal is to compare L_{patents} with L_{secrets}. The latter now comprises the expected deadweight loss and duplication costs and is therefore given by:

$$L_{\text{secrets}} = (1-\gamma)\left[\frac{D(s)}{r} + sk\right]. \tag{3}$$

PROPOSITION 2. *If a business stealing effect is present, so that individual output falls as the number of active firms increases, and the patent life is just long enough as to induce the innovator to patent, patents are better than secrecy.*

PROOF. We adapt an argument made by Gallini (1992) in her analysis of optimal patent breadth. Comparing (2) and (3) we have that $L_{\text{patents}} \leqslant L_{\text{secrets}}$ if and only if

$$k\frac{D_m}{\pi_m} \leqslant \frac{D(s)}{r} + sk.$$

Using (1), this condition reduces to

$$\frac{D_m}{\pi_m} \leqslant \frac{D(s)}{\pi(s)} + s. \tag{4}$$

To prove that (4) holds, define $H(s) \equiv \frac{D(s)}{\pi(s)} + s$ and note that the left-hand side of (4) is $H(0)$. Therefore, it suffices to show that $H'(s) \geqslant 0$. Noting that $\pi(s) = (p-c)\frac{X}{s+1}$ and $D'(s) = -(p-c)X'(s)$, differentiating and rearranging terms we get

$$H'(s) = \frac{(p-c)^2\frac{X}{s+1}[\frac{X(s)}{s+1} - X'(s)] - D(s)\pi'(s)}{[\pi(s)]^2}. \tag{5}$$

But the business stealing effect means that an increase in the number of firms reduces individual output. This requires that

$$\frac{d}{ds}\left[\frac{X(s)}{s+1}\right] = \frac{(s+1)X'(s) - X(s)}{(s+1)^2} < 0$$

implying that the term inside square brackets in (5) is positive. It follows that $H'(s) > 0$.[14] □

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[14] With non-drastic innovation, the left-hand side of (4) should be replaced by $D(s_0)/\pi(s_0)$, where s_0 is the number of duplicators that makes the equilibrium price equal to c_0. Clearly, the fact that

The condition that an increase in the number of firms reduces individual output is met under weak regularity conditions in a large class of oligopoly models, including the Cournot model. Note also that this result continues to hold when some duplication takes place under the patent regime (e.g., by inventing around the patent), provided that the number of duplicators is lower with patents than under secrecy.

Next, we argue that Proposition 2 vindicates the contract theory of patents. The optimal patent life, that is to say, is positive even *ex post*, when the need of providing incentives to conduct innovative activity is no longer at issue, and even if the one-size-fits-all problem is taken into account. To see this, assume that the probability of leakage varies across innovations, as in Rogers' and Boldrin and Levine's arguments. Such heterogeneity means that patents entail an extra cost, as they cannot be tailored to each individual innovation; as a consequence, some infra-marginal innovations will inevitably end up being over-protected. An increase in the patent life has now two effects on social welfare: the positive effect is that it induces disclosure of marginal innovations, which is now socially desirable; the negative effect is that it increases the deadweight loss associated with infra-marginal innovations that would have been disclosed anyway. But with a zero patent life nobody patents, so there are no infra-marginal innovations. Thus, at $z = 0$ only the positive effect is at work which means that the optimal patent life is necessarily positive.[15]

5. *Preemptive licensing*

The results of the previous section are based upon the assumption that the innovator does not license her know-how to potential duplicators. However, if the innovator anticipates entry by duplicators, she has an incentive to engage in preemptive licensing. It is open to debate whether the licensing of trade secret information is feasible or not, and whether or not the licensor can net a sizeable share of saved duplication costs. However, deferring the discussion on these issues until Section 6, we now contrast the no-licensing case developed in Section 4 with the polar case in which the innovator can license trade secret information maintaining full control over it and can extract all the bargaining surplus in the licensing agreement.[16]

Specifically, we adapt the analysis of patent licensing developed by Maurer and Scotchmer (2002) and Cugno and Ottoz (2004) to the case of trade secret licensing. The innovator preemptively licenses potential duplicators in such a way that no duplication actually occurs in equilibrium; in other words, she issues a

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$s_0 > 0$ and $H'(s) \geqslant 0$ imply that patents are better than secrecy also for non-drastic marginal innovations.

15 See Denicolò and Franzoni (2003) for details.

16 See Cugno and Ottoz (2006) for a similar analysis.

number of licenses large enough that no potential duplicator has any further incentive to duplicate the innovation. If the innovator has all the bargaining power in the licensing agreement, she will then be able to appropriate all the saved duplication costs.

With free-entry of duplicators, the equilibrium number of firms will still be given by (1), but now the innovator's profit under secrecy is

$$(1-\gamma)\left[\frac{\pi(s^*)}{r}+s^*k\right]=(1-\gamma)(s^*+1)\frac{\pi(s^*)}{r}$$

because she can appropriate all the saved duplication costs by charging a fixed licensing fee equal to the duplication cost (minus an arbitrarily small amount). Consequently, the innovator will now prefer to patent if and only if

$$z\geqslant(1-\gamma)\frac{(s^*+1)\pi(s^*)}{\pi_m}.$$

Assuming once again that this condition holds as an equality, the welfare loss under patents is

$$L_{\text{patents}}=(1-\gamma)\frac{(s^*+1)\pi(s^*)}{\pi_m}\frac{D_m}{r}.$$

The welfare loss under secrecy no longer comprises duplication costs and is therefore given by:

$$L_{\text{secrets}}=(1-\gamma)\frac{D(s)}{r}.$$

The comparison of secrets and patents then depends on whether the ratio of deadweight losses to industry profits under monopoly, $\frac{D_m}{\pi_m}$, is greater or lower than under oligopoly, $\frac{D(s)}{(s^*+1)\pi(s^*)}$. More precisely, secrets are better than patents if

$$\frac{D(s)}{(s^*+1)\pi(s^*)}<\frac{D_m}{\pi_m}. \tag{6}$$

Thus,

PROPOSITION 3. *Under licensing and full surplus extraction, secrets are socially preferable to patents if the deadweight loss to industry profits ratio under oligopoly is greater than under monopoly.*

Various authors have found sufficient conditions for inequality (6) to hold. In general, inequality (6) will hold for any value of s^* (and hence of k) if and only if the ratio of deadweight loss to industry profits

$$\frac{D(X)}{\Pi(X)}=\frac{\int_X^{X(c)}[p(\chi)-c]\,d\chi}{[p(X)-c]X}$$

where $X(c)$ is competitive output, decreases with X. It has been shown that the ratio $\frac{D(X)}{\Pi(X)}$ decreases with X if the demand function is linear or isoelastic

(La Manna et al., 1989), or, more generally, with decreasing marginal revenue or when the elasticity of demand decreases with X (Gilbert and Shapiro, 1990).

The next proposition generalizes these sufficient conditions.

PROPOSITION 4. *The ratio of deadweight loss to industry profits,* $\frac{D(X)}{\Pi(X)}$, *monotonically decreases (respectively, increases) with* X *in the interval* $X_m \leqslant X \leqslant X_c$ *if the price-cost margin* $p-c$ *is a log-concave (respectively, log-convex) function of the log of total output.*

PROOF. Let

$$\log(p-c) \equiv f(\log X)$$

and consider any point X_0 with $X_m \leqslant X_0 \leqslant X_c$. Take a Taylor expansion of $f(.)$

$$\log(p-c) = f(\log X_0) - \beta(\log X - \log X_0) + R_2(\log X)$$

where $\beta \equiv -f'(\log X_0)$. The remainder term $R_2(\log X)$ is the integral

$$R_2(\log X) = \int_{\log X_0}^{\log X} f''(t)(\log X - t)\, dt$$

and thus is negative (respectively, positive) if $f(.)$ is concave (respectively, convex). The linear approximation of f near X_0 can be rewritten as

$$p(X) = \Theta X^{-\beta} + c,$$

where Θ is a positive constant. Direct calculation shows that along the linear approximation the ratio $\frac{D(X)}{\Pi(X)}$ is:

$$\frac{\int_X^{X_c}[\Theta\chi^{-\beta} + c - c]\, d\chi}{[\Theta X^{-\beta} + c - c]X} = \frac{\int_X^{\infty} \Theta\chi^{-\beta}\, d\chi}{\Theta X^{-\beta+1}} = \frac{1}{\beta - 1},$$

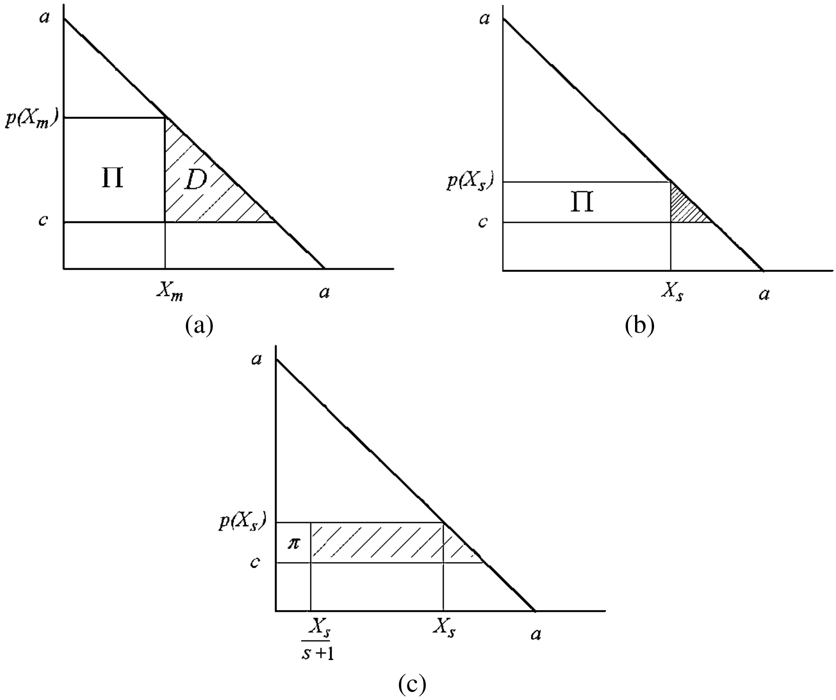
and thus is constant. (Note that $\beta > 1$ when $X > X_m$.)

Next note that at point X_0, $\Pi(X)$, $\Pi'(X)$ and $D'(X)$ are the same as along the linear approximation. However, if $f(.)$ is concave (respectively, convex), $D(X)$ is smaller (respectively, greater) than it would be along the linear approximation. Because the ratio $\frac{D(X)}{\Pi(X)}$ would be constant along the linear approximation, it follows that in a neighborhood of X_0 the ratio increases (respectively, decreases) with X if $f(.)$ is concave (respectively, convex). Because this is true for all X_0 with $X_m \leqslant X_0 \leqslant X_c$, the result follows. □

The assumption that the price-cost margin $p - c$ is a log-concave function of the log of total output is equivalent to Shapiro's (2006) condition that the product of the elasticity of demand and the Lerner index

$$\varepsilon(p)\frac{p-c}{p} = X'(p)\frac{p-c}{X(p)}$$

Figure 1.



rises with p.[17] It can be easily checked that this condition is implied by the stronger conditions that marginal revenue decreases with output or that the elasticity of demand increases with price.

To get a feeling for why seemingly contradictory Propositions 2 and 3 can simultaneously hold true, note that Proposition 3 deals with the ratio of deadweight loss to *industry* profits, whereas Proposition 2 deals with the ratio of deadweight loss *plus duplication costs* to *individual* profits. Figure 1 provides a geometric illustration.

Panel *a* displays monopoly profits (Π) and the monopoly deadweight losses (D). The ratio between these two areas is the relevant benchmark. Panel *b* displays industry profits and the associated deadweight loss when licensing drives the equilibrium price below the monopoly price, but the innovator captures all of the rents and no duplication costs are actually borne. Panel *c* displays the innovator's profits (π) and the sum of deadweight losses and duplication costs (the shaded area) in the presence of duplication. With duplication, price is lower than under monopoly, but the innovator's profit is only a fraction of the ensuing rents; the remaining fraction is dissipated in the duplication process.

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[17] Shapiro (2006) acknowledges that the condition was developed in joint work with Joseph Farrell.

6. *Beyond polar cases*

In this section we compare patents and secrets in between the two extremes of no licensing and efficient preemptive licensing. Instead of modeling the transaction costs entailed by licensing explicitly, we propose a simple reduced-form analysis that encompasses the models developed in Sections 4 and 5 as special cases. Our goal is to get a better understanding of how prevalent and how efficient should trade secret licensing be in order for secrets to be better than patents.

Specifically, the market equilibrium arising when the innovator relies on trade secret protection is described as follows: For any given output X with associated equilibrium price $p(X)$, we posit that potential profits $(p-c)X$ can be divided into three parts: the innovator captures a fraction α of potential rents $(p-c)X$; a fraction γ of these rents is dissipated in duplication or transaction costs; and the remaining fraction $1-\alpha-\gamma$ is reaped by other firms. The two polar cases examined so far correspond to $\gamma=1$ (free entry of duplicators with no licensing) and $\alpha=1$ (preemptive licensing), respectively. The case in which α and γ do not add up to one may arise when potential duplicators are finite in number,[18] and either licensing occurs but duplicators have some bargaining power, or (in the absence of licensing) duplicators obtain a positive profit and potential rents are not entirely dissipated in duplication costs.

Proceeding as above, the comparison of patents and secrets depends on the comparison of the ratio of overall deadweight losses to the innovator profit. With secrecy, the innovator's profit is now a fraction α of industry profits $(p-c)X$, and the deadweight losses now include also duplication or transaction costs. Consequently, patents are better than secrets if and only if

$$\frac{D(X)+\gamma(p-c)X}{\alpha(p-c)X} > \frac{D_m}{\pi_m}. \tag{7}$$

To get more insight into condition (7), let us consider the case of linear demand $p=a-X$ and set

$$X \equiv \frac{a-c}{1+\kappa}$$

[18] One reason why entry by duplicators may be restricted is that successful duplicators can be eligible to patent protection. Which forms of protection can a successful duplicator adopt if the first inventor opts for secrecy is, indeed, a matter of policy. Notable differences are observable from nation to nation and over time. For instance, under the British 1956 Patent Act second inventors were not entitled to valid patents, but currently second inventors can patent in most European countries and the US. Differences persist, however, regarding whether the first inventor is allowed to continue to practice an innovation patented by others. In Europe, being first inventor is a defense against infringement (in the legal jargon, first inventors are granted *prior user rights*). In the US, by contrast, second inventors can exclude anybody else, including first inventors, from the innovation. See Denicolò and Franzoni (2004), Bulut and Moschini (2006) and Shapiro (2006) for further discussion and analysis of prior user rights.

so that κ is an index of monopoly power that ranges from $\kappa = 0$ (perfect competition) to $\kappa = 1$ (monopoly). Then, condition (7) becomes

$$\kappa + 2\gamma > \alpha. \tag{8}$$

It is clear that inequality (8) never holds for $\gamma = 0$ and $\alpha = 1$ (the efficient licensing, full-bargaining-power case). In contrast, it always hold when $\gamma = \frac{s}{s+1}$ and $\alpha = \frac{1}{s+1}$ (the case of no-licensing with free entry of duplicators), provided that $s \geqslant 1$. It also necessarily holds when κ is close to 1, i.e., when successful duplicators tend to collude with the innovator.

With Cournot competition, κ equals the inverse of the number of active firms: $\kappa = \frac{1}{s+1}$ and the above inequality becomes

$$\gamma > \frac{1}{2}\left(\alpha - \frac{1}{s+1}\right).$$

To interpret this condition, note that $\frac{1}{s+1}$ is the rent that the innovator obtains by directly competing against duplicators and/or licensees in the product market, and so $(\alpha - \frac{1}{s+1})$ is the innovator's revenue from licensing. Therefore, with linear demand and Cournot competition patents are better than secrets provided that duplication or transaction costs exceed 50% of the revenue from licensing.

To see how inequality (8) applies in other cases, consider for instance Denicolò and Franzoni's (2004) framework in which there is only one potential duplicator with no licensing. In this case, $\alpha = \frac{1}{2}$ (with symmetric duopoly and no licensing, the innovator captures a half of potential rents) and with Cournot competition $\kappa = \frac{1}{2}$ (upon successful duplication, there are two active firms). Therefore, patents and secrets would be equally good only if duplication was costless; any positive duplication cost ($\gamma > 0$) breaks the indifference in favor of patents. This result immediately extends to any fixed number of duplicators s (i.e., $\alpha = \kappa = \frac{1}{s+1}$ under the stated assumptions).

As another example, suppose there is preemptive licensing and that licensing involves no transaction costs, so that $\gamma = 0$. Suppose, however, that the licensor captures only a share β of the bargaining surplus in the licensing agreements with each of her s licensees. In this case, $\alpha = \frac{\beta s+1}{s+1}$. Because with Cournot competition $\kappa = \frac{1}{s+1}$, it follows that secrets are better than patents whenever the licensor gets a positive share of the bargaining surplus ($\beta > 0$).

As a final example, suppose that there are two entrants ($s = 2$), a licensee and a duplicator. Suppose also that a half of the duplicator's profit is dissipated in duplication costs, and that the licensor captures a half of the bargaining surplus in the licensing agreements with the licensee. In this case, $\alpha = \frac{1}{2}$, $\gamma = \frac{1}{12}$ and $\kappa = \frac{1}{3}$; therefore, formula (8) implies that patents are exactly as good as secrets from the social viewpoint.

These examples confirm that in theory anything can happen. Whether patents are socially preferable to secrets is ultimately an empirical question, that can only be answered by trying to assess the prevalence of trade secret licensing and duplicative activity. Although there is little empirical evidence on these issues, the following remarks make us lean towards patents.

First, the economics literature on licensing has shown that a number of transaction costs impede licensing agreements of proprietary innovative knowledge. To begin with, innovative technological knowledge may be difficult to codify and transmit to others. In addition, incomplete information over the size of the innovation can lead parties to introduce inefficient terms in the licensing agreement, thereby destroying part of the bargaining surplus and preventing some potentially profitable agreements. Moreover, royalty licensing is possible only if output is verifiable; when individual output is not verifiable, and only fixed-fee licensing is feasible, licensing will occur at equilibrium only if the size of innovations is sufficiently small. In the specific framework of this paper, where the innovator preemptively licenses in order to deter duplication, licensing agreement may fail to be reached if there is incomplete and asymmetric information on the size of duplication costs, or on the timing of successful duplication. This means that the assumption that licensing agreements prevent wasteful duplicative efforts and allow the innovator to capture all of the potential rents is demanding even when the innovator is protected by a patent.

Second, duplicative activity is amply documented even in industries where patent protection is notoriously strong. The pharmaceutical industry is a case in point: it is generally agreed that many new medicines are “me-too” drugs that in fact duplicate path-breaking innovations. Inventing around patents is probably even more frequent in industries where patent protection is weaker.

Third, the assumption that the innovator can, through licensing, capture all of the bargaining surplus is especially demanding when the licensor is relying on secrecy. The special difficulty of selling unprotected ideas has first been articulated by Arrow (1962). The problem is particularly severe when the trade secret information is licensed to multiple parties. In this case, it is often exceedingly difficult to craft licenses permitting the licensors to maintain full control over the trade secret information.[19] For example, licensees might in turn sell the trade secret information to others, undermining the licensing equilibrium analyzed in the previous section.

Finally, what empirical evidence is available seems to confirm that trade secret licensing is much less common than patent licensing. For example, Arora and Ceccagnoli (2006, p. 294) find that in their data “only 12% of the non-patentees license, whereas about 40% of the patentees license.” They conclude that “the presence of a patent is almost essential for licensing.” If this is indeed true, our analysis implies that patents tends to be better than secrets as a tool to stimulate innovative activity.

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[19] See however Anton and Yao (1994) and Arora (1996) for alternative mechanisms that allow innovators to engage in trade secret licensing. These mechanisms work in theory but seem fragile, and it is hard to tell whether they are frequently used in practice.

7. Concluding remarks

It is an historical fact that patents grew as alternatives to trade secrets (see, for instance, David, 1993). Many of the first patents (*privilegi*) were granted to people who had not invented the technology at hand, but just ferreted it out from foreign guilds.[20] In this perspective, patents were instrumental to the diffusion of jealously held technology.

In this paper we have looked at patents as alternative to trade secrets. To disentangle this disclosure motive for patent protection from the traditional reward motive, we have adjusted the level of patent protection so as to make the innovator just indifferent between patenting and keeping the innovation secret. One interpretation of this exercise is that the innovation is the product of "serendipity," so that stimulating R&D effort is not a concern. A more general interpretation is that when the innovator is just indifferent between patenting (disclosing) and keeping the innovation secret, these two tools provide exactly the same payoff to the innovator; consequently, a comparison of the welfare losses tells us which form of protection is relatively more efficient.

When duplication is not possible and an innovator who relies on secrecy faces only the risk of a leakage, patents and secrets are perfect substitutes. In this case, disclosure of the innovative technological knowledge is not an independent motive for granting patents. However, secrecy precludes neither inadvertent disclosure nor independent creation by others. When the possibility of duplication is taken into account, whether or not patents are socially preferable to secrets depends on whether duplicative activity is actually exerted or is avoided by means of preemptive licensing. Because trade secret licensing is unlikely to fully preempt duplicative activity in practice, we are inclined to believe that patents are, indeed, better than secrets. However, more empirical work is needed to assess the issue.

At the theoretical level, there are at least three important issues that should be addressed in future work. First, some duplicative activity may be socially desirable. For example, me-too drugs sometimes are better tolerated by (or are more effective for) certain patients. As long as duplicators do not mechanically replicate the innovation, their efforts may have positive social value.

Second, we have assumed that innovators cannot rely both on patents and secrecy. This is true in principle, but in practice things are more complex. For example, an innovation may consists of several components, some of which are patented while others are kept secret. In this case, secrecy complements patents as a tool for protecting innovators. Such a complementarity also arises in those industries where the disclosure requirement is too weak to guarantee interoperability (like, e.g., in the software industry), and may explain why trade secret

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[20] Although the Statute of Monopolies of 1624 stated that patents could only be granted to the "true and first inventor" of new manufactures, initially inventors could just be importers of foreign skills and know-how: "whether they learned by travel or by study, it is the same thing," declared an English court in 1693 (Machlup, 1968).

licensing often occurs in tandem with patent licensing. When trade secrecy complements patents, and the same innovation can enjoy both forms of protection, new issues arise: for example, the existence of complementary patents can facilitate the licensing of trade secrets.

Third, the disclosure motive for granting patents is weakened when firms voluntarily avoid studying their competitors' patents, and prefer to reproduce all the relevant technological knowledge, for fear of additional liability for willful infringement of those patents. Whether such additional liability (which is present in the US, but not in Europe) is socially desirable is an interesting policy issues. These extensions are worth pursuing and can help explain why secrecy is also protected by the law.

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CHAPTER 3

On Patent Licensing

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Abstract

This chapter proposes a survey of the main results produced by the literature on licensing and some original insights, with a particular focus on globalization, North–South models of technology transfer, the issue of how the intellectual property rights influences international licensing, and asymmetric information.

Keywords: innovation, technology transfer, licensing, fixed fee, royalty, auction, two-part tariff, screening, adverse selection, spatial competition, IPRs

JEL classifications: D43, D45, L13, L14

1. Introduction

Patent licensing is a fairly common practice that takes place in almost all industries. It is a source of profit for the innovator (also called patentee) who earns rent through licensing a patent. The theoretical literature has mainly considered the following three modes of patent licensing: a royalty on per unit of output produced with the patented technology, a fixed fee that is independent of the quantity produced with the patented technology, or an auction of a certain number of licenses, i.e., offering a fixed number of licenses to the highest bidders. Patent licensing is a mode of technology transfer from technologically advanced firm to a less advanced one. There is a vast literature which studies the optimal licensing arrangement by the patentee in a wide variety of situations. At the same time, studies are devoted to analyze various aspects of patent licensing. For example, when the patentee is an outsider as opposed to an insider, or when the competition among the rival firms or the potential licensees takes place in prices or quantities, or when there is asymmetric information between the patentee and

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licensee, or the type of industry structure where all these issues are considered (whether it is a single-firm industry, oligopolistic or competitive). Given this wide variety of interests under patent licensing, the two major branches where the literature developed side by side overtime are (i) the case of outsider patentee and (ii) the case of insider patentee. When the patentee is an independent R&D organization and not a competitor of the licensee in the product market, it is an outsider patentee; whereas when it competes with the licensee it becomes an insider patentee. So far, the studies of insider and outsider patentee are done separately in different models. The general result for optimal licensing policies under a complete information framework is: if the patentee is an outsider, a fixed fee licensing or auctioning a certain number of licenses is optimal to the patentee (see Kamien and Tauman, 1986; Katz and Shapiro, 1986; Kamien et al., 1992; Kamien, 1992, among others); whereas a royalty licensing is optimal to the patentee when the patentee is an insider (see Rockett, 1990; Marjit, 1990; Wang, 1998, among others). Recently, Sen (2005a) showed that for an outside innovator in a Cournot oligopoly, royalty licensing could actually be superior to both fee and auction.[1]

Now, given these theoretical findings, in reality, then one should expect that either a fixed licensing or a per unit royalty licensing contract is being offered by the patentee to the licensee depending on whether the patentee is an outsider or insider. But empirical facts say otherwise, e.g., Rostoker (1983) in a firms survey finds out royalty plus fixed fee licensing accounts for 46 percent of the licensing arrangements, royalty alone 39 percent and fixed fee alone 13 percent. Similar studies by Taylor and Silberston (1973) find that arrangements with royalties or a mixture of fixed fee and royalty are far more common than a simple fee.[2] In response to this empirical observation, in the first part of this chapter, we provide a plausible theoretical explanation of this empirically observed fact in licensing arrangements.

We consider a simple model of asymmetric information with adverse selection. There is one patentee and one potential licensee. The patentee holds a patent for a cost reducing technology and wishes to license it with an objective to maximize its own profit. The licensee is the only firm operating in the product market. The patentee is an outsider. The licensee has the private information regarding the market demand (whether it is high or low) whereas the patentee has only a prior belief about it. The patentee wants to offer an optimal licensing contract for two possible demand situations (high or low) to the licensee, and hence faces an adverse selection problem. The licensee has always an incentive to convince the patentee that the demand condition is low in order to pay lower price for the license as compared to the high demand situation (since high demand

[1] The result depends on the fact that the number of licenses can take only integer values. This particular feature was overlooked by the previous literature.

[2] See also Caves et al. (1983), Macho-Stadler et al. (1996), Jensen and Thursby (2001) among others for similar findings.

state generates more surplus to the licensee, which in turn increases the license fee). Given this adverse selection problem, we develop a monopolistic screening model and explore what would be an optimal licensing contract offered by the patentee. We believe many real-life licensing arrangements are similar to the situation described here. We show that the optimal licensing involves royalty, fixed fee and a combination of both depending on the parameter configurations of our model. The results we obtain in the analysis are also empirically relevant and testable. In the context of business cycle, if we follow the hypothesis suggested here, we would expect to observe only fixed fee or only royalty contract offered by the patentee in the boom period or during big fluctuation of market demand; whereas a combination of fixed fee and royalty or only fixed fee should be observed during bust or when there is less variation in market demand.

There are also other studies which also try to explain the prevalence of per unit royalty or a mixture of royalty and fixed fee in a licensing contract when the patentee is an outsider. For example, see Macho-Stadler et al. (1991), Beggs (1992), Gallini and Wright (1990), Bousquet et al. (1998), Choi (2001), Sen (2005b).

Macho-Stadler et al. (1991) have considered a model of asymmetric information where an innovator interacts with a monopolist who is privately informed of the value of the innovation. There the source of asymmetry of information arises from the innovation itself. They have shown that the optimal menu of contracts proposed by the innovator is separating: The contract for the good innovation involves fixed fee, while for the bad innovation, the contract is a combination of fixed fee and royalty. Sen (2005b) analyzed a screening model where the private information of the monopolist is its cost and came up with similar conclusions. Beggs (1992) examined a situation where the licensee has a very clear idea of the market for a new product or the reduction in costs from a new process, hence possesses private information about the actual value of the patent which the patentee does not know. In this context he considers a signaling game and shows that royalty contracts make a separating equilibrium possible and may allow a more efficient outcome than a fixed fee licensing. Gallini and Wright (1990) consider another signaling game where the patentee has private information about the actual value of the patent and explained that royalty rate in the contract can act as a signaling device for the patentee. Bousquet et al. (1998) considered a licensing arrangement under demand or cost uncertainty and justified the use of royalty in addition to fixed fee using risk-related considerations. Choi (2001) considered a moral hazard problem in a licensing relationship where effective transmission of knowledge (i.e., value of the patent) requires costly inputs by both dispensing and receiving parties which may not be observable to any other party, and explains the prevalence of royalty contract in the licensing relationship.

So far most of the studies on patent licensing are done in a standard framework of price or quantity competition. In the next part of the chapter, we introduce the study of patent licensing in a spatial framework based on Poddar and Sinha (2004). Studying competition in spatial models is already an established area of research in industrial organization. Here we use the platform of a spatial framework to study patent licensing and bring these two important themes of research in one platform. We discuss some important aspects of optimal patent licensing in a particular spatial framework, namely, the very well known Hotelling's linear city model. We study the optimal licensing behavior (strategy) of an outsider patentee as well as an insider patentee in this new environment and contrast our findings with the existing results in the conventional framework of patent licensing literature. We find significant differences in the licensing outcomes arise due to the spatial competition we consider here. We thus believe it opens up a new avenue of research in patent licensing. When the patentee is an outsider, it faces two firms, i.e., the two potential licensees, who are engaged in a price competition *a la Bertrand*, and located at the two end points of the linear city. On the other hand, when the patentee is an insider, it is also a competitor in the product market, and we assume it competes with a rival firm in price. Here also both firms are located at the end points of the city. In each case, the locations of the competing firms are fixed and both firms produce a particular good. Consumers are uniformly distributed over the linear city, and willing to buy exactly one unit of the good. The good produced by both firms is identical in nature; however, due to the presence of transport cost incurred by the consumer to buy the good from either of the firms, the goods are differentiated in the eyes of the consumers. In this framework, we find the optimal strategy of the patentee in offering the license(s). Following the literature on patent licensing on the technology side, we consider two types of innovations, namely, drastic and non-drastic. We completely characterize the equilibrium licensing outcomes in each case, under different possible licensing arrangements of auction, fixed fee and royalty.[3]

Throughout the analysis, we keep the location of the competing firms fixed at the two end points of the city. This may need some explanation. Location is not a choice variable to the firms due to the following reason. We assume that the transportation cost faced by the consumers in the model is linear. It is well known in the literature (see d'Aspremont et al., 1979) that with linear transportation costs, the equilibrium in location does not exist for all possible locations of firms; it only exists when firms are sufficiently far from each other. In our analysis, to avoid any such non-existence problem in locations, we assume the case when firms are farthest from each other, namely, when they are located at the end points of the city. From the consumers' point of view this means we consider the case when the products are maximally differentiated. We believe this assumption is reasonable since our main focus in this paper is to see the optimal licensing policies by the patentee in a certain specified location model.

We also show the existing result in the literature about the outsider patentee is not always true when we consider licensing in a spatial framework of linear

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[3] We also consider the mixed licensing contract involving fixed fee plus royalty (i.e., two-part tariff) and show that in this general licensing scheme, the royalty turns out to be the optimal contract with fixed fee component being zero. Details are available on request from the authors.

city. We find offering royalty licensing can be better than fixed fee or auction.[4] We also show in the case of insider patentee offering no license is optimal when the innovation is drastic.[5] On the other hand, in the case of an outsider patentee licensing takes place to two competing firms even if the innovation is drastic. Finally, we show that in this framework the incentive for innovation is always higher when the patentee is an outsider as compared to an insider.

We end the chapter, by looking into some pertinent issues related to international technology transfer and IPRs with a particular focus on globalization and North–South models of technology transfer. We consider a simple model to analyze how the intellectual property rights might influence international licensing.

2. *The screening model of patent licensing*

We consider a model of technology licensing with one patentee and one licensee. The patentee holds a patent for a cost reducing technology. There is an incumbent firm in the market, which is the potential licensee for this technology. The patentee cannot enter into the market and produce the product. Thus we consider the case of an outside patentee, for example an R&D Laboratory. We are interested in the linear optimal licensing strategy of the outside patentee with one potential licensee, who has private information about the market demand condition.

The market (inverse) demand function is given by $p = A - q$, where p and q denote price and quantity respectively whereas A is the demand intercept. The essential ingredient of our model is that the market demand is uncertain. There can be two states of demand of the product under consideration: high or low. We capture this fact by assuming that the intercept term A can take two values A_h and A_l depending on whether the demand is high(h) and low(l) (naturally $A_h > A_l$). The incumbent firm has private information about this demand conditions, i.e., it knows for sure whether the market demand is high or low. On the other hand, the patentee being an outsider does not know the actual demand but has a prior belief about these demands. With probability θ, the patentee believes that the demand is low and with probability $(1 - \theta)$ it believes the demand is high. θ is common knowledge to both parties.

Suppose the incumbent firm can serve the market with its existing technology for which the marginal cost of production is c. However the patentee has a new technology which is more efficient and it reduces the cost of production

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[4] Muto (1993) considers licensing policies under price competition in a standard Bertrand differentiated product framework, and like us assumed an external patentee who is willing to offer licensing contract when two potential licensees are competing in prices in a differentiated product market. Muto's main result is that a royalty is superior to other two polices, namely fixed fee and auction, when innovations are not large, i.e., the innovation is non-drastic.

[5] This is in contrast with the result of Fauli-Oller and Sandonis (2002) in a licensing game under differentiated Bertrand competition.

by ε ($\varepsilon > 0$). Thus, if this new technology is used for the production, the marginal cost of production would be $(c - \varepsilon)$. We consider the licensee to be high type or low type depending on whether it knows the demand to be high or low respectively.

We consider the following game. The patentee makes an offer of the new technology by charging some payment schedule. The licensee can accept or reject the offer. After this the production is undertaken by the licensee either with the new technology (if it has accepted the offer) or with the existing technology (in case it has rejected the offer). The profit is realized at the end of the game.

Let us note some of the variables, which would be useful for subsequent calculations. Since the licensee is the only one firm in the market so the market is served under monopoly. The reservation payoff for each type of the licensee is the payoff it receives without the new technology, i.e.,

$$R_i = \frac{(A_i - c)^2}{4} \quad \text{for each } i = h \text{ or } l. \tag{1}$$

And the corresponding output is $q_i = \frac{(A_i - c)}{2}$ for $i = h$ or l.

Suppose the new technology is used for production then the profit of the firm would be

$$\frac{(A_i - c + \varepsilon)^2}{4} \quad \text{for } i = h \text{ or } l.$$

On the other hand, if some per unit royalty r is charged then the profit of the licensee would be $\frac{(A_i - c + \varepsilon - r)^2}{4}$ and the corresponding output would be

$$q_i(r) = \frac{(A_i - c + \varepsilon - r)}{2} \quad \text{for } i = h \text{ or } l.$$

It is well known in the literature that the royalty is distortionary as it increases the marginal cost of production leading to lower overall surplus that can be divided between the patentee and the licensee. Suppose both the patentee and the licensee knows the actual demand in the market. Then the game is one of complete information. Then the optimal licensing strategy in this case is to charge a fixed fee such that the licensee receives its reservation payoff. Thus the optimal fixed fee is given by:

$$T_i = \frac{(A_i - c + \varepsilon)^2}{4} - \frac{(A_i - c)^2}{4} \quad \text{depending on } i = h \text{ or } l. \tag{2}$$

2.1. Pooling contracts

2.1.1. Fixed fee

Let us consider the asymmetric information problem where the licensee has the private information about demand and the patentee has only prior belief about that. Due to this asymmetric information the patentee will face an adverse selection problem in licensing the technology as the high type licensee would like to hide its private information and pretend to be low type in order to pay lower amount for the technology. First consider the simplest contract which is the fixed fee licensing contract. If the patentee charges only fixed fee for its license, then either it has to charge T_l and in that case both type of the licensee will accept the license, or it has to charge T_h, in that case only high type will accept the technology, and the low type will reject the offer. Thus, if the patentee charges T_l, then the total payoff it receives is T_l. On the other hand, if the patentee charges T_h, then only the high type accepts the offer and the low type will not accept the license.

Thus, the expected payoff would be: $\theta.0 + (1-\theta)T_h = (1-\theta)T_h$. Now depending on the prior belief about the type of the licensee, the patentee will choose either of these two license fees which maximize its payoff. A simple calculation shows that there exists a $\theta^* = (1 - \frac{T_l}{T_h})$ such that for $\theta \geqslant \theta^*$ both types of the licensee is offered the technology and the low fixed fee is charged. And for $\theta < \theta^*$ only high type is offered the license and the high fixed fee is charged. Thus, for $\theta < \theta^*$ the market is not going to be served with the new technology if the market demand is truly low. Only the high type of the licensee accepts the offer and serves the market. So there is an inefficiency due to asymmetric information as the market is not served by new technology with probability θ for the prior belief $\theta < \theta^*$. The patentee's payoff $\pi = \text{Max.}[T_l, (1-\theta)T_h]$. In this context, we define efficiency as a situation where the new technology is used to serve the market irrespective of the prior belief of the patentee.[6] Thus, we have our first proposition.

PROPOSITION 2.1. *Suppose the patentee charges only fixed fee for licensing its technology. Then, for $\theta \geqslant \theta^*$ the patentee charges T_l as fixed fee and both types of the licensee accept the offer. For $\theta < \theta^*$, the patentee charges T_h and only the high type licensee accepts the offer, and as a result the market is not served by new technology with all prior belief $\theta < \theta^*$, i.e., when the market demand is truly low.*[7]

Now, we would like to introduce more general kind of contract, which is a linear function of output having both fixed and a variable component. This kind of linear contract is very common in the context of technology licensing in practice.

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[6] Note that this is different from the notion of social efficiency (i.e., social surplus maximization). However, the relationship between the two will be discussed at the end of Section 4.2.

[7] This case is similar to what is mentioned in Beggs (1992, page 174). The only difference with Beggs is that when the license is offered with high fixed fee in case of rejection by the low type, the patentee has a fall back payoff which is non-zero (unlike zero in our case) as the patentee can turn to some other alternative licensee as assumed there. Although Beggs had mentioned about the royalty contract which is contingent on the output produced, in the similar set up like ours, but his non-linear royalty contract ultimately in this simple case turned out to be like fixed fee contract as analyzed above.

2.1.2. Fixed fee plus royalty contract

We consider royalty as per unit fee charged on the output produced by the licensee and the fixed fee is a lump sum payment independent of output. We consider a uniform payment scheme the patentee designs for licensing the technology. Suppose the patentee designs a linear contract $F + rq$ where F is the fixed fee and r is the royalty per unit of output produced ($F, r \geqslant 0$). This payment schedule is uniform irrespective of the licensee's type. However, if the licensee produces more output which is expected in case of high demand then the ex-post payment to the patentee is more because of the royalty rate r. This is a pooling contract as the same contract (F, r) is offered to both types of the agent (licensee).

With the pooling contract the patentee's problem is to maximize its payoff

$$\pi = \theta\big(F + rq_l(r)\big) + (1-\theta)\big(F + rq_h(r)\big) \tag{3}$$

subject to the participation constraints of both types of the licensee given by (using (1)),

$$-F + \frac{(A_i - c + \varepsilon - r)^2}{4} \geqslant \frac{(A_i - c)^2}{4} \quad \text{for } i = h \text{ and } l. \tag{PC}$$

Given this problem it is easy to see that the high type licensee would receive some rent and the participation constraint of the low type would be satisfied with equality under this pooling contract. To solve for the payoffs first note that the optimal fixed fee

$$F = \frac{(A_l - c + \varepsilon - r)^2}{4} - \frac{(A_l - c)^2}{4}.$$

Substituting this F and also $q_l(r)$, $q_l(r)$ into patentee's payoff π (from (3)), we find patentee's payoff becomes a function of r only, and thus we write:

$$\begin{aligned}\pi(r) = {} & \frac{(A_l - c + \varepsilon - r)^2}{4} - \frac{(A_l - c)^2}{4} + \theta r.\frac{(A_l - c + \varepsilon - r)}{2} \\ & + (1-\theta).r.\frac{(A_h - c + \varepsilon - r)}{2}.\end{aligned} \tag{4}$$

Now maximizing $\pi(r)$ with respect to r we get optimal royalty under pooling contract as $r = (1-\theta)(A_h - A_l)$.

Since the fixed fee can never be negative (i.e., $F \geqslant 0$) so given the participation constraint (PC) the royalty rate can never be greater than ε. Thus, the optimal royalty rate under pooling contract $r^* = \text{Min.}[(1-\theta)(A_h - A_l), \varepsilon]$. As a result, F is also determined.

Putting the value of r^* and F, we get the patentee's payoff under pooling contract $\pi(r*)$. The following lemma characterizes the royalty scheme r^* under pooling contract.

LEMMA 2.1. *There exists $\bar{\theta}_1 = \frac{A_h - A_l - \varepsilon}{A_h - A_l}$ such that for $\theta \leqslant \bar{\theta}_1$ the optimal royalty rate is ε and for $\theta > \bar{\theta}_1$ the optimal royalty rate is $(1-\theta)(A_h - A_l) < \varepsilon$.*

Alternative to the above pooling contract the patentee can only offer license to the high type licensee and charge the high fixed fee T_h (using (2)). In this case the patentee's payoff would be $(1-\theta)T_h$. Now comparing the payoffs we get the optimal strategy of the patentee. Note that there exists $\hat{\theta} = (1 - \frac{\pi(r^*)}{T_h})$ such that for $\theta \geqslant \hat{\theta}$ both types of the licensee is offered the technology with both fixed fee ($F \geqslant 0$) and royalty payment (r^*).[8] And for $\theta < \hat{\theta}$ only high type is offered the license and the high fixed fee (T_h) is charged. The patentee's payoff under this pooling contract is: $\pi^P = \text{Max.}(\pi(r^*), (1-\theta)T_h)$.

Thus, the following proposition characterizes the licensing strategy under pooling contract.

PROPOSITION 2.2.

(i) *When the technology is offered under pooling contract of royalty plus fixed fee then for $\theta \geqslant \hat{\theta}$ the patentee offers the new technology to both types of the licensee. And for $\theta < \hat{\theta}$ the patentee offers the technology to the high type only by charging the high fixed fee.*

(ii) *When the technology is offered to both types, expected profit of the patentee under the pooling contract of royalty plus fixed fee, is higher than the earlier simple fixed fee contract. Formally, $\pi(r^*) > T_l$.*

(iii) *Under the pooling contract of royalty plus fixed fee inefficiency is reduced as compared to the situation when only the fixed fee licensing is offered since $\hat{\theta} < \theta^*$. In other words, under the pooling contract of royalty plus fixed fee, the market is being served for greater range of prior belief than simple fixed fee contact.*

PROOF. (i) follows from above discussion. (ii) Note that $\pi(0) = T_l$ and $\pi(r)$ is a positive function of r when $0 < r < r^*$. (iii) Notice the fact that $\pi(r^*) > T_l$. □

COROLLARY 2.1 (Consistency with complete information). *Observe that under pooling contract when $\theta = 1$ (i.e., the demand is known to be low) then $r^* = 0$ and $\pi(r^*) = T_l$; whereas when $\theta = 0$ (i.e., the demand is known to be high) then $(1-\theta)T_h = T_h$.*

Now the question is whether the patentee can do any better by designing a separating contract and what happens to the efficiency as a result of that.

2.2. Separating contract

Suppose the patentee can offer a discriminatory contract between the two types of licensee. Note that this kind of separating contract must satisfy another two constraints apart from the participation constraints (PC). These are incentive compatibility constraints. Suppose, the contract offered to the licensee is (F_l, r_l)

[8] Note that if $r^* = \varepsilon$, then $F = 0$; otherwise $F > 0$.

and (F_h, r_h) to low type and high type respectively and the respective type accepts the offer. Now the incentive compatibility means that neither type would mimic and accepts the contract meant for the other type. So we write the following incentive compatibility constraints for the low type (IC1) and the high type (IC2) respectively,

$$-F_l + \frac{(A_l - c + \varepsilon - r_l)^2}{4} \geqslant -F_h + \frac{(A_l - c + \varepsilon - r_h)^2}{4}, \tag{IC1}$$

$$-F_h + \frac{(A_h - c + \varepsilon - r_h)^2}{4} \geqslant -F_l + \frac{(A_h - c + \varepsilon - r_l)^2}{4}. \tag{IC2}$$

First note that any (F_l, r_l) must satisfy the participation constraint of the low type. Now by mimicking to be low type the high type licensee would get the RHS of (IC2). It is easy to check that high type gets a rent above its reservation payoff by mimicking to be low type licensee. Thus, to separate out the high type, (F_h, r_h) must be such that the high type gets that rent in equilibrium. Since royalty has distortionary effects on surplus, so reducing r_h to zero and increasing F_h (subject to (IC2)) would increase the surplus extracted by the patentee. This mechanism does not violate the (IC1) also. As a result, $F_h = F_l + \frac{(A_h-c+\varepsilon)^2}{4} - \frac{(A_h-c+\varepsilon-r_l)^2}{4}$ (from (IC2)). Since the participation constraint of the low type will be satisfied with equality we get

$$F_l = \frac{(A_l - c + \varepsilon - r_l)^2}{4} - \frac{(A_l - c)^2}{4}. \tag{5}$$

Thus, the patentee's payoff π becomes a function of r_l only, and we write:

$$\pi(r_l) = \theta\big[F_l + r_l q_l(r_l)\big] + (1-\theta)F_h. \tag{6}$$

Therefore, the maximization of $\pi(r_l)$ with respect to r_l would yield $r_l = \frac{(1-\theta)(A_h-A_l)}{\theta}$. However, we have already noted that r_l cannot exceed ε. Thus, the optimal $r_l^* = \text{Min.}[\frac{(1-\theta)(A_h-A_l)}{\theta}, \varepsilon]$.

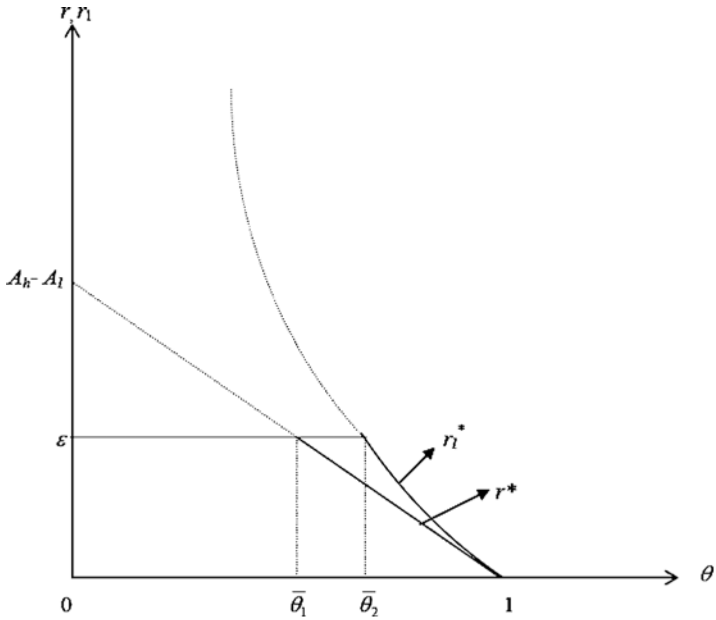
As a result the corresponding F_l^* and F_h^* are also determined. Hence the Patentee's payoff under separating contract is achieved from (6).

The following lemma characterizes the royalty scheme r_l^* under separating contract with fixed fee plus royalty.

LEMMA 2.2. *There exists $\bar{\theta}_2 = \frac{A_h-A_l}{A_h-A_l+\varepsilon}$ such that for $\theta \leqslant \bar{\theta}_2$ the optimal royalty rate is ε and for $\theta > \bar{\theta}_2$ the optimal royalty rate is $\frac{(1-\theta)(A_h-A_l)}{\theta} < \varepsilon$.*

Thus, for $\theta \leqslant \bar{\theta}_2$, $F_l^* = 0$ and $F_h^* = \frac{(A_h-c+\varepsilon)^2}{4} - \frac{(A_h-c)^2}{4}$ which is the maximum fixed fee charged under complete information. Also for $\theta > \bar{\theta}_2$, $F_l^* > 0$ and F_h^* is less than the complete information fixed fee. In particular when $\theta = 1$ then the royalty rate is zero. And low type is charged only with the fixed fee equivalent to the entire surplus as it should be like under complete information. The above separating contract is the best for the patentee under the linear contract scheme we are considering in the present context.

Figure 1.



Also observe that optimal royalty rate r_l^* under separating contract is higher than that of r^* in the case of fixed fee plus royalty pooling contract. See Figure 1.

Now, comparing Equations (3) and (6), we state the following lemmas.

LEMMA 2.3. *For all $r = r_l$, we must have $F = F_l$ and $\pi(r_l) > \pi(r)$.*

PROOF. From (3), note that $\pi(r) = \theta(F + rq_l(r)) + (1-\theta)(F + rq_h(r))$ where, $F = \frac{(A_l-c+\varepsilon-r)^2}{4} - \frac{(A_l-c)^2}{4}$. From (6), note that $\pi(r_l) = \theta[F_l + r_l q_l(r_l)] + (1-\theta)F_h$, where $F_l = \frac{(A_l-c+\varepsilon-r_l)^2}{4} - \frac{(A_l-c)^2}{4}$.

It is easy to see that when $r = r_l$, then $F = F_l$ and also $q_l(r) = q_l(r_l)$. Thus, the first term of $\pi(r)$ and $\pi(r_l)$ coincides. Hence remains to show the second term of $\pi(r_l)$ is bigger than second term of $\pi(r)$.

Leaving aside the common term $(1-\theta)$, second term of $\pi(r_l)$,

$$F_h = F_l + \frac{(A_h - c + \varepsilon)^2}{4} - \frac{(A_h - c + \varepsilon - r_l)^2}{4}.$$

Since, $F = F_l$, it is enough to show $\frac{(A_h-c+\varepsilon)^2}{4} - \frac{(A_h-c+\varepsilon-r_l)^2}{4} > rq_h(r)$.

Now putting the value of $q_h(r)$ and simplifying, we get: $-\frac{r_l}{2} > -r$, which is true for $r = r_l$. Hence the result. $\square$

LEMMA 2.4. *It is true that $\pi(r_l^*) > \pi^P =$ Max.$(\pi(r^*), (1-\theta)T_h)$.*

PROOF. First observe that $\pi(r_l^*) > \pi(r^*)$ for all $\theta \geqslant \hat{\theta}$. This follows directly from Lemma 2.3. To show $\pi(r_l^*) > (1-\theta)T_h$ for all $\theta < \hat{\theta}$. Consider a feasible separating contract as follows: $r_l = \varepsilon$, $F_l = 0$, $F_h = T_h$. Note that this contract is accepted by both types. This contract achieves a payoff of $\pi(r_l) = \theta(0 + \varepsilon q_l(\varepsilon)) + (1-\theta)T_h > (1-\theta)T_h$. Now, since $\pi(r_l^*) \geqslant \pi(r_l)$ as r_l^* is optimal. Hence the result. Thus, we state our final proposition. □

PROPOSITION 2.3.

(i) *Expected payoff of the patentee under the separating contract is greater than that of fixed fee plus royalty pooling contract. Formally,* $\pi(r_l^*) > \pi^P$.
(ii) *When the licensee offers the technology under separating contract, then for all prior belief, the technology is offered to both types of the patentee, hence it is also efficient.*
(iii) *The high type of the licensee is always charged with fixed fee. In case of low type licensee, for* $\theta \leqslant \bar{\theta}_2$ *the optimal royalty rate is* ε *with zero fixed fee and for* $\theta > \bar{\theta}_2$ *the optimal royalty is less than* ε *and also some fixed fee is charged.*

PROOF. (i) follows directly from Lemma 2.4.

(ii) Note that an alternative option of the patentee is to offer licensing contract only to the high type (which is actually optimal in the earlier pooling contract under some prior belief, see Proposition 2.2(i)). Using that option the patentee receives $(1-\theta)T_h$. However, from Lemma 2.4, we note that $\pi(r_l^*) > \pi^P = \text{Max.}(\pi(r^*), (1-\theta)T_h) \geqslant (1-\theta)T_h$. So under the separating contract, it is always optimal for the patentee to offer the patent to both types of the licensee irrespective of the prior belief.

(iii) follows from Lemma 2.2 and the discussion after that. □

This finding is interesting as it establishes that under adverse selection the optimal licensing arrangement can be found with a separating contract. Recall that in the pooling contract with royalty, when licensing is offered to both types then, $\pi^P \geqslant \pi$; now under separating case, we find that $\pi(r_l^*) > \pi^P$, hence the optimal licensing contract for the patentee is a separating contract as described above. This optimal contract could involve only fixed fee, only royalty and a mixture of fixed fee and royalty depending on the parameter configurations. The royalty is never used for the high type of licensee under separating contract and it is used only for low type of licensee.[9] Also note that unlike the pooling contracts described before where both types are offered with new technology over a restricted range of prior belief of the patentee, in the separating contract case irrespective of the prior belief of the patentee, new technology is always

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[9] This finding appears to be consistent with empirical observation in licensing arrangements that royalty rate decreases with output (Taylor and Silberston, 1973).

offered to both types. Thus, the optimal licensing contract is more efficient in nature as compared to the pooling contract case. However, it should be noted here that this separating contract is still not the first best contract from the point of view of social surplus maximization. The social surplus is maximized when the technology is used for both types of demand and production taking place according to the true marginal cost of production associated with the technology. In the separating contract analyzed above although the market is being served in both states of demand but the presence of royalty per unit of output distorts the social surplus available in the relationship. Thus we find a second best contract from the social welfare point of view with a linear contract scheme.

COROLLARY 2.2 (Consistency with complete information). *Observe that under separating contract when* $\theta = 1$ (*i.e., the demand is known to be truly low*) *then* $r^* = 0$ *and* $\pi(r_l^*) = T_l$; *whereas when* $\theta = 0$ (*i.e., the demand is known to be truly high*) *then* $r^* = \varepsilon$ *which implies* $F_l = 0$ *and hence* $F_h = T_h$.

Empirical significance

Let us now demonstrate the empirical significance of our result. Note that our model is especially relevant in an uncertain environment when the market demand is fluctuating. The incumbent monopolist firm who has the private information about the true state of demand would have to pay the license fee charged by the outside patentee. Under this circumstance, we observe that if the patentee is optimistic about the market demand (i.e., for lower values of prior belief θ), then the optimal menu consists of fixed fee (for high demand type) and royalty (for low demand type). On the other hand, when the patentee is pessimistic about the market demand (i.e., for higher values of prior belief θ), then the optimal menu consists of fixed fee and a combination of royalty (for low demand type) and fixed fee (for high demand type). Thus, in the context of business cycle, during boom (i.e., when the probability of high demand realization is high) we would observe that licensing contract would involve either fixed fee or royalty. On the other hand, during bust, we would observe that either a fixed fee or a combination of royalty and fixed fee is changed by the patentee for licensing its innovation. This is an interesting empirically testable hypothesis of our analysis.

From Lemma 2.2, it is also obvious that as $(A_h - A_l)$ decreases; the likelihood of $\theta > \bar{\theta}_2$ increases. So for lower degree of demand variation the optimal licensing contract that will be observed would involve a fixed fee or a combination of fixed fee and royalty, whereas for higher degree of demand variation the observed licensing contract should involve only fixed fee or only royalty. This is another interesting empirical significance of the exercise.

Now we turn on to the study of patent licensing in a spatial framework.

3. *The spatial model for patent licensing*

Consider a linear city along the unit interval [0, 1], where firm A is located at 0 and firm B is located at 1, i.e., at the two extremes. Consumers are uniformly distributed along the interval. Each consumer buys exactly one unit of the good, which can be produced by firm A or B. The utility of the consumer located at $x \in [0, 1]$ is given by[10]

$$\begin{aligned} u_x &= -x - p_\mathrm{A} \quad \text{if buys from A} \\ &= -(1-x) - p_\mathrm{B} \quad \text{if buys from B.} \end{aligned}$$

We derive the demand for firm A and firm B by equating the utility of the person who is indifferent between buying from A or B and obtain:

$$D_\mathrm{A} = \frac{p_\mathrm{B} - p_\mathrm{A} + 1}{2} \quad \text{and} \quad D_\mathrm{B} = \frac{p_\mathrm{A} - p_\mathrm{B} + 1}{2}.$$

Assume the existing marginal cost of production for firm A and firm B are $c_\mathrm{A} > 0$, $c_\mathrm{B} > 0$ respectively. If these two firms compete in price, the equilibrium prices, demand and profits are given by:

$$p_\mathrm{A} = \frac{2c_\mathrm{A} + c_\mathrm{B}}{3} + 1, \qquad p_\mathrm{B} = \frac{2c_\mathrm{B} + c_\mathrm{A}}{3} + 1; \tag{7}$$

$$D_\mathrm{A} = \frac{c_\mathrm{B} - c_\mathrm{A} + 3}{6}, \qquad D_\mathrm{B} = \frac{c_\mathrm{A} - c_\mathrm{B} + 3}{6}; \tag{8}$$

$$\pi_\mathrm{A} = \frac{(c_\mathrm{B} - c_\mathrm{A} + 3)^2}{18}, \qquad \pi_\mathrm{B} = \frac{(c_\mathrm{A} - c_\mathrm{B} + 3)^2}{18}. \tag{9}$$

3.1. The case of outsider patentee

Assume pre-innovation marginal costs of the existing firms are $c_\mathrm{A} = c_\mathrm{B} = c$. An outsider patentee (independent innovator) comes up with a cost reducing innovation, which could lower the marginal cost by $\varepsilon > 0$. We say that the innovation is drastic if one firm buys the license while the other firm does not then the unlicensed firm is unable to compete anymore and goes out of business.[11] For example, if firm A buys the license and firm B does not, then because of competitive disadvantage D_B becomes 0, and as a result firm A serves the whole market, i.e., D_A becomes 1. This is the case when the innovation is drastic. Whereas in case of non-drastic innovation, in spite of cost disadvantage, D_B still remains positive even after firm A becomes the only license holder. Now, using the equilibrium demand from (2), the above is same as saying that as long as $0 < \varepsilon < 3$, the innovation is non-drastic and when $\varepsilon \geqslant 3$, the innovation is drastic. Thus, if the cost difference between the firms is greater than equal to 3, then the firm with the new technology monopolizes the market. So if firm A buys the drastic technology from the outside innovator, then $D_\mathrm{A} = 1$ and $D_\mathrm{B} = 0$.

Note that what the non-licensee can charge at the minimum is c, since charging less would mean loss. Now to cater to the whole market the firm A can charge

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[10] This particular formulation of the utility function in a Hotelling's linear city model is typical, see Shy (1996), Shy (2000), Shy and Thisse (1999) among others.

[11] A new technology is said to be 'drastic' when a firm with this new technology charges a monopoly price and the other firms with the older technology produce nothing (see Tirole, 1988).

at best $(c-1)$. The reason is the following. It is not worthwhile for firm A to charge less as it would cater to the whole market in any case. However, charging more than $(c-1)$ would create a space for the non-licensee to produce and sell to some consumers close to its location, which is not optimal for the licensee. Thus, by charging the price $(c-1)$ the licensee would keep its competitor out of the market and supply the whole market. It is also interesting to note that the price charged by the licensee for any $\varepsilon \geqslant 3$ would remain the same in this case and thus the price is independent of the innovation level for drastic innovations.

The outsider patentee has three licensing policies to offer: auction, fixed fee, and royalty. We consider a three-stage game where in the first stage the patentee decides on a licensing policy among the above three policies and announces the number of license to be offered. In the second stage the firms simultaneously and independently decides whether to accept or reject the offer in case of fee and royalty policy, or they simultaneously bid for license in case of auction. In the third stage the firms compete in price in the market depending on the availability of the technology inherited from the second stage of the licensing game. We focus on the subgame perfect equilibrium of the game.

Auction and fixed fee policy

In case of auction or fixed fee in the first stage the outside patentee has to decide whether to auction or offer one or two licenses with the corresponding fee for each license. It is shown in (Poddar and Sinha, 2004) that under these two licensing policies the outside patentee always offers one license irrespective of the amount of cost reduction. In case of non-drastic innovation the patentee receives $\frac{2}{3}\varepsilon$ and in case of drastic innovation it receives $(\varepsilon - 1)$. The intuition can be found in the very nature of price competition considered in a spatial framework. If both firms are offered the technology then due to competition both firms profit becomes $\frac{1}{2}$. On the other hand, if one firm is offered the license, then due to the cost asymmetry in the post licensing stage the licensee receives the high payoff. As a result, the patentee can extract greater surplus than offering two licenses.

Royalty policy

In the case of royalty policy, the patentee charges a payment per unit of output produced by the licensee. In this case the patentee always offers two licenses as opposed to one irrespective of the amount of cost reduction and in both drastic and non-drastic innovation the patentee receives ε (see Poddar and Sinha, 2004). The intuition is under the royalty scheme the maximum attainable surplus for the patentee is ε, i.e., the amount of cost reduction (since the market size is unity). This maximum payoff is attainable if both firms are offered the license at ε royalty rate and the firms share the market equally at the post-licensing stage. On the other hand, in case of one license being offered either the licensee is not serving the whole market after licensing or the patentee is restricted to charge less than ε as royalty.

Thus, the optimal licensing policy for an outsider patentee in a spatial model is as follows.

PROPOSITION 3.1. *An outsider patentee would always license out the technology to both firms in the market using a royalty contract as opposed to either auction or fixed fee.*

The optimal policy of licensing (i.e., offering one license) under auction or fixed fee affects the nature of competition between firms, and hence the price. The prices in the post-licensing stage are found to be lower than pre-innovation stage under these policies. On the other hand, the optimal policy under royalty, which is to offer licenses to both firms (i.e., offering two licenses) at a royalty rate ε, does not affect the competition across pre and post-licensing stage between the firms, and as a result the post-licensing price remains at the pre-innovation level leading to more surplus that can be extracted by the patentee as compared to auction and fixed fee policies. This additional surplus is actually being extracted by the patentee through royalty payment. Thus, royalty contract turns out to be the dominant licensing strategy for the patentee. Here, it is also important to note that in optimal royalty licensing, under *drastic innovation*, both firms are licensed at a royalty rate equal to the amount of cost reduction by the patentee. This is a result that has never been shown in the literature before with an outsider patentee.[12]

It should be noted here that we analyze the licensing policy of the outsider patentee with respect to the different regimes as auction, fixed fee and royalty. One might wonder what happens if we consider the general licensing policy involving both fixed fee and royalty together (i.e., as two-part tariff). It can be shown that even if we allow for such a mixed licensing policy, the optimal licensing strategy for the patentee would be to offer two licenses at the royalty rate ε with fixed fee component being zero.

3.2. The case of insider patentee

In the previous section we analyze the optimal licensing policy of a patentee who is an outsider to the product market. Now we consider the case of an insider patentee who is also a competitor in the product market (see Poddar and Sinha, 2004). Given the structure of our spatial competition, we assume that one of the firms has a cost-reducing innovation. Let us assume pre-innovation marginal costs of the firms are $c_{\mathrm{A}} = c_{\mathrm{B}} = c$. Firm A comes up with a cost-reducing innovation, which lowers its marginal cost by $\varepsilon > 0$, so that post-innovation $c_{\mathrm{A}} = c - \varepsilon$ and $c_{\mathrm{B}} = c$.

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[12] Muto (1993) considers licensing policies of an outsider patentee under price competition in a standard Bertrand differentiated product framework with two potential licensees. Muto's main result is that royalty is superior to other two polices, namely fixed fee and auction, when innovations are non-drastic only.

No licensing

Here, both firms compete in price with above costs configuration. In non-drastic case both firms share the market and the profits are:

$$\pi_A = \frac{(3+\varepsilon)^2}{18} \quad \text{and} \quad \pi_B = \frac{(3-\varepsilon)^2}{18}. \tag{10}$$

In drastic case, firm A undercuts firm B and the demands, prices and profits are given by

$$\begin{aligned}
&D_A = 1 \quad \text{and} \quad D_B = 0,\\
&p_A = c - 1,\\
&\pi_A = (\varepsilon - 1) \quad \text{and} \quad \pi_B = 0.
\end{aligned} \tag{11}$$

Note that under drastic case: $\pi_A \geqslant 2$.

Licensing game

In the case of an insider patentee, we modify the licensing game as follows. A licensing game consists of three stages. In the first stage, the patent holding firm A sets a fixed licensing fee or a royalty rate.[13] In the second stage, the rival firm B decides whether to accept or reject the offer from firm A. In the last stage, both firms compete in prices. Firm A sets fixed fee or royalty rate in order to maximize the sum of the profit from its own production and the licensing revenue.

Fixed fee licensing

First consider licensing by means of a fixed fee only. Under the fixed fee licensing, firm A licenses its cost-reducing technology to firm B at a fixed fee F (say), which is invariant of the quantity firm B produces using the new technology. The maximum license fee firm A can charge firm B is what will make firm B indifferent between having the license and not having the license of the new technology. In case the licensing occurs, both firms will produce at the same marginal cost of $(c - \varepsilon)$ and earn a profit: $\pi_A = \pi_B = \frac{1}{2}$.

Therefore, $F = \frac{1}{2} - \frac{(3-\varepsilon)^2}{18}$ (using (10)). Hence, total profit of firm A from licensing is:

$$\pi_A^F = \frac{1}{2} + F = 1 - \frac{(3-\varepsilon)^2}{18}. \tag{12}$$

In the case of drastic innovation: $F = \frac{1}{2} - 0 = \frac{1}{2}$ (using (11)). Hence, total profit of firm A is:

$$\pi_A^F = \frac{1}{2} + \frac{1}{2} = 1. \tag{13}$$

[13] The case of auction does not arise here since there is just one firm to license.

Now comparing (10) and (12) as well as (12) and (13) we get the following result.

PROPOSITION 3.2. *Both under non-drastic and drastic innovation, offering no license to the rival is better for the insider patentee than offering a fixed fee licensing.*

This result is interesting because in the situation where the patentee is also a competitor in the product market, and the competition takes place in price, there will be no fixed fee licensing. This happens exactly because of the nature of price competition. When the patentee offers a fixed fee license to the rival, both the patentee and the licensee compete on equal footing, and the price competition results in low profit to both firms. As a result, the patentee cannot charge a high fixed fee from its rival because the difference between the competing profit and the reservation payoff becomes small. On the other hand, if the patentee does not license the rival, it can hold a significant cost advantage when it shares the market with rival in the non-drastic case, which enables the patentee to get a significantly higher profit. On the other hand, in the case of drastic innovation the patentee actually serves the whole market just as a monopoly and naturally gets a high profit. Thus, offering no license is better than offering a fixed fee licensing when the patentee competes with the rival in price.[14]

Royalty licensing

Under a royalty licensing, firm A licenses its new technology to firm B at a royalty rate r (say), and the amount of total royalty firm B pays will depend on the quantity firm B produces using the new technology. In this case, firm A's marginal cost of production is $(c - \varepsilon)$ and firm B's marginal cost of production becomes $(c - \varepsilon + r)$. Note that the maximum royalty that firm A can charge is ε (given $0 < r \leqslant \varepsilon$). Now, if firm B buys the license at a royalty rate r then $D_{\mathrm{B}} = \frac{3-r}{6}$ (using (8)). Note that for $D_{\mathrm{B}} \geqslant 0$, we must have $r \leqslant 3$. Firm A's profit from competing is: $\pi_{\mathrm{A}} = \frac{(3+r)^2}{18}$. In the case of non-drastic innovation firm A's total profit under royalty licensing is: $\pi_{\mathrm{A}}^{R} = \frac{(3+r)^2}{18} + r(\frac{3-r}{6})$, which is maximum when $r = \varepsilon$ (< 3). Hence,

$$\pi_{\mathrm{A}}^{R} = \frac{(3+\varepsilon)^2}{18} + \varepsilon\left(\frac{3-\varepsilon}{6}\right). \tag{14}$$

In the drastic case firm A's total profit under royalty licensing is:

$$\pi_{\mathrm{A}}^{R} = \frac{(3+r)^2}{18} + r\left(\frac{3-r}{6}\right).$$

[14] When the competition takes place in quantities where under certain parametric configuration fixed fee licensing is actually better than no licensing (see Wang, 1998).

Unconstrained maximization of the above expression with respect to r, gives $r^* = 3.75$. Note that π_A^R is a concave function in r and it is increasing for $r < 3.75$. Also recall that $D_B \geqslant 0$, when $r \leqslant 3$. Hence, the (constrained) optimal r^* in the drastic case is 3. Thus,

$$\pi_A^R = \frac{(3+3)^2}{18} + 3.0 = 2. \tag{15}$$

Now comparing (10) and (14) as well as (11) and (15) we have the following.

PROPOSITION 3.3. *Offering royalty licensing is superior to offering no license for the insider patentee when the innovation is non-drastic, while offering no license is superior to royalty when the innovation is drastic.*

This result is in contrast with the result obtained by Fauli-Oller and Sandonis (2002), where they show in a standard framework of differentiated Bertrand competition, whenever the goods are not perfect substitutes, even drastic innovations are licensed. In Fauli-Oller and Sandonis (2002), the reason for licensing drastic innovation arises from the market expansion effect of bringing the rival back into operation and the resulting gain in the royalty payment to the insider patentee. In our case, the market size is always fixed across pre and post-licensing regimes. Thus, under drastic technology bringing back the rival into the market operation reduces the total surplus for the patentee.[15]

3.3. Incentive for innovation

Now we focus our attention to one of the much-debated issues in innovation and licensing literature, namely the incentive for innovation. In particular, we are interested to compare the incentive for innovation in two cases depending whether the innovator is an insider or an outsider. Note that the incentive for innovation is what an agent expects as a gain in payoff from undertaking innovation.

First, in the case of insider innovator, the incentive for non-drastic innovation is given by the difference between its payoff under innovation with selling the license and its pre-innovation payoff under the old technology, which is given by $\frac{(3+\varepsilon)^2}{18} + \varepsilon(\frac{3-\varepsilon}{6}) - \frac{1}{2}$. The incentive for drastic innovation is given by $(\varepsilon - 1) - \frac{1}{2}$. Recall that in the drastic case, the innovator does not license. On the other hand, an outsider patentee always receives a payoff of ε from the innovation followed by licensing irrespective of the fact the innovation is drastic or non-drastic. Hence, comparing the two payoffs in these two cases we find the following.

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[15] It is easy to verify that a general licensing scheme in the case of insider patentee with two-part tariff cannot be optimal.

PROPOSITION 3.4. *Irrespective of the nature of innovation, the incentive for innovation is always higher when the patentee is an outsider as opposed to an insider.*

This result has the following simple intuition. In the case of outsider patentee, the patentee receives nothing if it does not innovate. On the other hand, an insider patentee is already earning some profit for being in the market; thus, its incentive for innovation would be lower.

Next we focus on to international technology transfer and study how the intellectual property rights (IPRs) influence international licensing.

4. International technology transfer and IPRs

4.1. Modes of technology transfer from North to South

The developed countries (North) are the major producers of newer technologies. The developing countries (South) are almost totally dependent on the North for technologies needed for their growth and development. The emergence of globalization went hand in hand with an emergence of multinational enterprises (MNEs) and these multinational enterprises mainly based in North are the major producers of newer technologies. Developing countries are more or less depending on these multinational enterprises for technologies. The literature has considered mainly three modes of serving a host country market when an MNE has a superior technology as compared to the existing technology of the host firms. The modes include licensing of superior technology to the host firms, exports and foreign direct investment.[16] In the literature an MNE chooses one of these three modes depending on their relative profitability to serve a particular domestic economy. One way to describe and evaluate the market entry decision of the MNE is the use of "internalization" models. Internalization is a part of what has become known as Dunning's OLI framework (Dunning, 1981), which presents three key advantages and conditions under which direct investment will occur (Markusen, 1995). According to Dunning, a firm first needs to have at least one firm-specific ownership advantage. Ownership advantage consists of some product or production process, which the other firms do not have, such as a patent, blueprint, trade secret and even a trademark or reputation. These advantages give a firm competitive edge over other firms to do business abroad. In addition to this, Dunning identifies a location advantage that the host market must offer. This simply means that there have to be reasons for choosing to produce abroad rather than exporting the goods, the most obvious one being tariffs, quotas or transport costs. The importance of the internalization lies in the fact that even if a firm has "ownership" and "locational" advantages it can sell (or

[16] There is another mode, which is the acquisition of the host firm or forming a joint venture with it.

license) the blueprints or technology to a potential host country firm rather than setting up a production facility there. Whether a transaction should be internalized is basically a matter of cost associated with the exchange of information between agents. Rugman (1986) argues that the theory of internalization plays a central role in explaining the existence of MNEs. The problem with transfer of technology under licensing mainly arises from the pricing and the risk of dissipation of this firm specific advantage. Internalization models first introduce these reasons as costs when licensing is chosen over FDI and then examine the different parameters that cause the MNE to choose one over the other.

The rationale for FDI are provided by considering the FDI as multiplant production (Dunning, 1981; Ethier, 1986; Markusen, 1984; Helpman, 1984, 1985, etc.) or as the outcome of tariff jumping effect (e.g., Horstmann and Markusen, 1992; Motta, 1992; Buckley and Casson, 1998) or as an outcome of a trade-offs between FDI and acquisition or joint venture. Apart from the literature which captures the different costs and benefits of different modes of entry, a strand of literature is more concerned with the welfare effects for the host country (e.g., Bardhan, 1982; Saggi, 1999; Mattoo et al., 2004; Eicher and Kang, 2005; Mukherjee, 2004, etc.).

However, given the focus of this chapter on patent licensing we would concentrate on the issues pertaining to licensing as a mode of international technology transfer. The key issue in such international technology transfer is the issue of imitation by the host firms of developing countries, which helps them to develop technological capabilities to become effective competitors of the technology supplier. The imitation of foreign technology is facilitated by the host countries patent enforcement regimes, which are typically weak in the developing countries. Thus, we would discuss the licensing as a mode of technology transfer and the issue of IPR enforcement in the context of licensing.

Saggi (1999) considered a two period model of technology transfer. In each period FDI and licensing are two modes of entry for foreign firm. He focused on the R&D incentives of both foreign and local firms under different entry modes. It is shown that the local firm develops the best technology if initial licensing is followed by FDI, whereas the foreign firm transfers the most efficient technology under FDI in both periods. On the other hand, Ethier and Markusen (1996), in their two period product-cycle model, have examined the choice between exporting, licensing and subsidiary as different modes of serving the market of a developing country by an MNE. A wide range of equilibrium outcomes is obtained in their paper including exporting in both periods, exporting in first period followed by licensing in the second period, subsidiary in both periods etc. The equilibrium displays interplay of locational and internalization considerations depending on the importance of knowledge capital, the discount rate, cost of exports etc. A key feature of the above models is that licensing leads to imitation of foreign technology by the local firms.

The theoretical literature on licensing has dealt with the issue of imitation (Kabiraj and Marjit, 1993; Katz and Shapiro, 1985; Rockett, 1990, etc.) as well as the incentive to innovate (Gallini, 1984; Gallini and Winter, 1985; Kabiraj and Yang, 2001, etc.) at great length. An explicit treatment of costly imitation is available in Rockett (1990), where she has extended the licensing literature to allow the licensor to choose the "quality" of the licensed technology as well as "the structure of payments" for the license. The product market is characterized by Cournot competition and both the licensor and the licensee compete in the same market. Gallini (1984) examined the ex-ante incentive for licensing and showed that an incumbent firm might license its production technology to reduce the incentive of a potential entrant to develop on its own, possibly a better technology. Kabiraj and Yang (2001) have discussed the innovative incentives of a local firm when an advanced technology may be available through licensing from a foreign firm.[17]

Here we present a simplified version of Ethier and Markusen (1996) (as discussed in Markusen, 1995). Consider a two period model in which a multinational firm wishes to exploit the technology in a host market either by licensing it to a host firm or by setting up a subsidiary (exporting option is ignored for simplicity). Both the MNE and the licensee decide about continuing the license agreement at the beginning of the second period. Licensing arrangement generates the most potential rent since there is additional cost of doing business abroad through subsidiary operation. In case of licensing the host firm learns the technology during the first period production and in the second period it can defect to start a rival firm. On the other hand, the MNE can defect by issuing a new license to a rival host firm in the second period. If both the licensee and the MNE defects in the second period then the original licensee and the new licensee compete as duopolists in the second period. Therefore, for the contract to be self-supporting, neither the MNE nor the licensee would wish to defect at the beginning of the second period. If the licensing agreement lasts both periods, total rents are $2R - F$, where R is the rent available in each period, and F is the cost for physical capital cost required for starting the production. If the MNE sets up a subsidiary, the rents will be $2M - F$, where M represents the rents from the subsidiary operation. Our assumption that licensing generates more rents than the subsidiary leads to $2R - F > 2M - F$. The third possibility is that the licensing arrangement only lasts one period and a duopoly exists in the second period. Then the rents will be $R + D - 2F$, where D represents the total rents for the both members of the duopoly in one period and the capital cost F must be doubled because there are two producers. We also assume that the rents from the duopoly option is the lowest of theses three scenarios, that is $2R - F > 2M - F > R + D - 2F$. Finally, licensing fees are L_1 in the first period and L_2 in the second.

[17] Gallini and Wright (1990) have considered the problem of technology transfer under asymmetric information in a static framework (with multistage game) when sharing of pre-contractual information about the economic value of innovation facilitates imitation at a fixed cost. They show that a licensor signals her technology type with an output based payment (royalty), but the imitation possibility restricts the size of that output based payment. This leads to the situation where the licensor leaves some of the rents with the licensee.

For the licensing arrangement to hold (from the perspective of the licensee):

$$R - L_2 > R - F.$$

For the licensing arrangement to hold (from the perspective of the MNE):

$$L_2 > R - F.$$

Therefore, the licensing will continue if $R < 2F$, that is, if the rent is not greater than twice the fixed costs. In this case, the MNE can also extract the maximum rents $L_2 = F$ and $L_1 = 2R - F$ from its licensee. If so, the licensee makes zero profit because the MNE extracts all the rents ($2R - F + F = 2R$), but also does not have any incentive to defect. If the condition $R < 2F$ does not hold, then overall rents go down because the fixed costs occur again after the first period, since the licensee will defect at the beginning of the second period and a duopoly will form. In the case of $F = 0$ there are no fixed costs of production; this is a situation of the case that only knowledge-capital is involved. In this case licensing will never be sustained in equilibrium and FDI will take place (Markusen, 1995). This simplified model therefore also makes the point of showing the reasons for intangible assets being crucial when it comes to deciding whether to produce via a licensee, or directly via a subsidiary.

4.2. Licensing and IPRs

The issue of patent protection is one of the most contentious issues in the context of technology transfer from the developed North to the developing South. Many developed countries feel that the present system provides an inadequate protection to intellectual property rights (IPRs) and they are interested in strengthening this protection in the world. The poorer countries, on the other hand, are against this protection, as it would increase the profits of the monopolistic Northern firms at the expense of their domestic consumers. The important questions, however, are whether an increase in patent enforcement in the South always leads to more innovation by the North and whether this increases the level of welfare in the South.

How the patent enforcement affects the mode of operation (exports or subsidiary) of the multinational corporation and welfare was analyzed by Markusen (2001). He noted that if tighter patent protection leads to a mode switch from exporting by Multinational Corporation to subsidiary operation, then the welfare of both the Northern firm and the host country (South) improves. On the other hand, if a subsidiary is chosen initially then tightening patent protection implies either no change or, a fall in host country welfare (due to an increase in Northern firm's rent). Fosfuri (2000) analyzed the mode of entry of Northern firms and the vintage of technology in terms of quality, which are influenced by the degree of patent protection in the recipient country. He showed that the welfare in the South is not a monotonic function of patent protection and both weak and strong patent protections are preferable to intermediate levels. In his model this happens because of the switch of modes of technology transfer with respect to the degree of patent protection.[18] In a screening model with asymmetry of information regarding imitation risk, Vishwasrao (1994) considered that the Northern firm could choose between licensing, exports and subsidiary and she argued that the gains from weaker IPRs protection might be offset by the strategic behavior of the Northern firms, who opt for subsidiary or monopoly (export) production rather than licensing the technology. In Vishwasrao (1994), the gain from weaker patent protection is the duopoly market structure due to 'multiplant' licensing (under pooling equilibrium). Only licensing as a mode of technology transfer was considered by Yang and Maskus (2001). In a dynamic general equilibrium model with product cycle, Yang and Maskus (2001) argued that stronger IPRs in the South would generate a higher rate of innovation. In their paper a stronger IPR in South reduces the licensing cost associated with monitoring and enforcing the licensing contract and increases the licensor's share of rent. As a result, both licensing and innovation would rise and additional resources would be available in the North for R&D. Here we provide below a simple adaptation of Sinha (2006).

In a North–South framework, consider a two period model. An MNE possesses a technology (call it technology 1), which may be used to produce a particular product in the South. There is patent protection in the North for technology 1. We assume that the MNE can innovate a new technology (cost reducing type) in the first period in its R&D laboratory by incurring an expenditure. However, the outcome of this process innovation is uncertain. The Northern firm would be successful in innovation with probability p and the related R&D expenditure is $\frac{1}{2}Kp^2$ where K is a positive constant, p is common knowledge to both the firms. Also, the innovation outcome (success or failure) is observable to all. This new technology (call it technology 2), if available, will be used only for the second period's production. For simplicity, we assume that these technologies are not used for the production in the North to serve the consumers there. We restrict ourselves to the modes of operation for the MNE between licensing and subsidiary.[19]

We assume that technology 2 is 'drastic' as compared to technology 1. We assume that Π_1 and Π_2 are one-period monopoly profits (net of marginal costs) that can be generated by the Northern firm in the Southern market by utilizing technology 1 and technology 2 respectively either through licensing or subsidiary. Obviously, $\Pi_2 > \Pi_1$. If the Southern firm continues with its existing technology it earns its reservation payoff that, for simplicity, is taken to be zero in both periods.

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[18] See Markusen (2001) and Fosfuri (2000) for detailed working of their models. However, it should be noted here that in Markusen (2001) technology transfer through a subsidiary creates an opportunity for the local agent to imitate the technology and thus, the local agent may "defect" to start a rival firm in future. On the other hand, Fosfuri (2000) assumed that the technology transfer under licensing facilitates imitation by the licensee and subsidiary production or exports circumvent imitation.

[19] See Sinha (2006) for an analysis of exports also.

We also assume that the technology transfer under licensing facilitates imitation without any cost through a process of "learning by doing" during production in the first period. Due to this imitation, in the second period the Southern firm will have the necessary technical knowledge to carry out the production with technology 1, without depending on the Northern firm. When the market is served through the subsidiary, the Southern firm cannot imitate the Northern technology. However, when the Northern firm sets up a wholly owned subsidiary it has to incur a setup cost $F > 0$. This is a once for all fixed cost of setting up a business in the South and once the subsidiary is set up the MNE would continue with it for both periods.

Under subsidiary operation the MNE expects to receive from its R&D

$$p(\Pi_2) + (1 - p)\Pi_1 - \frac{1}{2}Kp^2. \tag{16}$$

The Northern firm would choose p (under subsidiary (S) operation) to maximize the above payoff from its R&D. Thus, the first order condition implies

$$p^S = \frac{(\Pi_2 - \Pi_1)}{K} \tag{17}$$

which is positive.

Since the Northern firm has to incur a setup cost F for its subsidiary in the first period, the Northern firm would receive the payoff $\Pi_1 - F$ in the first period. Thus, the Northern firm's total two period's payoff under the subsidiary operation is:

$$R^S = \Pi_1 - F + p^S(\Pi_2) + \left(1 - p^S\right)\Pi_1 - \frac{1}{2}Kp^{S^2}. \tag{18}$$

On the other hand, if the licensing is chosen in the first period then the licensing contract needs to be renewed in the second period. If the Southern firm does not renew the license in the second period the Northern firm may enter with a subsidiary. In the second period, if the Northern firm enters with technology 2 then it would monopolize the Southern market. However, if the Northern firm enters with technology 1, there will be Cournot duopoly competition in the Southern market as the Southern firm can operate with technology 1 because of imitation provided that the patent enforcement regime in the South allows that. If the patent enforcement regime does not permit the Southern firm to use technology 1 after imitation then the MNE would monopolize the Southern market with technology 1. We denote Cournot duopoly profit under technology 1 by Π_1^d.

We specify the following:

(A1) $\Pi_1^d - F > 0$.
(A2) $2\Pi_1^d < \Pi_1$.

The setting up of a subsidiary with technology 1 is feasible even when there is duopoly competition in the market. (A2) implies that the monopoly profit is larger than the sum of duopoly profits under technology 1.

Now we consider the outcome associated with the licensing contract. Assume that the patent enforcement in the host country is imperfect. Thus, we assume that the Southern firm can imitate the first period technology without any cost, but there is a positive probability, γ, that the local court in the South, in the beginning of the second period, will be able to detect the imitation and debar the Southern firm from using it in the second period (where $0 \leqslant \gamma < 1$).[20] On the other hand, if the imitation is not detected by the Southern court, the Southern firm can continue its production with the imitated technology. Thus, the Southern firm will be able to use the first period technology in the second period with probability $(1-\gamma)$. But with the imitated technology 1 the Sothern firm can compete with the MNE only when the MNE is not successful in developing the technology 2. So, the Southern firm would be able to earn by defection (by not renewing the licensing contract) in the second period either 0 or $(1-\gamma)\Pi^d(c_1)$, depending on whether the Northern firm is successful in innovation or not. So the Southern firm should be allowed to enjoy the above payoffs for the renewal of licensing contract. Note that the R&D expenditure made by the Northern firm in the first period depends on what the Northern firm expects to receive in the second period. Once the licensing contract is in place in the first period the Northern firm expects to get by investing in R&D under the partial patent enforcement

$$p(\Pi_2) + (1-p)\big\{\gamma\Pi_1 + (1-\gamma)\big(\Pi_1 - \Pi_1^d\big)\big\} - \frac{1}{2}Kp^2. \tag{19}$$

Thus, the maximization of the above payoff leads to the following choice of p under licensing (L).

$$p^L = \frac{\Pi_2 - \Pi_1 + (1-\gamma)\Pi_1^d}{K}. \tag{20}$$

Note that γ measures the degree of patent enforcement in the present setup. The patent enforcement becomes weaker as γ decreases. Now it is obvious from the above condition that the R&D expenditure under licensing $p^L(\gamma))$ would be higher, the lower the γ is, i.e., the lower the patent enforcement is. Thus, the innovation rate would be the highest when there is no patent enforcement in the South. Thus, we have found an inverse relationship between the patent enforcement in the South and innovation rate in the North under licensing contract. Also note that the innovation rates are the same both under subsidiary and licensing when $\gamma = 1$, i.e., when there is perfect patent enforcement in the South.

In the beginning of the first period, by accepting the licensing contract the Southern firm expects to receive a two period payoff as given below.

$$\Pi_1 + p^L.0 + \big(1-p^L\big)(1-\gamma)\Pi_1^d - T_1, \tag{21}$$

[20] We are assuming away any cost associated with the filing of application to the local court such as court fee and payment to lawyers for both parties. Also we rule out any penalty imposed by the court on the Southern firm in case the imitation is detected except that the court forbids the Southern firm to use that technology without the renewal of the license.

where T_1 is the upfront license fee that is paid to the Northern firm when the licensing contract is signed in the first period.

The Northern firm receives the total payoff in two periods by offering the licensing contract in the first period

$$T_1 + p^L(\Pi_2) + \left(1 - p^L\right)\left\{\gamma \Pi_1 + (1-\gamma)\left(\Pi_1 - \Pi_1^d\right)\right\} - \frac{1}{2}Kp^{L^2}.$$

The Northern firm would charge the fee T_1 optimally such that the Southern firm receives its two period reservation payoff, which is assumed to be zero (i.e., (21) becomes zero). Thus, the Northern firm receives the total payoff under the licensing contract,

$$R^L(\gamma) = \Pi_1 + p^L(\Pi_2) + \left(1 - p^L\right)(\Pi_1) - \frac{1}{2}Kp^{L^2}. \tag{22}$$

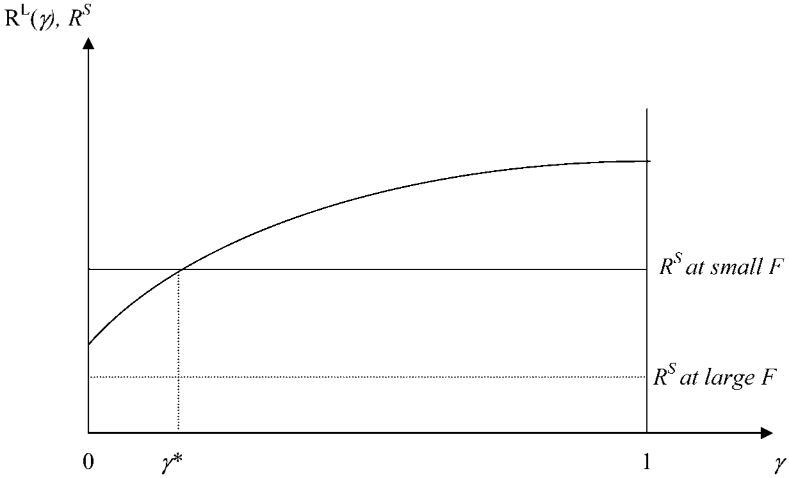
Now by comparing the probability of innovation under licensing and subsidiary operation we find that

PROPOSITION 4.1. *The innovation rate is higher under the licensing contract with imperfect patent enforcement* (*i.e.,* $0 < \gamma < 1$) *than under the subsidiary operation. Also, the lower is the degree of patent enforcement in the South, the higher is the innovation rate in the North under licensing contract.*

Let us discuss the intuition of the higher innovation rate under the licensing contract. Note that in the first period, the Northern firm can either set up a subsidiary or license out technology 1. If it sets up a subsidiary in the first period then it would serve the market under monopoly through the subsidiary operation with the best available technology in each period. On the other hand, if the Northern firm licenses out technology 1 in the first period then in the second period it receives the same payoff as in subsidiary operation in case it is successful in developing technology 2. However, it receives strictly lower payoff under licensing than under subsidiary in case it is not successful in innovation and the patent is not enforced by the host country. Note that the Northern firm's R&D expenditure depends on the premium it receives after being successful which is over and above what it receives when it fails to innovate. As a result, the Northern firm's R&D incentive is higher under licensing contract than under a subsidiary in the first period. Therefore, the innovation rate, i.e., the probability of successful innovation is higher under licensing contract.

The welfare in South is only dependent on consumer surplus since the Southern firm receives zero in two periods under licensing contract. The consumer surplus depends on the probability of introducing the better technology in the South. Therefore, the consumer surplus varies inversely with the degree of patent enforcement and the Southern welfare is maximum when the South has no patent enforcement at all. However, the above implications of patent enforcement hold only if the Northern firm chooses the licensing contract as opposed to subsidiary operations. Thus, the welfare maximizing Southern government would choose

Figure 2.



the minimum level of patent enforcement in order to induce the MNE to choose the licensing contract in the first period.

In order to compare the payoffs from the option of subsidiary and licensing, first note that the total payoffs from licensing $R^L(\gamma)$ is maximized when $p^L = \frac{(\Pi_2 - \Pi_1)}{K}$. By comparing with (20) it is clear that the actual R&D expenditure is suboptimal (over investment in R&D) under imperfect patent enforcement from the MNEs perspective and R^L (γ) is the maximum when $\gamma = 1$. For other values of γ, p^L is higher and given the concavity of R^L with respect to p^L we find that R^L decreases as γ goes down. Also note that R^L $(\gamma = 1) > R^S$ for any $F > 0$. The payoff functions under licensing and subsidiary with respect to γ are plotted in Figure 2 with the help of (18), (20) and (22).

Observe that for large enough F, the optimal degree of patent enforcement would be $\gamma = 0$ and for smaller F, the optimal degree of patent enforcement is given by γ^* at the intersection of two payoff functions. At γ^* the MNE is indifferent between subsidiary and licensing operation and we assume that the MNE would license out the technology to the host firm. Thus, under the optimal patent enforcement which is always imperfect as $F > 0$, the innovation rate is higher in the North and the welfare in the South is higher as compared to the situation of perfect patent enforcement. Moreover, as the fixed set up cost F goes down the optimal degree of patent enforcement goes up and thus, the Southern government needs to strengthen the patent enforcement in order to induce the MNE to choose licensing as the optimal mode of operation in the South.

To sum up, we have the following result.

PROPOSITION 4.2. *For large F, the optimal degree of patent enforcement for the South is zero. However, for smaller F, the optimal degree of patent enforcement is positive and given by γ^*.*

Thus, it is clear from the above discussion that the degree of IPR protection in South does affect the licensing of advanced technology to the host country firms. It is also interesting to note that the innovation in the North is higher in the North when the licensing is the mode of technology transfer to South. Keeping in view this behavior of the Northern firms, the Southern governments can decide on the degree of optimal patent enforcement.

5. *Conclusion*

We begin this chapter by offering a plausible explanation of the empirically observed pattern of patent licensing. We considered a simple environment of asymmetric information (with regard to the true state of demand) with adverse selection. In such an environment under complete information, the optimal licensing contract would be to charge a fixed fee contingent upon the state of demand. But due to asymmetric information, where the licensee has private information about the true demand, an adverse selection problem arises. We showed that an optimal licensing contract of the patentee is to offer a separating contract, one for the low demand type and the other for the high demand type. A low demand type is offered with a contract which is either only royalty or a combination of fixed fee and per unit royalty and the high demand type is offered with a contract with only fixed fee. We proved that the expected payoff to the patentee from the separating contract is higher than any pooling contract. We also showed that irrespective of the prior belief of the patentee, new technology is always offered to both types under the separating contract. In other words, the market is always served by the new technology irrespective of the prior belief of the patentee, unlike the pooling contracts where both types are offered with new technology over a restricted range of prior belief of the patentee. Thus, the optimal separating licensing contract also turned out to be more efficient than an optimal pooling contract. This kind of linear scheme is indeed observed in practice.

We also derived some testable hypotheses from our theoretical analysis. We would expect to observe only fixed fee or only royalty contract in the boom period or during big fluctuation of market demand; whereas a combination of fixed fee and royalty or only fixed fee should be observed during bust or when there is less variation in market demand.

Next, we establish that the optimal licensing policy may be quite different under spatial competition as compared to the usual Bertrand competition with differentiated products. In the case of an outsider patentee, we show that auction and fixed fee yield equivalent payoff to the patentee, and only one of the competitors is offered the license irrespective of the nature of innovation, i.e., drastic or non-drastic. On the other hand, in the case of royalty licensing both the competing firms are offered with the license irrespective of the nature of innovation. Moreover, royalty licensing turns out to be better compared to auction or fixed fee, as it always yields higher payoff to the patentee. In the case of outsider patentee, we also find the interesting result that the licensing takes place to two competing firms, even if the innovation is drastic. In the case of insider patentee with a rival competitor, we find licensing by means of royalty is superior to no licensing or fixed fee licensing to the patentee when the innovation is non-drastic. When the innovation is drastic, no licensing is optimal to the patentee. We also focus our attention to the issue of incentive for innovation and show that in a spatial framework like this, irrespective of the nature of innovation, i.e., drastic or non-drastic, incentive for innovation is always higher for an outsider patentee compared to an insider patentee.

Finally, we end the chapter by focusing on international technology transfer. Licensing serves as an important mode of international technology transfer. It often helps the technology recipient country to develop its own domestic technological capabilities. However, it is not clear whether the strengthening of patent enforcement in the developing countries under the current WTO regime would actually increase the innovation rate in the world. Thus, the debate on patent enforcement must take into account the different aspects of R&D organization and the enforcement of different contract laws to make any policy prescription related to patent enforcement and innovation.

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PART II

Information and cost sharing

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CHAPTER 4

Spillovers, Stable R&D Cooperations, and Social Welfare

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Abstract

This paper analyzes the stability and the welfare properties of R&D cooperations in an oligopolistic market with n firms. It is shown that the sizes of stable coalitions vary significantly with the kind and the actual value of spillovers, the institutional arrangement of cooperation between the firms and the underlying stability concept. Moreover, the welfare maximizing coalition is rarely a stable equilibrium outcome, hence there is scope for political intervention. However, the informational requirements on part of the policy makers are high, and they are at risk to adopt inappropriate measures that are detrimental to social welfare.

Keywords: research and development, internal and external stability, farsighted coalitional stability

JEL classifications: D43, L13, O31

1. Introduction

During the last 15 years, research and development (henceforth R&D) at the firm level has been one of the major fields of interest in industrial economics. Building upon the seminal work of d'Aspremont and Jacquemin (1988) and Kamien et al. (1992) most studies have focused on the optimal R&D investment of firms under different kinds of spillovers and under various institutional frameworks of cooperation between the firms, and have derived implications for the overall technological performance, equilibrium outputs and prices in the subsequent product market competition, and social welfare.[1] In doing so, most of the papers

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[1] For an overview of the vast literature the reader is referred to De Bondt (1997) and Amir (2000). See also Amir et al. (2003) for a generalized approach.

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in this field adopt two important simplifying assumptions. Firstly, the analysis is usually restricted to the special case of a duopoly. This is particularly important with regard to the possible forms of cooperation, because when there are two firms they can only cooperate or act individually. In reality, however, an industry consists of more than two firms, such that research coalitions of different sizes are observed. However, even if product markets with n firms are considered this issue is usually not addressed since it is mostly assumed that all firms participate in the (grand) coalition when cooperation in R&D takes place.[2] Secondly, the stability of research cooperations is generally not discussed in further detail. While this seems appropriate for the case of a duopoly, where a coalition is only formed if it is profitable for both parties, ignoring the question of stability is less reasonable for markets with n firms, because the *size* of a coalition becomes an additional determinant of whether it is attractive to join or leave a research cooperation.[3] To the best of our knowledge, there are only a few studies that explicitly address the problem of stable cooperations in a model with n firms. While Bloch (1995) focuses on the process of coalition formation in this respect, Poyago-Theotoky (1995), De Bondt and Wu (1997) and Yi and Shin (2000) consider the standard model with output spillovers introduced by d'Aspremont and Jacquemin (1988) (d'Aspremont and Jacquemin model henceforth referred to as the AJ model). They derive the size of stable R&D coalitions under different membership rules and also discuss the implications for the firms' profits and for social welfare in the resulting equilibrium outcomes.

In this paper we provide a comprehensive analysis of the welfare properties of stable R&D coalitions in an oligopolistic market with n firms. Unlike Poyago-Theotoky (1995), De Bondt and Wu (1997) and Yi and Shin (2000), however, we do not restrict ourselves to the AJ model but also consider the case of input spillovers based on Kamien et al. (1992) (Kamien et al. model henceforth the KMZ model). In addition we employ the concept of farsighted coalitional stability and also discuss different kinds of cooperation between the firms. It is shown that there generally are several stable coalitions whose sizes depend crucially on the kind of spillovers that prevails, on the actual value of the spillover rate, on the institutional arrangement of cooperation, on the fact whether free entry to an existing coalition is possible or not, and on whether firms are myopic or farsighted regarding the future behavior of their competitors. Likewise, the size of the welfare maximizing coalition varies significantly across the different types of spillovers and cooperations. Moreover, there is no endogenous rule

[2] See, e.g., Kamien et al. (1992), Suzumura (1992) and Kamien and Zang (1993). Notable exceptions are Bloch (1995), Poyago-Theotoky (1995), De Bondt and Wu (1997) and Yi and Shin (2000), see the discussion below.

[3] Empirical evidence provided by Kogut (1989) suggests that the (in)stability of research cooperations is in fact a relevant issue. Veugelers and Kesteloot (1994) and Kesteloot and Veugelers (1995) analyze the stability of such cooperations in the framework of a duopolistic market, but they employ a different notion of stability, viz. cheating within an existing coalition instead of leaving it. Other authors (Lambertini, 2000; Lambertini et al., 2003) address the stability of collusive behavior in the product market competition that follows the firms' R&D investments.

or mechanism which ensures that stability and social optimality of a coalition coincide. Our results thus suggest that obtaining the welfare maximizing coalition as a stable equilibrium outcome requires very specific constellations of the aforementioned components of the model. This, of course, opens up the scope for political intervention to bring about the socially optimal coalition size, e.g., by subsidizing R&D investments. However, if the welfare maximizing coalition is unstable, this would require a *permanent* intervention because the cooperation breaks down immediately once the subsidies are canceled. A less far-reaching policy could thus amount to just *inducing* a stable coalition with the highest social welfare among all stable coalitions. While this need not be the socially optimal outcome, the cooperation will be maintained by the firms even without subsequent subsidies. In any case, the informational requirements on part of the policy makers to achieve their goal are enormous since they need to have detailed information about the kind and the size of spillovers as well as the exact institutional arrangement of cooperation between the firms. If this information is incomplete, distorted or associated with uncertainty, the policy measure is likely to induce a suboptimal coalition size which might even lead to a lower social welfare than without state intervention. In particular inducing the grand coalition as often suggested by related theoretical models may be detrimental to social welfare. The central message of our analysis is thus a disappointing one: if we leave the well-behaved framework of a duopolistic market, a suboptimal equilibrium outcome is the rule rather than the exception, and the scope for improving this situation by policy measures is somewhat limited. In particular, recommendations for R&D policies derived from the standard models have to be treated with caution unless the “type” of industry under consideration is really “obvious.”

The remainder of the paper is organized as follows. In Section 2 we present general versions of the well-known AJ and KMZ models and derive the optimal R&D investments of the firms under different kinds of cooperation. In Section 3 we then compare the sizes of stable coalitions for various stability concepts by means of a numerical analysis. In this context we also study the welfare properties of the different models and discuss the associated policy implications. Some concluding remarks are presented in Section 4. Finally, Appendix A contains technical details that are omitted in Section 2.

2. *The models*

In this section we present particular versions of the well-known AJ and KMZ models. We consider N symmetric firms that produce a homogeneous good and compete with each other in a two-stage game. In the first stage, the firms decide upon their investment in cost reducing R&D. After the successful completion of the respective R&D projects they engage in Cournot competition on the product market in the second stage. The AJ and the KMZ model only differ in the way how R&D activities are transformed into cost reductions and hence with respect to the first stage. The second stage is formally identical, so it may be captured in a unique framework. Here, the firms decide simultaneously on their profit maximizing outputs q_i, $i = 1, \ldots, N$. They are all confronted with a single inverse demand function

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

where $a, b > 0$ are given parameters and $Q = \sum_{i=1}^{n} q_i$ is total output. The firms' production technology is summarized by a linear cost function

$$C_i(q_i) = c_i \cdot q_i, \tag{2}$$

where c_i denotes the constant marginal costs of firm i *after* a successful completion of an R&D project. Hence, total second stage profits of firm i are given by

$$\Pi_i(q_i) = p(Q) \cdot q_i - c_i \cdot q_i, \tag{3}$$

and are maximized with respect to q_i for given expectations about the competitors' outputs q_j, $j \neq i$. Solving the first order condition for q_i gives firm i's reaction function

$$q_i = \frac{a - c_i - b \sum_{j \neq i} q_j}{2b}. \tag{4}$$

Combining these expressions for $i = 1, \ldots, N$ then yields the optimal output as

$$q_i = \frac{a - (N+1)c_i + C}{b(N+1)}, \tag{5}$$

where $C = \sum_{i=1}^{n} c_i$ are aggregate marginal costs. Inserting (5) into (3) we finally obtain the second stage profits of firm i:

$$\Pi_i = \frac{(a - (N+1)c_i + C)^2}{b(N+1)^2}. \tag{6}$$

For the subsequent welfare analysis we do not only consider the firms' profits but are also interested in consumer surplus. In view of the linear demand function, the latter is given by $CS = (1/2)bQ^2$. By summing up the reaction functions (4) over all i and solving for Q we thereby obtain

$$CS = \frac{(Na - C)^2}{2b(N+1)^2}. \tag{7}$$

When deciding on their R&D investments (which determine the precise value of c_i) in the first stage, the firms correctly anticipate the resulting Nash-equilibrium on the product market which is summarized by (5) and (6). As the AJ and the KMZ model differ significantly in this respect, however, we present the first stage in separate sections to solve for the subgame perfect equilibrium of the total two-stage game.

2.1. Output spillovers

In the AJ model, a firm's original cost function is given by $C_i^0(q_i) = c \cdot q_i$, where $c > 0$ is a parameter that is the same for all firms. In the first stage, every firm decides on a cost reduction $x_i \geqslant 0$ that shall become effective in the second stage, and which gives rise to the R&D production costs $(\gamma/2)x_i^2$, where $\gamma > 0$ is a parameter. The main feature of the AJ model is the presence of output spillovers, which imply that part of any firm's cost reduction is also beneficial to all its competitors. If we denote the relevant spillover rate by σ, $0 \leqslant \sigma \leqslant 1$, a cost reduction x_i of firm i thus leads to a cost reduction amounting to σx_i for every other firm. Hence, the second period effective marginal costs of firm i are given by

$$c_i = c - \left(x_i + \sigma \sum_{j=1, j\neq i}^{N} x_j\right) = c - \big[(1-\sigma)x_i + \sigma X\big], \tag{8}$$

where $X = \sum_{i=1}^{N} x_i$. For the total marginal costs it thus follows that

$$C = Nc - (1-\sigma)X - \sigma N X, \tag{9}$$

and by inserting (8) and (9) into (6) and (7), we see that the profit of an individual firm π_i and the consumer surplus CS are given by

$$\pi_i(x_i) = \frac{[(a-c) + (N+1)(1-\sigma)x_i + (2\sigma - 1)X]^2}{b(N+1)^2} - \frac{1}{2}\gamma x_i^2 \tag{10}$$

and

$$CS = \frac{[N(a-c) + [1 + (N-1)\sigma]X]^2}{2b(N+1)^2}, \tag{11}$$

respectively.

As common in the literature, we discuss three different forms of cooperation in R&D between the firms.[4] In the first case, several firms set up an R&D cartel by choosing the same cost reduction so as to maximize their joint profits. Since there are N firms in the market, there may be cartels of different sizes. For simplicity, though, we only allow for the existence of one single cartel (but with arbitrary size), i.e., there are no competing research coalitions. All firms that are not a member of the R&D cartel simply choose their individual cost reduction in order to maximize their own profits π_i. Thus, the benchmark case of no cooperation in R&D is included in this variant of the model for the case that no cartel is agreed upon.

Most papers in the literature either consider a duopoly version of the AJ model or the case that all or none of the firms in the market participate in the

[4] Those forms of cooperation have already been introduced within the seminal papers of d'Aspremont and Jacquemin (1988) and Kamien et al. (1992), and are discussed intensively in Amir (2000).

R&D cartel. Then, nonnegativity constraints for the cost reductions cause no essential problem under plausible parameter restrictions. In our setup, however, where coalitions of any size are feasible, binding nonnegativity constraints turn out to be the rule rather than the exception for any reasonable (and even unreasonable) parameter constellation. Therefore, all optimization problems have to be solved by means of the Kuhn–Tucker Theorem, but despite of this the derivation of the optimal cost reductions is quite straightforward. For brevity, we thus only present the results in the main text and refer to Appendix A for a more detailed exposition.

Suppose that firms $i = 1, \ldots, K$, $2 \leqslant K \leqslant N$, build an R&D cartel, and denote their optimal cost reduction by x^C, where C indicates the cartel solution. The optimal cost reduction for the non-members is denoted by x^{nC}.[5] If the nonnegativity constraints of both the cartel members and non-members are not binding in equilibrium, x^C and x^{nC} are given by

$$x^C = \frac{A(K) + (N-K)(2\sigma - 1)}{A(K)B(K) - K(N-K)(2\sigma-1)^2}(a-c) \tag{12}$$

and

$$x^{nC} = \frac{B(K) + K(2\sigma - 1)}{A(K)B(K) - K(N-K)(2\sigma-1)^2}(a-c), \tag{13}$$

where $A(K)$ and $B(K)$ are (rather complicated) terms that depend on the cartel size K and on the other parameters of the model, see (A.3) and (A.5) in Appendix A. If, on the other hand, it is optimal for one of the parties not to engage in R&D, then the cost reductions are given by $x^C = (a-c)/B(K)$ for $x^{nC} = 0$ as well as $x^{nC} = (a-c)/A(K)$ for $x^C = 0$.

In the second mode of cooperation, some (or all) firms may set up a (non-cooperative) research joint venture (henceforth RJV), in which the members still choose x_i so as to maximize their individual profits but perfectly share the R&D related information by setting the spillover rate equal to one for all members. This case is subsequently referred to as case NJ (non-cooperative, joint research). Here, assuming that firms $i = 1, \ldots, K$ set up an RJV, the second period marginal costs of an RJV member are given by

$$c_i = c - \left(\sum_{j=1}^{K} x_j + \sigma \sum_{j=K+1}^{N} x_j\right) = c - \left[(1-\sigma)\sum_{j=1}^{K} x_j + \sigma X\right], \tag{14}$$

whereas the one of a non-member are still given by (8). Accordingly, the profits of an RJV member, a non-member as well as consumer surplus now take the

[5] Note that all firms are symmetric, so we may omit the index i that identifies the specific firms.

form[6]

$$\pi_i^{RJV}(x_i) = \frac{[(a-c) + (N+2-K)(1-\sigma)\sum_{j=1}^{K} x_j + (2\sigma-1)X]^2}{b(N+1)^2} - \frac{1}{2}\gamma x_i^2, \tag{15}$$

$$\pi_i(x_i) = \frac{1}{b(N+1)^2}\Bigg[(a-c) + (N+1)(1-\sigma)x_i + (1-K)(1-\sigma)\sum_{j=1}^{K} x_j + (2\sigma-1)X\Bigg]^2 - \frac{1}{2}\gamma x_i^2 \tag{16}$$

and

$$CS = \frac{[N(a-c) + [1+(N-1)\sigma]X + (K-1)(1-\sigma)\sum_{j=1}^{K} x_j]^2}{2b(N+1)^2}. \tag{17}$$

Routinely applying the Kuhn–Tucker Theorem to the various optimization problems gives

$$x^{NJ} = \frac{E(K) + (N-K)(2\sigma-1)}{D(K)E(K) - [K(1-K)(1-\sigma) + K(2\sigma-1)](N-K)(2\sigma-1)} \times (a-c) \tag{18}$$

and

$$x^{nNJ} = \frac{D(K) + K(1-K)(1-\sigma) + K(2\sigma-1)}{D(K)E(K) - [K(1-K)(1-\sigma) + K(2\sigma-1)](N-K)(2\sigma-1)} \times (a-c) \tag{19}$$

as the optimal cost reductions for an RJV member and a non-member, respectively, if all firms choose positive cost reductions. Here, $D(K)$ and $E(K)$ denote complicated terms that depend on the various parameters of the model, see (A.10) and (A.8) in Appendix A. Otherwise, we have $x^{NJ} = (a-c)/D(K)$ for $x^{nNJ} = 0$ as well as $x^{nNJ} = (a-c)/E(K)$ for $x^{NJ} = 0$.

In the final scenario we consider an RJV cartel as a possible form of cooperation between the firms. This case is referred to as case CJ, and reflects the situation where the members of the RJV choose the cost reductions to maximize their joint profits and set the internal spillover rate equal to one at the same time. Here, the profit functions of RJV members and non-members as well as consumer surplus are identical to those in the case NJ. By standard calculations we

[6] As before, those expressions are obtained by inserting (8) and (14) into (6) and (7).

thus obtain

$$x^{CJ} = \frac{E(K) + (N-K)(2\sigma - 1)}{E(K)F(K) - [K(1-K)(1-\sigma) + K(2\sigma-1)](N-K)(2\sigma-1)} \times (a-c) \tag{20}$$

and

$$x^{nCJ} = \frac{F(K) + K(1-K)(1-\sigma) + K(2\sigma - 1)}{E(K)F(K) - [K(1-K)(1-\sigma) + K(2\sigma-1)](N-K)(2\sigma-1)} \times (a-c) \tag{21}$$

as the optimal cost reductions for an RJV member and a non-member, respectively, in the case that both reductions are strictly positive. Here, $F(K)$ is another term depending on the parameters of the model, see (A.13) in Appendix A. In case of a binding nonnegativity constraint we have $x^{CJ} = (a-c)/F(K)$ for $x^{nCJ} = 0$ and $x^{nCJ} = (a-c)/E(K)$ for $x^{CJ} = 0$.

2.2. Input spillovers

The KMZ model differs from the AJ model in two respects. First, the firms do not directly choose the second period cost reductions but decide on their investments in R&D. These expenditures are then transformed into cost reductions via an R&D technology. Second, the firms do not benefit from the successful R&D projects of their rivals, i.e., there are no output spillovers. Instead, part of the R&D investment of one firm flows directly to all its competitors and adds on their own expenditures as an input of the R&D production function, i.e., there are input spillovers. Let $y_i \geqslant 0$ denote the R&D expenditures of firm i, $i = 1, \ldots, N$, and $0 \leqslant \theta \leqslant 1$ the spillover rate. Then the total R&D investment of firm i is given by $y_i + \theta \sum_{j=1, j\neq i}^{N} y_j$. For better comparison with the AJ model, we assume a specific R&D production function[7] which yields exactly the same results as the AJ model when there are no spillovers, i.e., $\sigma = \theta = 0$. Under this R&D technology a total input of y leads to a cost reduction of $\sqrt{(2/\gamma)\cdot y}$, where $\gamma > 0$ is a parameter. Hence, the second period cost of firm i is given by

$$c_i = c - \sqrt{\frac{2}{\gamma}\left(y_i + \theta \sum_{j=1, j\neq i}^{N} y_j\right)} = c - \sqrt{\frac{2}{\gamma}\big[(1-\theta)y_i + \theta \mathcal{Y}\big]}, \tag{22}$$

where $\mathcal{Y} = \sum_{i=1}^{N} y_i$ are the total R&D expenditures. The aggregate costs $C = \sum_{i=1}^{N} c_i$ are given by

$$C = Nc - \sum_{i=1}^{N} \sqrt{\frac{2}{\gamma}\big[(1-\theta)y_i + \theta \mathcal{Y}\big]}. \tag{23}$$

[7] This functional form of the production function has been introduced by Amir (2000) and is also applied in Hauenschild (2003).

Using these terms in (6) and (7), we obtain the following expressions for the profits π_i of firm $i, i = 1, \ldots, N$, and for the consumer surplus:

$$\pi_i(y_i) = \frac{1}{b(N+1)^2}\left[(a-c) + (N+1)\sqrt{\frac{2}{\gamma}\big[(1-\theta)y_i + \theta\mathcal{Y}\big]} - \sum_{j=1}^{N}\sqrt{\frac{2}{\gamma}\big[(1-\theta)y_j + \theta\mathcal{Y}\big]}\right]^2 - y_i, \tag{24}$$

$$CS = \frac{[N(a-c) + \sum_{j=1}^{N}\sqrt{\frac{2}{\gamma}[(1-\theta)y_j + \theta\mathcal{Y}]}]^2}{2b(N+1)^2}. \tag{25}$$

As for the AJ model, we consider three different forms of cooperation between the firms, where any number K, $2 \leqslant K \leqslant N$, may join such a cooperation but where we only allow for the existence of one single research coalition. In the first scenario, some firms build an R&D cartel and choose the same R&D expenditures that maximize their joint profits subject to a nonnegativity constraint.[8] Suppose that firms $i = 1, \ldots, K$ are members of the cartel and firms $i = K+1, \ldots, N$ are not. If both groups choose strictly positive R&D investments, the relevant first order conditions are (again see Appendix A for more details on the derivation of the results presented below)

$$\big[(a-c) + (N+1)Y^C - Y\big] \cdot \left(\frac{[1+\theta(K-1)](N-K+1)}{Y^C} - \frac{K(N-K)\theta}{Y^{nC}}\right) = \Gamma \tag{26}$$

for a cartel member and

$$\big[(a-c) + (N+1)Y^{nC} - Y\big] \cdot \left(\frac{N-(N-K-1)\theta}{Y^{nC}} - \frac{K\theta}{Y^C}\right) = \Gamma \tag{27}$$

for a non-member, where we have set

$$Y^C = \sqrt{\frac{2}{\gamma}\big[(1-\theta)y^C + \theta\mathcal{Y}\big]} \tag{28}$$

as well as

$$Y^{nC} = \sqrt{\frac{2}{\gamma}\big[(1-\theta)y^{nC} + \theta\mathcal{Y}\big]} \tag{29}$$

for the effective cost reductions of a cartel member and a non-member, respectively, and where y^C and y^{nC} denote the individual R& D expenditures.

[8] We have already claimed for the AJ model that binding nonnegativity constraints are the rule rather than the exception for either coalition members or non-members when the size of the coalition is less than N, so we have to take explicit account of them in the firms' optimization problem.

Furthermore, $Y = KY^C + (N-K)Y^{nC}$ and $\Gamma = b\gamma(N+1)^2/2$. Unlike the AJ model, (26) and (27) cannot be solved explicitly for the reaction functions and for Y^C and Y^{nC}, so we have to rely on numerical results below. From (28) and (29) the individual expenditures can then be obtained as

$$y^C = \frac{\gamma/2}{1+(N-1)\theta}\left(\left(Y^C\right)^2 - \frac{\theta(N-K)}{1-\theta}\left[\left(Y^{nC}\right)^2 - \left(Y^C\right)^2\right]\right) \tag{30}$$

and

$$y^{nC} = \frac{\gamma/2}{1+(N-1)\theta}\left(\left(Y^C\right)^2 + \frac{1+(K-1)\theta}{1-\theta}\left[\left(Y^{nC}\right)^2 - \left(Y^C\right)^2\right]\right), \tag{31}$$

where we have made use of $\mathcal{Y} = Ky^C + (N-K)y^{nC}$. If the nonnegativity constraint is binding for members of one group, the optimal investment for members of the other group is still derived from their optimality condition. The only required modification is to set the respective value of y in (28) or (29) equal to zero.

When the cooperating firms build an RJV instead of a cartel, they keep on determining their optimal expenditures individually so as to maximize their own profits but perfectly share information between all coalition members. Hence, the total realized cost reduction of an RJV member is obtained as

$$\begin{aligned} c_i &= c - \sqrt{\frac{2}{\gamma}\left(\sum_{j=1}^{K} y_j + \theta \sum_{j=K+1}^{N} y_j\right)} \\ &= c - \sqrt{\frac{2}{\gamma}\left((1-\theta)\sum_{j=1}^{K} y_j + \theta\mathcal{Y}\right)}, \end{aligned} \tag{32}$$

while the one of a non-member is still given by (22). This implies that the profits of an RJV member, a non-member as well as consumer surplus now take the form

$$\begin{aligned} \pi_i^{RJV}(y_i) = \frac{1}{b(N+1)^2}\Bigg[&(a-c) + (N+1)\sqrt{\frac{2}{\gamma}\left((1-\theta)\sum_{l=1}^{K} y_l + \theta\mathcal{Y}\right)} \\ &- K\sqrt{\frac{2}{\gamma}\left((1-\theta)\sum_{l=1}^{K} y_l + \theta\mathcal{Y}\right)} \\ &- \sum_{j=K+1}^{N}\sqrt{\frac{2}{\gamma}\big((1-\theta)y_j + \theta\mathcal{Y}\big)}\Bigg]^2 - y_i, \end{aligned} \tag{33}$$

$$\pi_i(y_i) = \frac{1}{b(N+1)^2}\Bigg[(a-c) + (N+1)\sqrt{\frac{2}{\gamma}\big((1-\theta)y_i + \theta\mathcal{Y}\big)} - K\sqrt{\frac{2}{\gamma}\left((1-\theta)\sum_{l=1}^{K} y_l + \theta\mathcal{Y}\right)} - \sum_{j=K+1}^{N}\sqrt{\frac{2}{\gamma}\big((1-\theta)y_j + \theta\mathcal{Y}\big)}\Bigg]^2 - y_i, \tag{34}$$

and

$$CS = \frac{1}{2b(N+1)^2}\Bigg[N(a-c) + K\sqrt{\frac{2}{\gamma}\left((1-\theta)\sum_{l=1}^{K} y_l + \theta\mathcal{Y}\right)} + \sum_{j=K+1}^{N}\sqrt{\frac{2}{\gamma}\big((1-\theta)y_j + \theta\mathcal{Y}\big)}\Bigg]^2, \tag{35}$$

respectively. Solving the different optimization problems we obtain the relevant first order conditions

$$\big[(a-c) + (N+1)Y^{NJ} - Y\big]\cdot\left(\frac{N-K+1}{Y^{NJ}} - \frac{(N-K)\theta}{Y^{nNJ}}\right) = \Gamma \tag{36}$$

for an RJV member and

$$\big[(a-c) + (N+1)Y^{nNJ} - Y\big]\cdot\left(\frac{N-(N-K-1)\theta}{Y^{nNJ}} - \frac{K\theta}{Y^{NJ}}\right) = \Gamma \tag{37}$$

for a non-member, where we have set

$$Y^{NJ} = \sqrt{\frac{2}{\gamma}\big[(1-\theta)Ky^{NJ} + \theta\mathcal{Y}\big]} \tag{38}$$

and

$$Y^{nNJ} = \sqrt{\frac{2}{\gamma}\big[(1-\theta)y^{nNJ} + \theta\mathcal{Y}\big]} \tag{39}$$

for the total effective cost reductions. The latter then yields the individual R&D investments as

$$y^{NJ} = \frac{\gamma/2}{K(1+\theta(N-K))}\left(\big(Y^{NJ}\big)^2 - \frac{\theta(N-K)}{1-\theta}\Big[\big(Y^{nNJ}\big)^2 - \big(Y^{NJ}\big)^2\Big]\right) \tag{40}$$

and

$$y^{nNJ} = \frac{\gamma/2}{1+\theta(N-K)}\left(\big(Y^{NJ}\big)^2 + \frac{1}{1-\theta}\Big[\big(Y^{nNJ}\big)^2 - \big(Y^{NJ}\big)^2\Big]\right). \tag{41}$$

If the nonnegativity constraint is binding for members of one of the groups, the optimal investment for the other group is obtained in exactly the same way as described for the case of an R&D cartel.

In the final case, where the cooperating firms build an RJV cartel to maximize their joint profits and set the spillover rate equal to one, the profit functions and consumer surplus are just the same as those denoted in (33)–(35) for the NJ case. Hence, by applying the Kuhn–Tucker Theorem to the respective optimization problems we obtain the first order conditions

$$\left[(a-c)+(N+1)Y^{CJ}-Y\right]\cdot\left(\frac{K(N-K+1)}{Y^{CJ}}-\frac{K(N-K)\theta}{Y^{nCJ}}\right)=\Gamma \tag{42}$$

for an RJV member as well as

$$\left[(a-c)+(N+1)Y^{nCJ}-Y\right]\cdot\left(\frac{N-(N-K-1)\theta}{Y^{nCJ}}-\frac{K\theta}{Y^{CJ}}\right)=\Gamma \tag{43}$$

for a non-member, where Y^{CJ} and Y^{nCJ} are exactly identical to Y^{NJ} and Y^{nNJ} as defined in (38) and (39). Hence, the individual R&D investments y^{CJ} and y^{nCJ} are obtained from Y^{CJ} and Y^{nCJ} by the very same set of equations as in (40)–(41). Moreover, we may proceed exactly as described above if the nonnegativity constraint is binding for members of one group.

3. *Stability of R&D cooperations and policy implications*

After having derived the firms' optimal R&D investment decisions inside and outside a research cooperation, we will now apply different stability concepts to analyze the respective sizes of stable coalitions that prevail in equilibrium. Furthermore, policy implications with respect to the promotion or prohibition of research coalitions are deduced under the general premise to maximize social welfare. In this context we also discuss the extent of information required by the policy makers to choose the "right" measures.

3.1. *Stability concepts*

In what follows we consider four different stability concepts that are built on how firms anticipate potential reactions of their competitors and on the rule of coalition formation. Regarding the first aspect we consider both myopic and farsighted behavior of the firms. In the former case, they only account for the fact that their competitors reoptimize their R&D investments if one firm joins or leaves a coalition, whereas in the latter case all subsequent entry or exit decisions of the other firms are anticipated as well. With respect to coalition forming we allow for open and exclusive membership, where the first rule reflects free entry of any firm to a given coalition while in case of the exclusive membership rule the members of a coalition may deter other firms from joining their cooperation. Table 1 shows the fundamental categories as well as the associated stability concepts.

Table 1. Categories of stability analysis

	Open membership	Exclusive membership
Myopic	$I\&E$	EX
Farsighted	FS	FSE

For the case of myopic firm behavior and open membership the concept of internal and external stability ($I\&E$) is adopted.[9] A coalition is called internally stable (*IS*) if it does not pay to a firm to leave it under the assumption that all other members remain in the coalition and reoptimize their investment decisions once the exit has occurred. In the context of R&D cooperation this means that it is better to be part of a larger coalition than to free-ride on the investments of a smaller one. External stability (*ES*) is characterized by the fact that no firm outside of the cooperation can improve its payoff by entering. When the assumption of open membership is replaced by exclusive membership, the resulting stability concept is denoted as *EX*.

If we assume anticipatory firm behavior in the sense described above in conjunction with the open membership rule, the concept of farsighted stability (*FS*) can be employed.[10] In contrast to the myopic perspective the farsighted view takes into account *all* reactions of the other firms including their possible leaving and joining of the coalition. Hence a coalition is farsighted stable if it is not attractive for a firm to quit or join once it takes into consideration all triggered consequences. Moreover, we also consider a variant of this stability concept that makes use of the exclusive coalition membership rule (*FSE*).

In the following sections we apply these stability concepts to the models outlined in Section 2 and derive the sizes of the stable coalitions. Since no analytical solutions are available we have to resort to a numerical analysis. The subsequent results are presented for a benchmark scenario with $N = 10$ firms and normalized parameter values of $a = 120$, $c = 10$, $b = 6$, and $\gamma = 3$. All results are qualitatively robust against variations in the parameter values, so we have chosen a parameter constellation for which the results are clearly visible and binding nonnegativity constraints are not observed in too many cases.

At first, however, we demonstrate by an instructive example how the results of our simulations may be analyzed and transformed into the graphical expositions of Figures 1–6. Table 2 summarizes the results for all possible coalitions in the CJ setting of the AJ model for a spillover rate $\sigma = 0.3$.

Column K contains the number of members of a potential coalition, where $K = 0$ and $K = 1$ both represent the non-cooperative case with no coalition

[9] See d'Aspremont et al. (1983). Regarding cooperation between firms in R&D this well-established concept is also adopted by De Bondt and Wu (1997).

[10] See Chwe (1994).

***Table 2.* Stable coalitions for σ = 0.3**

K	x^{CJ}	x^{nCJ}	X	π^{CJ}	π^{nCJ}	$I\&E$	EX	FS	FSE	SW
0	0.76	0.76	7.56	16.67	16.67					1042.94
1	0.76	0.76	7.56	16.67	16.67					1042.94
2	1.55	0.74	9.00	19.00	15.82					1052.52
3	2.47	0.67	12.09	22.61	13.09					1078.36
4	3.45	0.53	16.93	27.02	8.04					1134.21
5	4.22	0.30	22.60	30.81	2.55					1230.46
6	4.40	0.05	26.61	31.84	0.07		*EX*		*FSE*	1339.10
7	3.86	0.00	27.03	29.36	0.28		**EX**		**FSE**	**1394.71**
8	2.93	0.00	23.45	25.20	0.28		*EX*		*FSE*	1369.11
9	1.97	0.03	17.74	21.23	0.02		*EX*		*FSE*	1292.89
10	1.11		11.12	18.35		*I&E*	*EX*	*FS*	*FSE*	1193.89

formation.[11] The columns x^{CJ} and x^{nCJ} show the equilibrium R&D investments of each member and non-member of a coalition given by Equations (20) and (21), respectively, while π^{CJ} and π^{nCJ} are the associated payoffs. Observe that the nonnegativity constraints are binding for x^{nCJ} if the coalition contains $K = 7$ or $K = 8$ members, i.e., the non-members do not invest in R&D at all. For these coalition sizes, free-riding on the high R&D investments of the coalition members is so attractive that non-members prefer not to engage in R&D.[12] Finally, the column *SW* contains the social welfare which is defined as the sum of aggregated firm profits and consumer surplus. Moreover, the table also presents the results for stable R&D cooperations for the different stability concepts introduced above. Obviously, no myopic firm wants to leave any of the coalitions, hence all of them are internally stable (cf. Table 3). On the other hand, it always pays to enter an existing coalition so that only the grand coalition is internally and externally stable[13] ($I\&E$). The possibility to prevent other firms from joining the coalition is crucial in this setting because for $K \geqslant 6$ members the per-member payoff π^{CJ} decreases when additional firms join the coalition. Thus, provided their internal stability, these coalitions are stable under the exclusive membership rule.

Taking a farsighted perspective into consideration does not alter the results in this scenario because anticipating all reactions of the other firms is not relevant for the firms' decisions to join or leave an R& D cooperation. Observe that the bold letters in Table 2 indicate the socially optimal RJV cartels. A coalition with

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[11] There is no difference between no coalition ($K = 0$) and a "coalition" consisting of one firm ($K = 1$) in our models.

[12] For the case of a coalition consisting of nine members, coordination leads to a significant decline in the R&D investments of the members such that the outside firms also invest (a small amount) in R&D.

[13] Since a grand coalition consists of all possible members, there are no more firms to join the coalition. Therefore, a grand coalition is always externally stable.

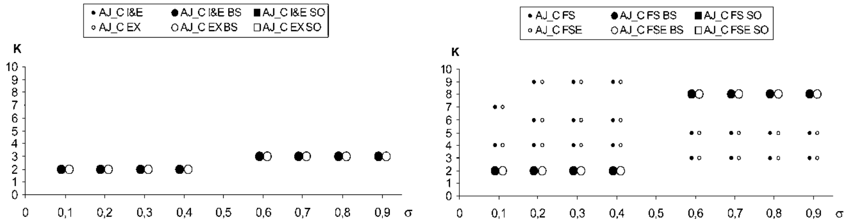
Table 3. Sizes of stable coalitions with output spillovers

σ	Model	*IS*	*ES*	*EX*	*FS*	*FSE*	*SW*
0.1	AJ_C	2	2–10	2	2, 4, 7	2, 4, 7	0
	AJ_NJ	2–10	10	4–10	10	4–10	6
	AJ_CJ	2–6, 9–10	6, 7, 10	6, 9–10	6	6	6
0.2	AJ_C	2	2–10	2	2, 4, 6, 9	2, 4, 6, 9	0
	AJ_NJ	2–10	10	4–10	10	4–10	6
	AJ_CJ	2–10	10	6–10	10	6–10	7
0.3	AJ_C	2	2–10	2	2, 4, 6, 9	2, 4, 6, 9	0
	AJ_NJ	2–10	10	4–10	10	4–10	5
	AJ_CJ	2–10	10	6–10	10	6–10	7
0.4	AJ_C	2	2–10	2	2, 4, 6, 9	2, 4, 6, 9	0
	AJ_NJ	2–10	10	4–10	10	4–10	4
	AJ_CJ	2–10	10	6–10	10	6–10	8
0.5	AJ_C	–	–	–	–	–	–
	AJ_NJ	2–10	10	4–10	2, 10	4–10	2
	AJ_CJ	2–10	10	6–10	10	6–10	8
0.6	AJ_C	2–3	3–10	3	3, 5, 8	3, 5, 8	10
	AJ_NJ	2–10	10	4–10	2, 10	4–10	0
	AJ_CJ	2–10	10	6–10	10	6–10	8
0.7	AJ_C	2–3	3–10	3	3, 5, 8	3, 5, 8	10
	AJ_NJ	2–10	10	4–10	3, 10	4–10	0
	AJ_CJ	2–10	10	7–10	10	7–10	9
0.8	AJ_C	2–3	3–10	3	3, 5, 8	3, 5, 8	10
	AJ_NJ	2–10	10	4–10	4, 10	4–10	0
	AJ_CJ	2–10	10	7–10	10	7–10	10
0.9	AJ_C	2–3	3–10	3	3, 5, 8	3, 5, 8	10
	AJ_NJ	2–10	10	4–10	5, 10	4–10	0
	AJ_CJ	2–10	10	9–10	10	9–10	10

$K = 7$ cooperating firms leads to the highest social welfare in the considered setting.

Tables 3 and 4 present the sizes of stable coalitions under the four different stability concepts as well as the respective socially optimal numbers of cooperating firms for the models with output and input spillovers, respectively. In many cases we observe that several stable coalitions exist, and it is not obvious which of them prevails in equilibrium. From a political point of view, it thus seems desirable to try to bring about the socially optimal or at least the best stable coalition size (e.g., by subsidizing R&D activities). The latter could be relevant if the socially optimal coalition size is not stable under the respective stability concept. In this case the optimum can only be realized with a permanent state intervention because the cooperation would break down once the subsidies were stopped. Thus, a reasonable alternative that requires a less extensive policy

Figure 1. ***(a) AJ model, case C myopic behavior. (b) AJ model, case C far-sighted behavior.***



(a) (b)

is to induce the stable coalition with the highest associated social welfare by one single initial subsidy. Such a cooperation will subsequently be maintained because of the firms' individual rationality included in the stability concepts. In the following we analyze these issues for the different cases of R&D cooperation discussed in Section 2.

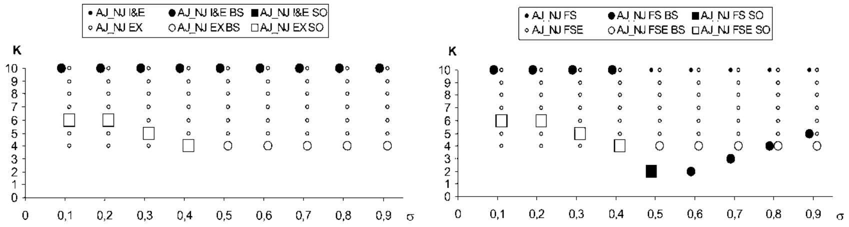
3.2. The AJ model

All the results concerning the AJ model are summarized in Table 3 for selected values of the spillover rate and depicted graphically in Figures 1, 2 and 3 for the case of a cartel (C), a research joint venture (NJ) and an RJV cartel (CJ), respectively. Under the open membership rule, small solid circles refer to stable coalitions, while large solid circles identify the best stable coalition in the sense that it is associated with the highest social welfare to be reached by a self-sustaining coalition but being smaller than maximal welfare (BS). A stable coalition which leads to the socially optimal welfare level (SO) is represented by a solid square. The corresponding coalitions under the exclusive membership rule are depicted by light circles and squares.

3.2.1. Case C

Let us first consider case C, where the firms may form an R&D cartel. If they are myopic as regards potential reactions from their competitors, Figure 1(a) shows that there is only one I&E stable cartel for any spillover rate and that the number of firms participating in that cartel is small (two members for $\sigma < 0.5$ and three members for $\sigma > 0.5$). This means that the gains associated with the coordination of R&D activities between the cartel members are only very limited and that most of the firms prefer to free-ride on these coordination efforts. Moreover, Table 3 makes evident that none of the stable cartels yields the highest possible social welfare, which is maximized with no cooperation for $\sigma < 0.5$ and by the grand coalition for $\sigma > 0.5$, respectively. Allowing for the exclusive instead of the open membership rule does not alter the results in this mode of cooperation because all coalitions are externally stable. Matters are a little different if

Figure 2. (a) AJ model, case NJ myopic behavior. (b) AJ model, case NJ farsighted behavior.



(a) (b)

the firms are farsighted regarding the future behavior of their competitors. Figure 1(b) reveals that in this case there are several stable coalitions for every value of the spillover rate. This phenomenon is essentially based on the fact that leaving a cartel is much less attractive if other firms will follow because then only a rather small cartel "survives," on which free-riding is possible. However, there is still no stable coalition that maximizes social welfare.

The policy implications in this scenario are twofold. For small spillover rates ($\sigma < 0.5$) the state is able to realize the social optimum associated with no R&D cooperation by simply prohibiting R&D cartels. For larger spillovers ($\sigma > 0.5$) the maximal social welfare could only be reached by permanently subsidizing the unstable grand coalition. In case of farsighted firms, there is also some scope for less extensive state intervention, viz. to encourage the formation of the stable coalition that is associated with the highest social welfare (referred to as the best stable coalition), and which will subsequently be maintained by the firms. Here, it is desirable to realize the largest stable cartel consisting of $K = 8$ firms.[14]

3.2.2. Case NJ

In the case of a non-cooperative joint venture Figure 2(a) reveals that for myopic firm behavior the concept of internal and external stability leads to the grand coalition for all values of σ. The reason for this can be found in Table 3, where only the grand coalition is characterized as being externally stable, i.e., for every smaller coalition there exists a firm that wants to accede. The economic rationale behind this result is that being excluded from the full spillover rate results in low profits, such that in the NJ mode the free-rider position is rather unattractive. In addition none of the I&E stable grand coalitions leads to the social optimum, which is reached for considerably smaller coalition sizes,[15] reflecting the well-known fact that non-cooperative RJVs are detrimental to innovative activities

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[14] In this variant of the model there is a monotone relationship between the coalition size and social welfare, hence a larger cartel is associated with a higher social welfare for $\sigma > 0.5$. Unfortunately this monotonicity property does not hold for all scenarios under consideration.

[15] Observe that the socially optimal coalition size decreases with the spillover rate σ.

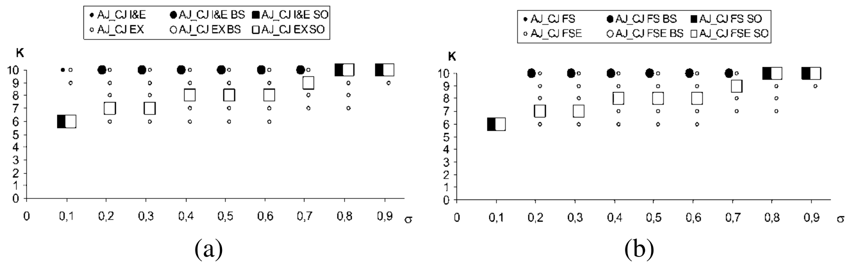
and thereby tend to reduce social welfare. In contrast to case C, in this scenario the situation changes if it is possible to avoid the entry of further firms. Under the exclusive membership rule all coalitions containing at least four members are stable, and for small values of σ even social optimality is achievable by a stable coalition as depicted by the light squares. It becomes clear that forming a joint venture of too many firms is not desirable both from the firms' and from a social point of view. A possible explanation can be seen in a combination of small R&D investments and the growing competition on the product market in the second stage, when too many firms have access to the superior technology. As shown in Figure 2(b) the results for farsighted firms are only different for larger values of the spillover rate and open membership, where smaller and therefore socially better coalition sizes are stable. A remarkable feature is that for certain spillover rates the open membership rule brings about outcomes superior to those with exclusive membership. This phenomenon appears because farsighted firms under the open membership rule anticipate that they cannot exclude potential members from larger coalitions and therefore avoid coalitions with many members from the outset.

The policy implications are different from the C setting of the model as there are much more possibilities for the state to realize the social optimum as a stable outcome. Since for large spillover rates no cooperation is optimal from a social point of view, prohibition is the best policy measure. For smaller values of σ the socially optimal coalition consists of $K = 2$ to $K = 6$ members and can be encouraged by the state without permanent subsidies if the firms apply the exclusive membership rule. Under open membership and small spillovers there is only scope for permanent policy intervention. It becomes evident, however, that the state has to be informed rather well about the situation that actually prevails, or otherwise is likely to adopt the "wrong" policy measure that could be detrimental to social welfare.

3.2.3. Case CJ

In the scenario where firms can form a cooperative joint venture there is (with the exception of a very small spillover rate) no external stability for coalitions under myopic firm behavior such that—like in the NJ setting—only the grand coalition is $I\&E$ stable. As before, the reason lies in the fact that the free-rider position is not attractive for this form of cooperation. Since—in complete contrast to the NJ mode—the socially optimal coalition size is increasing in the spillover rate the stable grand coalition is welfare maximizing for rather high values of σ, whereas for smaller spillover rates $I\&E$ stable coalitions consist of too many members to lead to the highest social welfare. Moreover Figure 3(a) reveals that the possibility to exclude firms from cooperation leads for all spillover rates to a variety of stable coalitions with the socially optimal (depicted by light squares) always being one of them. Therefore taking the exclusive membership rule into consideration, the social optimum can be realized, because it is individually rational for coalition members to avoid too large coalition sizes that are

Figure 3. ***(a) AJ model, case CJ myopic behavior. (b) AJ model, case CJ farsighted behavior.***



associated with lower profits. With the exception of a very small spillover rate all of these results carry over to the case of farsighted behavior of the firms. By comparing Figures 1–3, we obtain the notable result that the stability properties of R&D cooperations are rather similar in cases NJ and CJ, but differ substantially in case C. Obviously, perfect information sharing by setting the spillover rate equal to one in a joint venture has a significant impact on the stability of coalitions, whereas coordinating R&D activities in a cartel is less important in this respect. The main reason for this is that the former aspect renders free-riding rather unattractive, because firms outside the coalition benefit significantly less from their competitors' R&D investments.

Regarding the policy implications for RJV cartels one has to recognize that cooperation is always desirable from a social point of view. Coalitions of $K = 6$ to $K = 10$ firms bring about the highest possible welfare, whereby the optimal size is growing with the spillover rate. Under the exclusive membership rule the state can always encourage the socially optimal coalition as a stable outcome irrespective of the spillover rate. For open membership no moderate intervention of this kind is possible because there is only one stable coalition which is socially optimal for very large values of the spillover rate. As for the NJ scenario, however, we have to note that the state requires detailed and reliable information to choose the appropriate policy measures.

3.3. The KMZ model

All results for the model with input spillovers are presented in Table 4 and depicted graphically in Figures 4–6 for the different modes of cooperation. In the following we analyze—like in the AJ case—the different scenarios with respect to social welfare and stable R&D coalitions.

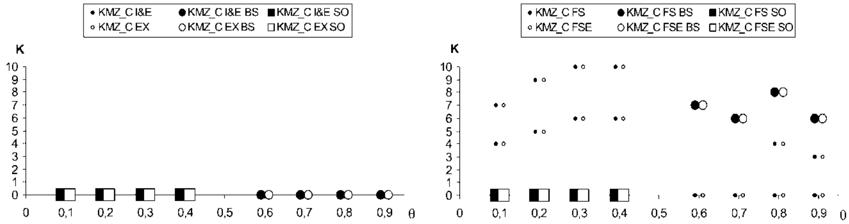
3.3.1. Case C

Firstly the case where the firms form an R&D cartel is considered. Under the assumption of myopic attitudes of the firms, Table 4 and Figure 4(a) display that no coalition is internally stable and thus no cooperation possible. This makes

Table 4. Sizes of stable coalitions with input spillovers

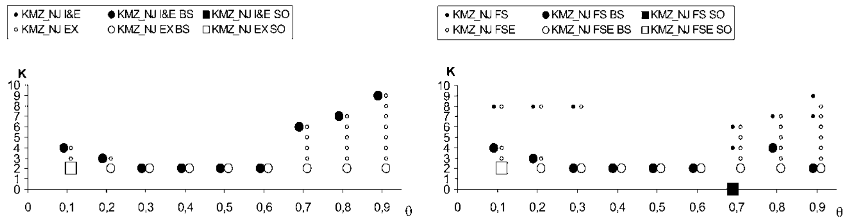
θ	Model	*IS*	*ES*	*EX*	*FS*	*FSE*	*SW*
0.1	KMZ_C	0	0–10	0	0, 4, 7	0, 4, 7	0
	KMZ_NJ	2–4	4–10	2–4	4, 8	2–4, 8	2
	KMZ_CJ	2–10	10	4–10	10	4–10	8
0.2	KMZ_C	0	0–10	0	0, 5, 9	0, 5, 9	0
	KMZ_NJ	2–3	3–10	2–3	3, 8	2–3, 8	0
	KMZ_CJ	2–10	10	4–10	10	4–10	8
0.3	KMZ_C	0	0–10	0	0, 6, 10	0, 6, 10	0
	KMZ_NJ	2	2–10	2	2, 8	2, 8	0
	KMZ_CJ	2–10	10	4–10	10	4–10	7
0.4	KMZ_C	0	0–10	0	0, 6, 10	0, 6, 10	0
	KMZ_NJ	2	2–10	2	2	2	0
	KMZ_CJ	2–10	10	4–10	10	4–10	7
0.5	KMZ_C	–	–	–	–	–	–
	KMZ_NJ	2	2–10	2	2	2	0
	KMZ_CJ	2–10	10	4–10	10	4–10	8
0.6	KMZ_C	0	0–10	0	0, 7	0, 7	10
	KMZ_NJ	2	2–10	2	2	2	0
	KMZ_CJ	2–10	10	5–10	10	5–10	8
0.7	KMZ_C	0	0–10	0	0, 6	0, 6	10
	KMZ_NJ	2–6	6–10	2–6	0, 4, 6	2–6	0
	KMZ_CJ	2–10	10	5–10	10	5–10	9
0.8	KMZ_C	0	0–10	0	0, 4, 8	0, 4, 8	10
	KMZ_NJ	2–7	7–10	2–7	4, 7	2–7	0
	KMZ_CJ	2–10	10	6–10	10	6–10	10
0.9	KMZ_C	0	0–10	0	0, 3, 6	0, 3, 6	10
	KMZ_NJ	2–9	9–10	2–9	2, 7, 9	2–9	0
	KMZ_CJ	2–10	10	10	10	10	10

Figure 4. (a) KMZ model, case C myopic behavior. (b) KMZ model, case C farsighted behavior.



(a) (b)

Figure 5. (a) KMZ model, case NJ myopic behavior. (b) KMZ model, case NJ farsighted behavior.



(a) (b)

evident that building a cartel is extremely unattractive because the firms want to avoid being exploited by free-riders. Regarding the associated welfare properties, we have to observe that for small values of the spillover rate ($\theta < 0.5$) no cooperation brings about the highest social welfare, while for $\theta > 0.5$ the grand coalition is socially optimal. Therefore with myopic firm behavior optimality is reached for small θ and the socially optimal grand coalition is missed by far if θ is large.[16] Since all coalitions are externally stable, the possibility of excluding firms from cooperation has no impact on the outcomes. Farsighted firm behavior, however, brings about additional stable coalitions. For $\theta > 0.5$ the best stable coalitions are not that far away from the social optimum as in the myopic scenario. In these cases the expectation that leaving a coalition would trigger the exit of further firms as well, induces firms to remain in the R&D cooperation and thus stabilizes certain coalitions. As with myopic behavior the excludability of firms is meaningless.

It is already evident from the above welfare considerations, that the policy implications depend on the actual value of the spillover rate. For $\theta < 0.5$ prohibition of R&D cooperation is the best policy measure if firms are farsighted, whereas no political intervention is necessary under myopic behavior, because no cooperation leads to social optimality. For larger spillover rates and myopic firm behavior the state only has the possibility to permanently subsidize the socially optimal but unstable grand coalition in order to avoid the rather bad outcome of no cooperation. In case of farsighted firms it is also possible to influence social welfare by encouraging the best stable coalitions of $K = 6$ or $K = 7$ members by a temporary subsidy. Nevertheless, the scope for political intervention is somewhat limited in this scenario.

3.3.2. Case NJ

Matters are quite different for the case of a non-cooperative joint venture. As Figure 5(a) shows, for myopic firm behavior the best $I\&E$ stable coalitions con-

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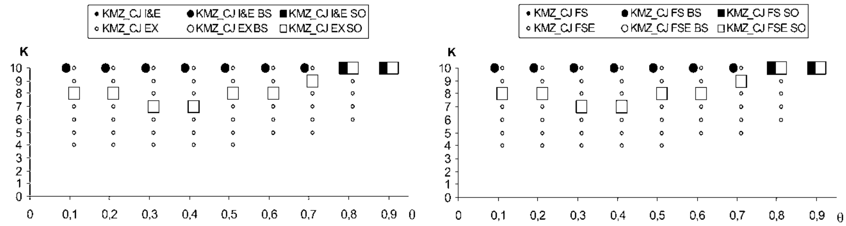
16 This is another case where social welfare depends monotonically on the coalition size such that a qualitative statement is possible.

Figure 6. (a) KMZ model, case CJ myopic behavior. (b) KMZ model, case CJ farsighted behavior.



(a) (b)

sist of between $K = 2$ and $K = 9$ firms, reflecting the fact that being excluded from the coalition is more disadvantageous than in the cartel scenario. Since with the exception of very small spillover rates no cooperation is the welfare maximizing solution all of these stable coalitions are too large from a social point of view. The possibility to exclude firms from the RJV gives prospect for potential improvements in this regard, because especially for large spillovers smaller coalitions are also stable in this case. In the farsighted case open membership leads to stable coalitions of $K = 4$ or less firms for any spillover rate and, for large θ, allows for smaller and therefore socially better coalition sizes than under myopic behavior. Under the exclusive membership rule the results do not depend in a relevant way on whether the firms are myopic or farsighted.

In this setting the policy implications are rather clear cut since with the exception of a very small spillover rate prohibition of an R&D cooperation always leads to the realization of the highest social welfare.

3.3.3. Case CJ

If the firms form a cooperative RJV there is no external stability such that only the grand coalition is $I\&E$ stable. This result is due to the great disadvantages of being an outsider when the coalition members both coordinate their R&D investments and perfectly share information. While the grand coalition is socially optimal for rather large spillover rates, smaller coalition sizes would be preferable for lower values of θ from a social point of view, hence the $I\&E$ stable coalition does not maximize social welfare. Figure 6(a) demonstrates that the exclusive membership rule makes such smaller coalitions possible, so that the social optimum is throughout reachable. As Figure 6(b) shows a farsighted attitude of the firms does not alter these results.

Even though research cooperation is desirable from a social point of view for every spillover rate, the scope for political intervention so as to realize the social optimum with non-permanent measures depends crucially on the membership rule applied by the firms. Under open membership, no such moderate intervention is possible because there is only a single stable coalition, and a prohibition of cooperation would be detrimental to social welfare. With exclusive membership, in contrast, the state can realize the socially optimal situation through a single intervention irrespective of whether the firms are myopic or farsighted.

3.4. Comparing the models

In this section we highlight some significant similarities and differences between the models with output and with input spillovers. Firstly in case C for both types of spillovers the possibility to exclude firms from a cooperation does not matter since all potential coalitions are externally stable, which shows that the free-rider position is quite attractive irrespective of the underlying model. However, for myopic behavior of the firms, it is a very notable feature of the KMZ model in the cartel setting that no internally stable coalition can form, while in the AJ model coalitions of two or rather three firms are $I\&E$ stable. The reason for this result can be found in Equations (10) and (24). The numerators of these expressions show that in the AJ model a firm's own R&D investment has a direct impact on its profits whereas in the KMZ model the own expenditures are only part of the total input in the R&D production function. This means that with output spillovers, coordinating the R&D activities with other firms leads to a greater increase in profits for coalition members than for free-riders, such that (small) coalitions are stable. In the KMZ model, on the other hand, the positive effect for free-riders outweighs the additional payoff to members, hence there is less internal stability in the model with input spillovers. From a political point of view the required policy measures to realize the welfare maximizing coalition are independent of the kind of spillovers. For spillover rates smaller than 0.5 the formation of research cartels should be prohibited, whereas for spillover rates greater than 0.5 policy makers have to encourage the formation of the socially optimal or the best stable coalitions. The latter contain $K = 6$ to $K = 8$ firms in the farsighted case with the grand coalition being the optimal solution. For settings with spillover rates higher than 0.5 and myopic firm behavior the social optimum in the AJ and even more in the KMZ model will be missed by far unless there is permanent state intervention. Moreover, the information requirements on part of the policy makers to adopt the "correct" measures are equally high in both models.

For the NJ scenario with open membership and myopic firms there is no external stability in the model with output spillovers, such that the grand coalition is throughout the only possible outcome. In contrast, for the same reasons as outlined in case C, only smaller coalitions are $I\&E$ stable when there are input spillovers. Taking the exclusive membership rule into account leads to more significant changes in the AJ model because the profit reducing entry of other firms is no longer possible. In the KMZ model, the firms already prefer the free-rider position so much that they do not even want to join a larger coalition. In particular then, for small spillover rates the socially optimal coalition size is attainable in the myopic variant of the AJ model, while for the KMZ setting the optimal solution is only reached for very small values of θ. Regarding social welfare the models show similar properties. In both cases the optimal coalition size is decreasing in the spillover rate, such that only for rather (AJ) or very small (KMZ) spillover rates any cooperation in R&D is desirable. Farsighted firm behavior under the open membership rule has a significant influence on the results for both kinds of spillovers if the spillover rate is high, which leads to smaller stable coalitions. The reason is that the firms anticipate the joining of further coalition members and therefore try to sustain rather small cooperations. Since with exclusive membership potential entrants can be deterred this effect does not prevail and the exclusive membership rule worsens the prospect of reaching social optimality without state intervention. The policy implications of the models are twofold. For spillover rates larger than 0.5 a prohibition of R&D cooperation is the best political measure irrespective of the kind of spillovers. In contrast to that, for spillover rates smaller than 0.5 the optimal policy depends crucially on whether there are output spillovers, where coalitions of a medium size should be encouraged, or input spillovers, where prohibition of cooperation is preferable.

In the CJ setting the results in the AJ and in the KMZ model are quite similar. For both kinds of spillovers there exist no externally stable coalitions (with the exception of very small spillover rates in the AJ model) under the open membership rule. Hence the grand coalition is the only stable outcome. Social optimality arises from coalitions with $K = 6$ to $K = 10$ members, where the optimal number of cooperating firms tends to increase with the spillover rate. The possibility to exclude firms from cooperation leads to higher social welfare unless the spillover rate is extremely high. Moreover (with the exception of very small spillover rates in the AJ model) it does not influence the outcomes whether the firms are myopic or farsighted. In contrast to the case C the appropriate policy measures do neither depend that much on the kind of spillovers nor on the precise value of the spillover rate. Therefore the information requirements for the policy maker are less demanding.

4. Concluding remarks

In this paper we have considered the formation and stability of R&D coalitions under diverse kinds of spillovers and for three forms of cooperation between the firms by using different stability concepts and membership rules to derive the welfare properties of the resulting equilibria. In contrast to the bulk of the existing literature, the possibility of various cartel sizes has been taken into account. Our results show that frequently several stable coalitions of different sizes with divergent welfare effects exist, hence there is scope for political intervention to improve social welfare. We have arrived at the conclusion, however, that the suitable policy measures crucially depend on the type and extent of spillovers, the mode of cooperation, the rules of coalition formation and whether the firms are myopic or farsighted regarding their competitors' behavior. Therefore the information requirements for a policy maker trying to improve social welfare are rather high, and there is no reason to expect these informations to be unambiguous and available. The policy implications derived from models of this kind should thus be handled cautiously because one is likely to adopt the wrong measure that could even be detrimental to social welfare. To narrow down the vast number of possible combinations which influence the results further considerations are necessary. For example, it could be argued that in the situation of a market economy with the freedom to conclude contracts the concept of excludability prevails. Moreover assuming myopic firm behavior might be questionable. Thus the suggested concept of a farsighted equilibrium with exclusive membership may be viewed as the most suitable for description of reality. Even under these conditions, however, in certain constellations the different kinds of cooperation lead to diametrically opposed implications for the policy maker. Presumably, empirical work can help to improve this situation by evaluating and distinguishing the plausibility of the various simulated settings.

Conceivable extensions of our work should take into account the possibility of competing research coalitions. Moreover, it seems reasonable to include uncertainty regarding the success of R&D investments in the analysis. Unfortunately our model framework is already quite complicated to handle, hence more sophisticated models can be expected to become rather intractable.

Appendix A

In this appendix we provide some more details regarding the solution of the firms' optimization problems that have been omitted in Section 2 of the main text.

Output spillovers

Case C

A firm that does not belong to the R&D cartel maximizes its profits $\pi_i(x_i)$ given by (10) subject to the nonnegativity constraint $x_i \geqslant 0$, taking the cost reductions x_j, $j \neq i$, of its competitors as given. Since the inequality restriction is linear we may apply the Kuhn–Tucker Theorem without referring to any constraint qualifications. The first order optimality conditions are given by $\pi_i'(x_i) \leqslant 0$ and $\pi_i'(x_i) \cdot x_i = 0$ together with the original restriction $x_i \geqslant 0$. Denote the optimal solution by x_i^{nC} and assume first that it is strictly positive. In this case it solves the equation

$$\begin{aligned} 0 &= \pi_i'(x_i) \\ &= \frac{2}{b(N+1)^2}\big[(a-c)+(N+1)(1-\sigma)x_i+(2\sigma-1)X\big] \\ &\quad \times \big[(N+1)(1-\sigma)+(2\sigma-1)\big]-\gamma x_i. \end{aligned} \tag{A.1}$$

Since the product market equilibrium is symmetric, the K cartel members choose x^C whereas the $N-K$ non-members all choose the same value x^{nC}. Solving (A.1) for x^{nC} thus yields the reaction function of a non-member as

$$x^{nC} = \frac{1}{A(K)}\big(a-c+K(2\sigma-1)x^C\big), \tag{A.2}$$

where $A(K)$ is given by

$$A(K) = \frac{b\gamma(N+1)^2}{2[(N+1)(1-\sigma)+(2\sigma-1)]} - \big[(N+1)(1-\sigma)+(N-K)(2\sigma-1)\big]. \tag{A.3}$$

A cartel member chooses its cost reduction x_i^C so as to maximize $\sum_{j=1}^{K} \pi_i(x_j)$ subject to $x_i \geqslant 0$, where we have assumed (without loss of generality) that firms $i = 1, \ldots, K$ join the cartel. Proceeding similarly as for the non-member, we obtain the reaction function of a cartel member as

$$x^C = \frac{1}{B(K)}\big(a - c + (N-K)(2\sigma-1)x^{nC}\big), \tag{A.4}$$

where $B(K)$ is given by

$$B(K) = \frac{b\gamma(N+1)^2}{2[(N+1)(1-\sigma)+K(2\sigma-1)]} - \big[(N+1)(1-\sigma)+K(2\sigma-1)\big]. \tag{A.5}$$

Combining (A.2) and (A.4) then yields (12) and (13) given in the main text. If one of these expressions is negative, then the optimal solution is given by $x^C = 0$ (or $x^{nC} = 0$), and the other group's cost reduction can be derived from (A.2) (or (A.4)).

Case NJ

The optimal solutions x^{NJ} and x^{nNJ} of an RJV member and a non-member are derived in a conceptually similar fashion as in case C, so we now keep the exposition rather short. If it is strictly positive, the cost reduction of a non-member is a maximum of the profit function π_i in (16) and is thus given as a solution to

$$\begin{aligned} 0 &= \pi_i'(x_i) \\ &= \frac{2}{b(N+1)^2}\Bigg[(a-c)+(N+1)(1-\sigma)x_i+(1-K)(1-\sigma)\sum_{j=1}^{K} x_j \\ &\quad + (2\sigma-1)X\Bigg] \cdot \big[(N+1)(1-\sigma)+(2\sigma-1)\big] - \gamma x_i. \end{aligned} \tag{A.6}$$

In the symmetric equilibrium where K firms choose x^{NJ} while the other $N-K$ choose x^{nNJ}, this yields the reaction function

$$x^{nNJ} = \frac{1}{E(K)}\big(a - c + \big[K(1-K)(1-\sigma)+K(2\sigma-1)\big]x^{NJ}\big) \tag{A.7}$$

of a non-member, where $E(K)$ is given by

$$E(K) = \frac{b\gamma(N+1)^2}{2[(N+1)(1-\sigma)+(2\sigma-1)]} - \big[(N+1)(1-\sigma)+(N-K)(2\sigma-1)\big]. \tag{A.8}$$

Starting from the profit function π^{RJV} in (15), similar calculations yield the reaction function

$$x^{NJ} = \frac{1}{D(K)}\big(a-c+(N-K)(2\sigma-1)x^{nNJ}\big) \tag{A.9}$$

of an RJV member, where $D(K)$ is defined as

$$D(K) = \frac{b\gamma(N+1)^2}{2[(N+2-K)(1-\sigma)+(2\sigma-1)]} - K\big[(N+2-K)(1-\sigma)+(2\sigma-1)\big]. \tag{A.10}$$

Combining (A.7) and (A.9), then gives (18) and (19) in the text. Moreover, the case of a binding nonnegativity constraint may be treated exactly as for the case C.

Case CJ

The optimization problem of a firm not participating in the RJV cartel is absolutely identical to the one of a non-member in case NJ. Thus, its reaction function is given by (cf. (A.7))

$$x^{nCJ} = \frac{1}{E(K)}\big(a-c+\big[K(1-K)(1-\sigma)+K(2\sigma-1)\big]x^{CJ}\big). \tag{A.11}$$

As in case C, assume that firms $i = 1, \dots, K$ build the RJV cartel. Every firm in this cartel thus maximizes $\sum_{j=1}^{K} \pi_i^{RJV}(x_j)$ with respect to $x_i \geqslant 0$ for $\pi_i^{RJV}(x_j)$ given by (15). In a symmetric equilibrium this yields the reaction function

$$x^{CJ} = \frac{1}{F(K)}\big(a-c+(N-K)(2\sigma-1)x^{nCJ}\big), \tag{A.12}$$

where $F(K)$ is defined as

$$F(K) = \frac{b\gamma(N+1)^2}{2K[(N+2-K)(1-\sigma)+(2\sigma-1)]} - K\big[(N+2-K)(1-\sigma)+(2\sigma-1)\big]. \tag{A.13}$$

Analogously to the cases considered above, (20) and (21) in the text directly follow from (A.11) and (A.12), and the case of a binding nonnegativity constraint is also obvious.

Input spillovers

Case C

The entire analysis is formally similar to the AJ model, the only exception lying in the fact that the respective optimality conditions cannot be solved explicitly for the effective cost reductions or the R&D expenditures. A firm that does not participate in the R&D cartel maximizes its profits (24) subject to the nonnegativity constraint $y_i \geqslant 0$. The Kuhn–Tucker optimality conditions for this firm are $\pi_i'(y_i) \leqslant 0$ and $\pi_i'(y_i)y_i = 0$, where the relevant derivative is given by

$$\begin{aligned}\pi_i'(y_i) = {} & \frac{2}{b(N+1)^2} \\ & \times \left[(a-c) + (N+1)\sqrt{\frac{2}{\gamma}\left[(1-\theta)y_i + \theta\mathcal{Y}\right]} \right. \\ & \left. - \sum_{j=1}^{N}\sqrt{\frac{2}{\gamma}\left[(1-\theta)y_j + \theta\mathcal{Y}\right]}\right] \\ & \times \left[\frac{N}{\gamma\sqrt{\frac{2}{\gamma}[(1-\theta)y_i + \theta\mathcal{Y}]}} \right. \\ & \left. - \sum_{j=1, j\neq i}^{N} \frac{\theta}{\gamma\sqrt{\frac{2}{\gamma}[(1-\theta)y_j + \theta\mathcal{Y}]}}\right] - 1.\end{aligned}$$

Suppose that firms $i = 1, \ldots, K$ join the cartel, and denote the optimal R&D expenditures of a cartel member and a non-member in the symmetric equilibrium by y^C and y^{nC}, respectively. If $y^{nC} > 0$, then it is obtained as a solution to the equation $\pi_i'(y_i) = 0$. Using the terms Y^C and Y^{nC} defined in (28) and (29), this is equivalent to (27) given in the main text. If the solution of $\pi_i'(y_i) = 0$ is negative, then $y^{nC} = 0$ is optimal for a firm not participating in the cartel. A cartel member, on the other hand, chooses its R&D expenditures y_i^C so as to maximize the joint profits $\sum_{j=1}^{K} \pi_j(y_j)$, and its optimality conditions are formally similar to those of a non-member. The relevant partial derivative is also analogous to the one denoted above, but we omit its presentation because it is rather complicated but not really instructive. In a symmetric equilibrium it yields Equation (26) given in the main text, which determines the optimal R&D investment y^C if the latter is strictly positive. Otherwise, we have $y^C = 0$.

Cases NJ and CJ

Taking the respective profits denoted in (33) and (34) as a starting point, the derivation of the optimality conditions (36)–(37) and (42)–(43) is absolutely identical to the ones described in the preceding sections. Therefore, we have refrained from repeating the details of this straightforward but somewhat cumbersome analysis.

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CHAPTER 5

Strategic R&D with Uncertainty

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Abstract

Uncertainty is introduced into a model of strategic R&D. The formation of an R&D cooperative increases the success rate of R&D. This increase in the R&D success rate can be reinterpreted as the realization of scope economies due to cooperation. It appears that within this setting the range of technological spillovers increases for which the formation of R&D cooperatives is beneficial to society. They are always beneficial if economies of scope are large. Absent the realization of economies of scope the traditional result apply in that the technological spillover should exceed some threshold value for R&D cooperatives to be desirable. If the economies of scope are intermediate this threshold value is lowered.

Keywords: R&D cooperation, uncertainty, economies of scope

JEL classifications: L12, L41

1. Introduction

In 2002 firms in the US spent nearly 3% of GDP—over $300 billion—on research and development (R&D). And in 1996 EU spending on R&D varied from 1% of GDP for Italy to 3.5% of GDP for Spain and Sweden (Hinloopen, 2003). Understanding why firms invest in R&D is crucial as it is understood that a continuous flow of innovations is the primary source for economic growth.

The public good aspect associated with R&D investments is detrimental for private investment in R&D. This refers to the free flow of knowledge between innovating firms, the so-called technological spillover. An important policy response to the existence of this positive externality is that firms are allowed to

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form R&D cooperatives (Martin, 1997). The idea here is that firms internalize the free flow of knowledge that comes with conducting R&D. Sustaining R&D cooperatives would then spur private R&D investments.

Meanwhile a large body of literature has developed that deals with many aspects of strategic R&D, foremost to the creation of R&D cooperatives (see, e.g., d'Aspremont and Jacquemin, 1988; Kamien et al., 1992; Suzumura, 1992; Amir and Wooders, 1998; Beath et al., 1998; Salant and Shaffer, 1998; or Hinloopen, 2000). Whether these market organizations lead to increased R&D activity depends on the relative strength of two externalities. On the one hand, any firms' own R&D investment reduces rivals' costs through the technological spillover, the so-called *competitive advantage externality* (Kamien et al., 1992). This externality reduces any firm's incentive to conduct R&D and is always taken into account, also if firms cooperate in R&D. On the other hand, if rivals' production costs are reduced through the technological spillover then joint industry profits might go up with any firm's R&D activities. This *combined-profits externality* (Kamien et al., 1992) is only taken into account when firms cooperate in R&D. It can be both negative (for small technological spillovers) and positive (for large technological spillovers). It is the net effect of these externalities that rules whether cooperation in R&D leads to increased R&D activity.

This chapter adds to our understanding of R&D cooperatives through the introduction of uncertainty into a model of strategic R&D. The way this uncertainty is operationalized allows for a reinterpretation in terms of economies of scope. A key feature of the analysis is that the probability of success in R&D is higher when firms cooperate in R&D compared to the scenario where both firms conduct their research independently.

It appears that when the increase in R&D success rate due to cooperation in R&D is high enough, effective levels of R&D always go up, independent of the size of the technological spillover. This happens when economies of scope are large. The combined profits externality in that case is always positive and outweighs the competitive advantage externality. When the R&D success rate is not affected by the R&D cooperative then the traditional results apply in the sense that the technological spillover has to be high enough for the R&D cooperative to trigger more R&D activity. In case economies of scope are intermediate the range of the technological spillover for which an R&D cooperative leads to more R&D activity is extended.

The levels of R&D activity generated by the market are shown to be below some second-best level. As a result, the formation of an R&D cooperative is beneficial to society whenever it leads to more R&D activity. In particular, when large economies of scope are realized due to cooperation in R&D, total surplus always goes up, independent of strength of the technological spillover. If economies of scope are intermediate then there is some threshold level of technological spillover for which cooperation in R&D leads to an increase in total surplus. But this threshold value is below the threshold absent the realization of economies of scope due to cooperation in R&D.

2. *R&D production*

Introduction of uncertainty into the R&D production process assumes that the process itself can be described adequately absent uncertainty. There is some debate however how technological spillovers should be treated analytically. Indeed, it is not possible for a firm investing in R&D to appropriate all the returns from this investment, even under an airtight patent system (an early empirical study addressing this issue is Mansfield et al. (1977); see Kaiser (2002) for an up-to-date overview). A seminal paper that takes explicitly into account these technological spillovers is d'Aspremont and Jacquemin (1988). This paper triggered many subsequent writings, not in the least because their set-up of a Cournot duopoly with linear demand allows for many generalizations (see, e.g., Hinloopen, 2000).[1]

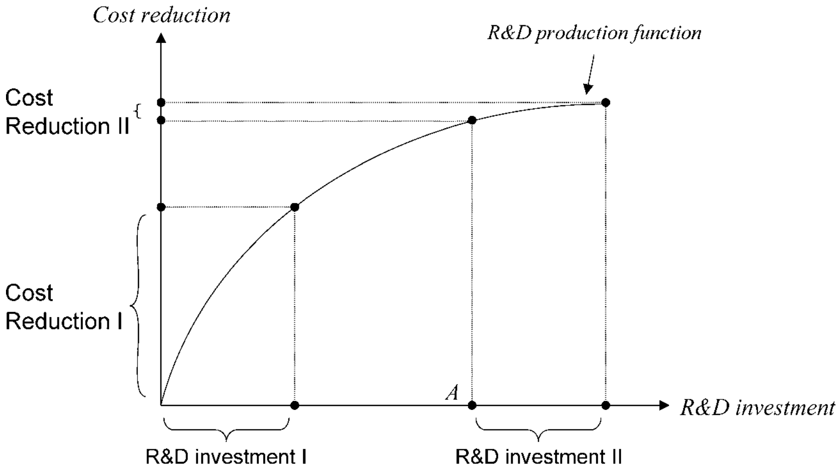
An important and probably implicit assumption in d'Aspremont and Jacquemin (1988) is that the technological spillover occurs when the R&D process has been completed. That is, they consider output spillovers. However, empirical studies have shown that technological spillovers are more likely to occur during the R&D process (Kaiser, 2002). According to Geroski (1995) this is exactly what we should expect. He identifies several channels through which a spillover occurs during the R&D process. First, researchers can deduct knowledge by observing rivals' actions. Second, knowledge workers move between employers thereby taking with them knowledge that is hard to codify and, therefore, to protect. And third, researchers exchange ideas at conferences, casual encounters, seminars, etc.

d'Aspremont and Jacquemin (1988) further assume perfectly additive output spillovers in combination with diminishing returns to scale. This modeling strategy carries at least two additional problems. First, as to the output spillovers to be perfectly additive note that the two firms are active in the same product market initially using the same production technology. In these situations we should expect to see some overlap in final R&D results. Moreover, the parts that do not overlap most likely are not a perfect match. Perfect complementarity is also not likely because firms differ in research strategy, corporate identify, and other aspects related to corporate cultures. These factors all diminish the maximum that an output spillover could obtain.

Second, as observed by Amir (2000), the combination of diminishing returns to scale and additive output spillovers yields counter intuitive predictions. This is illustrated in Figure 1. The first R&D investment, "R&D investment I," yields as benefit "cost reduction I." Now suppose that the firm to which this situation applies already has made a substantial investment in R&D and that it contemplates to make an additional investment. In particular, the firm has invested an amount A in Figure 1 and contemplates to make the next investment, "R&D

[1] In November 2007 Google Scholar lists 776 citations to d'Aspremont and Jacquemin (1988).

Figure 1. Diminishing returns to scale in R&D with additive output spillovers.



investment II." Note that this R&D investments is of equal size as "R&D investment I." This next investment in R&D yields "cost reduction II." Obviously this cost reduction is much smaller than "cost reduction I" due to the diminishing returns to scale in R&D. But if the other firm has not conducted much R&D yet, it could very well be in the interest of the firm contemplating to make "R&D investment II," to donate this entire investment to its rival and to appropriate a larger cost reduction through the spillover. Needless to say that this type of behavior is not observed in practice.

For all these reasons we consider the technological spillover to be an input of the R&D process. In particular, let there be two firms who both invest in cost-reducing R&D. Each firm i invests an amount x_i. The effective R&D activity of firm i is then given by:

$$X_i = x_i + \beta x_j, \tag{1}$$

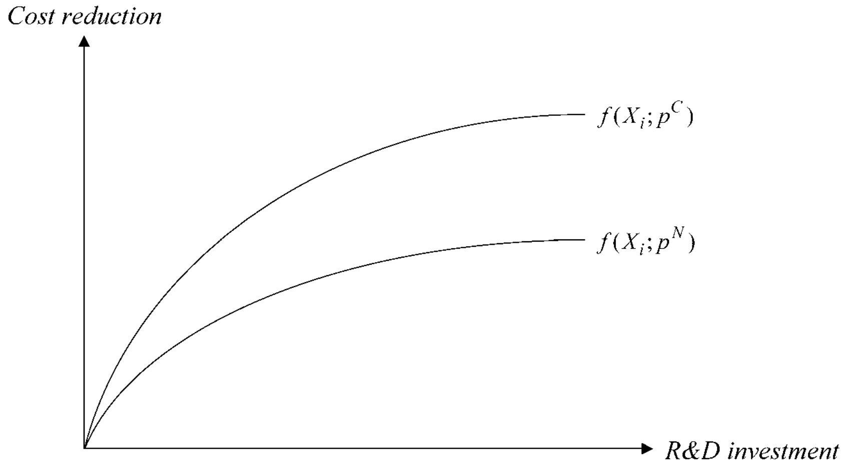
where $\beta \in [0, 1]$ is the technological spillover. Note that this spillover is an input of the R&D process as the cost reduction that results from these effective R&D effort is given by:

$$f(X_i). \tag{2}$$

This function $f(\cdot): \mathbb{R}_+ \to \mathbb{R}_+$ is the R&D production function and is introduced by Kamien et al. (1992). It specifies firm i's reduction in marginal production costs as a result of its effective R&D inputs, whereby $f(0) = 0$. To introduce diminishing returns to R&D is suffices that $f'(X) > 0$, and $f''(X) < 0$, given that the cost of R&D to firm i equals x_i.

To introduce uncertainty in the R&D process let $p_i \in [0, 1]$ be the fraction of $f(X_i)$ that reduces costs. As the R&D process itself is uncertain the production

Figure 2. The R&D production function for different success probabilities in R&D.



function describes what would be the maximal cost reduction for a given level of effective R&D input. In fact, it is possible that the entire R&D process fails such that no cost reduction at all is obtained. Accordingly, the R&D production function we use is:

$$f(X_i; p_i) = p_i \sqrt{\frac{x_i + \beta x_j}{\gamma}} = y_i, \tag{3}$$

where the parameter $\gamma > 0$ indicates the effectiveness of the R&D process (Qiu, 1997). The lower is the value for γ, the larger will be the cost reduction for a given level of R&D activity.

Figure 2 displays the R&D production function for two different values of the success probability. The higher probability, p^C, refers to the case where the two firms cooperate in R&D. The lower success probability, p^N, corresponds to a situation where the two firms carry out their research independently. Throughout this chapter we make the following assumption:

ASSUMPTION A1. $1 \geqslant p^C \geqslant p^N \geqslant 0$.

Assumption A1 implies that the probability of success goes up when firms cooperate in R&D. This assumption can be interpreted as an economies-of-scope argument in R&D. Indeed, in practice this appears to be an important motivation for firms to set up R&D cooperatives. In what follows we will examine what the consequences of these economies-of-scope are for assessing the benefits of allowing firms to cooperate in their R&D.

3. Product market competition

We analyze a two-stage game where firms first invest in R&D and then compete on the product market. Inverse market demand equals:

$$p = a - q_1 - q_2. \tag{4}$$

Each firm i initially produces with fixed marginal cost c. To assure production to be profitable in case R&D is not successful we maintain the following assumption:

ASSUMPTION A2. $a > c$.

Post-innovation production costs equal $c - f(X_i)$. One of the regularity conditions we impose is that post-innovation costs are positive. Firm i's profits then equal:

$$\pi_i = p_i q_i - (c - y_i)q_i - x_i, \tag{5}$$

$i, j = 1, 2, i \neq j$.[2] Maximizing these over q_i yields[3]:

$$\widehat{q}_i = \frac{1}{3}(a - c + 2y_i - y_j). \tag{6}$$

First-stage profits then equal:

$$\widehat{\pi}_i = \frac{1}{9}\big[(a - c) + 2y_i - y_j\big]^2 - x_i. \tag{7}$$

3.1. Noncooperative R&D

If firms carry out their R&D independently they maximize (7) over x_i. Assuming a symmetric equilibrium, whereby the probabilities of success are identical across firms, yields[4,5]:

$$\widetilde{y}^N = \frac{p^N(a - c)(2 - \beta)}{9\gamma - p^N(2 - \beta)}. \tag{8}$$

Note that $\widetilde{y}^N|_{p^N=0} = 0$, and that $\partial\widetilde{y}^N/\partial p^N > 0$. That is, if R&D is not successful there is no costs reduction while the higher is the R&D success rate, the higher is the investment in R&D activity, and the larger is the reduction in production cost. Industry output then equals:

$$\widetilde{Q}^N = 2\widetilde{q}^N = \frac{3\gamma(a - c)}{9\gamma - p^N(2 - \beta)}. \tag{9}$$

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[2] Unless stated otherwise, $i, j = 1, 2, i \neq j$ is assumed throughout the chapter.

[3] A hat refers to a conditional equilibrium expression.

[4] Second-order and stability conditions are dealt with below.

[5] Unconditional equilibrium expressions are denoted with a tilde. Noncooperative R&D carries the superscript N.

In equilibrium, producers' surplus and consumers' surplus then equal respectively:

$$\widetilde{PS}^N = \widetilde{\pi}_1^N + \widetilde{\pi}_2^N = \frac{2\gamma(a-c)^2[9\gamma(1+\beta)-(2-\beta)^2]}{(1+\beta)[9\gamma - p^N(2-\beta)]^2} \tag{10}$$

and

$$\widetilde{CS}^N = \frac{1}{2}\big(\widetilde{Q}^N\big)^2 = \frac{9\gamma^2(a-c)^2}{2[9\gamma - p^N(2-\beta)]^2}. \tag{11}$$

Quite obviously, both consumers' and producers' surplus are increasing in the R&D success rate. Total surplus boils down to:

$$\widetilde{TS}^N = \widetilde{PS}^N + \widetilde{CS}^N = \frac{\gamma(a-c)^2[45\gamma(1+\beta)-4(2-\beta)^2]}{2(1+\beta)[9\gamma - p^N(2-\beta)]^2}. \tag{12}$$

3.2. Cooperative R&D

If firms cooperate in R&D they maximize joint profits in the R&D stage:

$$\widehat{\Pi} = \widehat{\pi}_1 + \widehat{\pi}_2 = \sum_{\substack{i,j=1,2\\ i\neq j}} \left\{\frac{1}{9}\big[(a-c)+2y_i - y_j\big]^2 - x_i\right\}. \tag{13}$$

This yields:

$$\widetilde{y}^C = \frac{p^C(a-c)(1+\beta)}{9\gamma - p^C(1+\beta)}. \tag{14}$$

Note again that $\widetilde{y}^C|_{p^C=0} = 0$, and that $\partial\widetilde{y}^C/\partial p^C > 0$. Joint output is then:

$$\widetilde{Q}^C = \frac{3\gamma(a-c)}{9\gamma - p^C(1+\beta)}. \tag{15}$$

The concomitant equilibrium values of consumers' surplus and producers' surplus respectively are:

$$\widetilde{CS}^C = \frac{9\gamma^2(a-c)^2}{2[9\gamma - p^C(1+\beta)]^2} \tag{16}$$

and

$$\widetilde{PS}^C = \frac{2\gamma(a-c)^2[9\gamma-(1+\beta)]}{[9\gamma - p^C(1+\beta)]^2}. \tag{17}$$

Finally, total surplus with cooperative R&D is given by:

$$\widetilde{TS}^C = \frac{\gamma(a-c)^2[45\gamma-4(1+\beta)]}{2[9\gamma - p^C(1+\beta)]^2}. \tag{18}$$

3.3. Regularity conditions

The model gives rise to six regularity conditions: two second-order conditions, two conditions on post-innovation production costs to be positive, and two stability conditions, the latter of which relate to noncooperative R&D only. The second-order condition for the production stage is trivially met.

The second-order conditions for noncooperative R&D and cooperative R&D respectively read as:

$$\gamma > \frac{p^N(2-\beta)^3}{9(2-\beta^2)} \tag{R1}$$

and

$$\gamma > \frac{p^C(1+\beta)(5-8\beta+5\beta^2)}{9(1+\beta^2)}. \tag{R2}$$

For post-innovation production cost to be positive the following needs to be satisfied for noncooperative and cooperative R&D respectively:

$$\gamma > \frac{ap^N(2-\beta)}{9c} \tag{R3}$$

and

$$\gamma > \frac{ap^C(1+\beta)}{9c}. \tag{R4}$$

The Routh–Hurwitz stability condition for the R&D stage is that:

$$\frac{\partial^2\widehat{\pi}_i(x_i,x_j)}{\partial x_i^2}\frac{\partial^2\widehat{\pi}_j(x_i,x_j)}{\partial x_j^2} - \frac{\partial^2\widehat{\pi}_i(x_i,x_j)}{\partial x_j \partial x_i}\frac{\partial^2\widehat{\pi}_j(x_i,x_j)}{\partial x_i \partial x_j} > 0. \tag{19}$$

The way this condition bounds the parameter space depends on R&D being a strategic substitute or a strategic complement. Indeed, following Bulow et al. (1985), label decision variable x a strategic substitute in case $\partial^2\widehat{\pi}_i(x_i,x_j)/\partial x_i \partial x_j < 0$, and a strategic complement if $\partial^2\widehat{\pi}_i(x_i,x_j)/\partial x_i^2 > 0$. Accordingly, for strategic substitutes stability condition (19) boils down to:

$$\frac{\partial^2\pi_i(x_i,x_j)}{\partial x_i^2} < \frac{\partial^2\pi_i(x_i,x_j)}{\partial x_i \partial x_j}, \tag{20}$$

and for strategic complements it reads as:

$$\frac{\partial^2\pi_i(x_i,x_j)}{\partial x_i^2} < -\frac{\partial^2\pi_i(x_i,x_j)}{\partial x_i \partial x_j}. \tag{21}$$

These two stability conditions respectively translate into:

$$\gamma > \frac{p^N(2-\beta)^2}{3(2+\beta)} \tag{R5}$$

and

$$\gamma > \frac{p^N(2-\beta)}{9}. \tag{R6}$$

Not all regularity conditions are equally binding, as the following lemma shows.

LEMMA 1. *The parameter space is bounded by regularity conditions* (R2)–(R5).

PROOF. It is straightforward to derive that (R2) dominates (R1), and that (R5) dominates (R6). □

4. Policy analysis

The objective for sustaining R&D cooperative is that firms internalize the technological spillover and therefore invest more in R&D. Economies of scope could also play a role which, if present, enhance the effectiveness of the R&D process. Both effects should lead to an increase in R&D activity. This constitutes a widely shared policy goal as innovations are the primary source for economic growth in the long run.

4.1. R&D activity

Comparing then the level of cooperative R&D with noncooperative R&D levels leads to:

PROPOSITION 1. *Under* (R2)–(R5) *and Assumptions* A1 *and* A2 *the following holds*:

$$\tilde{y}^C > \tilde{y}^N \quad \Leftrightarrow \quad \beta > \frac{2p^N - p^C}{p^N + p^C} = \beta^*.$$

Obviously, when there are no economies of scope, that is $p^C = p^N$, the traditional result applies in that $\beta^* = \frac{1}{2}$. But the larger is the difference between p^C and p^N, that is the more economies of scope are realized through cooperation in R&D, the lower is β^*.[6] Indeed, an R&D cooperative will always lead to more R&D activity if the economies of scope that are realized are 'high enough':

COROLLARY 1. *For any given* $\beta \in [0, 1]$, $\tilde{y}^C > \tilde{y}^B$ *under* (R2)–(R5) *and* $p^C \geqslant 2p^N$.

[6] It is left to the reader to verify that $\partial\beta^*/\partial p^N > 0$, and $\partial\beta^*/\partial p^C < 0$.

Corollary 1 induces an ordering of R&D activities according to the extent to which economies of scope are present. In particular:

- $0 \leqslant p^N = p^C \leqslant 1$—no economies of scope.
- $0 \leqslant p^N < p^C < 2p^N < 2$—intermediate economies of scope.
- $0 \leqslant 2p^N < p^C \leqslant 1$—large economies of scope

When there are no economies of scope the traditional result applies (d'Aspremont and Jacquemin, 1988; Kamien et al., 1992) in that cooperative R&D exceeds noncooperative R&D whenever technological spillovers are larger enough, that is, $\beta \geqslant \frac{1}{2}$. If economies of scope are large, cooperative R&D levels always exceed noncooperative R&D levels (Corollary 1). And when economies of scope are intermediate the range of technological spillovers for which cooperative R&D levels exceed levels of noncooperative R&D is expanded from $(\frac{1}{2}, 1]$ to $(\beta^*, 1]$, where $\beta^* \in (0, \frac{1}{2})$.

4.2. Private incentives

Firms would always be in favor of an R&D cooperative. The joint decision process in Section 3.2 leads to different R&D investment levels than the competitive alternative in Section 3.1. But cooperating firms can always pick the noncooperative R&D levels if that would be more profitable. Hence, if allowed to firms will form R&D cooperatives.

4.3. Social incentives

Given that firms are always inclined to form R&D cooperatives, the question is when these cooperatives are socially desirable. To answer this question the central proposition is

PROPOSITION 2. *For any given* $\beta \in [0, 1]$, $\exists y^*$ *such that* $\partial TS(y)/\partial y > 0$ $\forall y \leqslant y^*$ *under* (R2)–(R5) *and Assumptions* A1 *and* A2.

PROOF. Total surplus conditional on R&D activity is given by

$$\widetilde{TS}(y) = \frac{4}{9}\big[(a-c)+y\big]^2 - \frac{2\gamma y^2}{p^2(1+\beta)}.$$

Then observe:

$$\frac{\partial \widetilde{TS}(y)}{\partial y} > 0 \quad \Leftrightarrow \quad y < \frac{2(a-c)p^2(1+\beta)}{9\gamma + 2p^2(1+\beta)} = y^*. \qquad \square$$

The value y^* in Proposition 2 is some second-best level of R&D activity. It is the level that maximizes total surplus given that firms compete in the product market over quantities.

The following lemma allows for the assessment of R&D cooperatives in relation to their effect on total surplus.

LEMMA 2. *For any given $\beta \in [0, 1]$, $\widetilde{y}^N$, $\widetilde{y}^C < y^*$ under (R2)–(R5) and Assumptions A1 and A2.*

PROOF. $\widetilde{y}^C < y^* \Leftrightarrow \gamma > p^2(1+\beta)/(2p-1)$. But this condition is dominated by (R4). $\widetilde{y}^N < y^* \Leftrightarrow \gamma > 4p^2(1+\beta)(2-\beta)/9[2p(1+\beta)-(2-\beta)]$. This condition is also dominated by (R4). □

Lemma 2 has a direct implication: whenever cooperative R&D levels exceed noncooperative R&D levels, total surplus has gone up due to the formation of an R&D cooperative. In what follows this will be specified further according to the extent that economies are realized due to cooperation in R&D.

4.3.1. No economies of scope

This case corresponds to the analysis of Kamien et al. (1992) where total surplus increases whenever R&D efforts increase. Any R&D cooperative is then desirable if, and only if, $\beta > \frac{1}{2}$ (see also Hinloopen, 1997).

4.3.2. Large economies of scope

In this case cooperative R&D levels always exceed noncooperative levels. The formation of an R&D cooperative that realizes large economies of scope is therefore always beneficial to society, no matter how strong the technological spillover is.

4.3.3. Intermediate economies of scope

Whether or not the formation of an R&D cooperative would enhance total surplus in this case depends again on the strength of the technological spillover. However, even if these spillovers are below the threshold value $\frac{1}{2}$ it could still be the case that total surplus increases due to the R&D cooperative, provided that the economies of scope are 'substantial enough.'

5. Conclusions

Meanwhile a substantial body of literature has developed that deals with the economics of strategic R&D. A rather robust finding that emerges from this literature is that for levels of cooperative R&D to exceed noncooperative R&D levels it suffices that the technological spillover is strong enough. In this chapter we have shown that also for small or even absent technological spillovers this result obtains provided that the economies of scope that are realized through R&D cooperation are large enough.

The policy implications of our analysis are quite obvious. Any R&D cooperative that leads to the realization of large economies of scope is beneficial to society, independently of the level of technological spillover. And even if economies of scope are not that large it is most likely that total surplus would increase due to the formation of an R&D cooperative. In these cases the technological spillover has to be positive but (much) lower than what is predicted absent the realization of economies of scope.

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CHAPTER 6

Coopting "Decisive" Technical Advances

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Abstract

The possibility of an established firm repelling a newcomer's cost reducing technical advances by providing the newcomer access to its currently superior technology, is explored. The oldtimer is supposed to offer his technology in return for the newcomer either ceasing R&D or sharing her findings. It is found that newcomers with the R&D potential to drive the oldtimer out of business cannot be coopted, but that less potent newcomers can. Whenever newcomers are deterred, the product price is higher and technical advance lower than it would be in the absence of a deal.

1. Introduction

According to Schumpeter:

> "... in capitalist reality as distinguished from its textbook picture, it is not that kind of competition [price] which counts but the competition from the new commodity, the new technology... competition which commands a *decisive* cost or quality advantage and which strikes not at the margins of the profits and the outputs of the existing firms but at their foundation and their very lives" (Schumpeter, 1975, p. 84).

Moreover, he claimed that

> "... even in the world of giant firms, new ones rise and others fall into the background. Innovations still emerge primarily with the 'young' ones, and the 'old' ones display as a rule symptoms of what is euphemistically called conservatism" (Schumpeter, 1964, p. 71).

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Schumpeter's insights were certainly prescient. By the 1980s, new businesses were replacing old ones on the *Fortune* 500 list at four times the pace they had twenty years earlier. Industries based on new technologies such as computer software and biotechnology were developed mainly by small firms. About one-half of today's high-tech companies began in the last 14 years. And, according to a 1992 Small Business Administration study, small businesses produced about two and one-half times as many innovations per employee as did big ones. This study was just one more in a long string, suggesting that small firms were more adept and efficient innovators than large ones (see Kamien and Schwartz, 1982, for a survey).

In an effort to ward off the onslaught of the "decisive" technical advances being generated by new, small rivals, some large established firms have practiced a cooption strategy. By freely providing small, currently less efficient rivals access to their superior production technologies they have sought to dull their incentives to develop a new "decisively" better technology. Of course, in pursuing this cooption strategy, the large established firm has to weigh the loss from strengthening a rival's immediate ability to compete against the future prospect of being driven from the market altogether by the rival's technical advance. The small rival must, in turn, consider whether or not the immediate gain is worth the sacrifice of a possibly larger future gain. Is it worth selling its birthright for a bowl of porridge? Our analysis is directed at characterizing the circumstances under which such a bargain is struck and what its impact is on the rest of society in terms of prices and technical advance.

We are not the first to recognize the possibility that a currently technologically superior firm might seek to forestall an inferior rival's R&D efforts to catch up to or surpass it, by sharing its know how. Gallini and Winter (1985), following Gallini (1984), addressed this issue in the context of the superior firm licensing its current technology to the inferior one on a royalty basis and developed the necessary and sufficient conditions for the existence of a subgame perfect Nash equilibrium in which neither firm conducts any R&D. Our analysis may be regarded as the case in which the superior technology is licensed freely. This means that the current technologically superior firm is eager to the extreme to stifle its rival's R&D activity. We also suppose that R&D activity is deterministic as the alternative assumption that it is stochastic does not appear to add much to the central issue. Our analysis provides new and sharper conclusions regarding when cooption of the currently technologically inferior firm by the technologically superior one will succeed and when it will fail.

We consider a homogeneous product duopoly facing linear demand and employing a constant marginal production cost technology. The industry consists of an established firm, the oldtimer, and a new aggressive firm, the newcomer, whose current production technology is inferior to the oldtimer's. However, the newcomer is more capable in research and development than the oldtimer, and we adopt the extreme assumption that she alone conducts R&D. Three possible scenarios are considered. In the first, the *benchmark* scenario, the oldtimer refrains from attempting to coopt the newcomer by offering his superior technology. In the second, the *giving* scenario, the oldtimer does attempt to coopt the newcomer by offering her his superior production technology in return for her ceasing R&D activities. Finally, in the third, the *sharing* scenario, the oldtimer offers his superior production technology to the newcomer in return for her sharing her R&D findings with him.

In each scenario we model the interaction between the firms as a two stage non-cooperative game, consisting of an R&D stage followed by a production stage, modeled via quantity (Cournot) competition. We characterize the pure strategy subgame perfect Nash equilibria obtained for each of the scenarios. Equilibria involving a deal between the oldtimer and the newcomer can occur in the second and the third scenarios only if both parties benefit relative to their benchmark scenario equilibria. We characterize these circumstances and show that a deal is impossible if the newcomer has the R&D potential to drive the oldtimer from the industry. Moreover, our analysis discloses that, whenever a bargain between the oldtimer and the newcomer is struck, the product's price rises and, depending on the terms of the bargain, technical advance either ceases or declines relative to the benchmark case in which there is no deal.

In Section 2 we discuss the general layout for our models and the benchmark scenario. The two other scenarios are discussed in Section 3 and 4, respectively, and compared to the benchmark scenario. Section 5 is devoted to conclusions.

2. *The benchmark cases*

In all the scenarios considered, only the newcomer conducts marginal cost reducing R&D in the game's first stage. In the game's second stage, the two firms engage in Cournot competition, with each employing its available production technology. In the absence of any R&D, the oldtimer's and the newcomer's constant marginal production costs are denoted by c and c_2 respectively, with $c < c_2$. The inverse demand function for the product is assumed to be linear, $P(Q) = a - Q$, where $Q = q_1 + q_2$ represents the combined quantity produced and q_1, q_2 the quantities produced by the two firms, respectively. We denote by ε the reduction in marginal cost from R&D, and assume a quadratic R&D cost function, $d\varepsilon^2/2$, where $d > 0$.

In the benchmark case, denoted by B, the newcomer's R&D outcomes are not shared with the oldtimer. Hence, following the R&D stage, the newcomer's marginal cost becomes $c_2 - \varepsilon^B$, while the oldtimer's remains c_1. If both the oldtimer and the newcomer profitably produce in the game's second stage, then their respective equilibrium outputs are

$$q_1^B = \frac{a - 2c_1 + c_2 - \varepsilon^B}{3}, \qquad q_2^B = \frac{a - 2c_2 + 2\varepsilon^B + c_1}{3}, \tag{1}$$

and profits are

$$\pi_1^B = \left(q_1^B\right)^2, \qquad \pi_2^B = \left(q_2^B\right)^2. \tag{2}$$

We assume that the newcomer is profitable even if she does not conduct R&D, namely, when $\varepsilon = 0$. This requires that her marginal cost not exceed the oldtimer's monopoly price, that is,

$$\frac{a + c_1}{2} \geqslant c_2, \tag{3}$$

or

$$a - c_2 \geqslant c_2 - c_1. \tag{4}$$

Note that this implies that $a - c_2 > 0$, and in turn that $a - c_1 > 0$, which assures the oldtimer's viability as long as the newcomer does not conduct R&D.

Turning back to the benchmark cases, it is possible that the newcomer's R&D induced cost reduction is decisive, that is, large enough to drive the oldtimer out of business. Hence, in the game's first stage, the newcomer takes this possibility into account by solving

$$\max_{\varepsilon} \begin{cases} q_2^2 - \frac{d}{2}\varepsilon^2, & \text{if } q_1 = \frac{a-2c_1+c_2-\varepsilon}{3} \geqslant 0 \quad \text{(i)}, \\ \left(\frac{a - c_2 + \varepsilon}{2}\right)^2 - \frac{d}{2}\varepsilon^2, & \text{if } q_1 = 0, \text{ or } \varepsilon > a - 2c_1 + c_2 \quad \text{(ii)}. \end{cases} \tag{5}$$

Here the profits, given by (5), (ii), correspond to the case where the oldtimer is driven from the market.

The interior solution to (5), (i), is

$$\varepsilon^B = 4\left(\frac{a - 2c_2 + c_1}{9d - 8}\right), \tag{6}$$

with the second order condition requiring that $d \geqslant 8/9$. For (6) to be the newcomer's optimal level of marginal cost reduction while the oldtimer continues to produce, the resulting quantity q_1, produced by the oldtimer, must be nonnegative. That is, condition (i) in (5) should hold. This is equivalent to the oldtimer's marginal cost not exceeding the newcomer's monopoly price, that is,

$$\frac{a + c_2 - \varepsilon^B}{2} \geqslant c_1, \tag{7}$$

which gives

$$d \geqslant \frac{4}{3}\frac{a - c_1}{a - 2c_1 + c_2}. \tag{8}$$

For the right-hand side of (8) to be no less than 8/9, (4) must be satisfied. Substituting from (6) into (5), (i), and (2) yields the oldtimer's and newcomer's respective profits

$$\pi_1^B = \left(\frac{a - 2c_1 + c_2 - \varepsilon^B}{3}\right)^2 = \left(\frac{3d(a - 2c_1 + c_2) - 4(a - c_1)}{9d - 8}\right)^2, \tag{9}$$

$$\pi_2^B = \left(\frac{a - 2c_2 + 2\varepsilon^B + c_1}{3}\right)^2 - \frac{d}{2}\left(\varepsilon^B\right)^2 = \frac{d}{9d-8}(a - 2c_2 + c_1)^2. \quad (10)$$

The two firms' combined output is

$$Q^B = q_1^B + q_2^B = \frac{2a - c_1 - c_2 + \varepsilon^B}{3}$$
$$= \frac{3d(2a - c_1 - c_2) - 4(a - c_1)}{9d-8} \quad (11)$$

and the market price is

$$P^B = a - Q^B = \frac{3d(a + c_1 + c_2) - 4(a + c_1)}{9d-8} \geqslant c_1, \quad (12)$$

where the inequality follows from (8). Since the oldtimer continues to produce, the newcomer's technical advance is indecisive.

If d does not satisfy (8), then the newcomer's optimal R&D level in region (i) in (5) is the corner solution given by

$$\varepsilon^B = a - 2c_1 + c_2, \quad (13)$$

and the oldtimer is just driven from the market so

$$\pi_1^B = 0, \quad (14)$$

while the newcomer's profit from (13) and (5), (i) is

$$\pi_2^B = (a - c_1)^2 - \frac{d}{2}(a - 2c_1 + c_2)^2. \quad (15)$$

It is possible to verify that if (8) fails to hold, then π_2^B, given by (15), is positive. In this benchmark case the overall quantity produced is

$$Q^B = q_2^B = \frac{a - 2c_2 + 2\varepsilon^B + c_1}{3} = a - c_1 \quad (16)$$

and the product's market price is

$$P^B = a - Q^B = c_1, \quad (17)$$

the oldtimer's marginal production cost. So, in this situation, the newcomer's technical advance is *virtually* decisive as it serves to "just" drive the oldtimer from the market but does not allow the newcomer to exploit her sole presence by charging a monopoly price.

We now turn to the analysis of (5), (ii), in which the oldtimer does not produce. An interior solution for the newcomer's optimal marginal cost reduction now yields

$$\varepsilon^B = \frac{a - c_2}{2d-1} \geqslant a - 2c_1 + c_2 \quad (18)$$

with the second order condition requiring $d \geqslant 0.5$. This, in turn, requires that

$$d \leqslant \frac{a - c_1}{a - 2c_1 + c_2}. \tag{19}$$

Substituting from (18) into (5), (ii), the firms' respective profits, combined output, and the product's market price are given by

$$\pi_1^B = 0, \tag{20}$$

$$\pi_2^B = \left(\frac{a - c_2 + \varepsilon^B}{2}\right)^2 - \frac{d}{2}\left(\varepsilon^B\right)^2 = \frac{d}{2(2d-1)}(a - c_2)^2, \tag{21}$$

$$Q^B = q_2^B = \frac{a - c_2 + \varepsilon^B}{2} = \frac{d}{2d-1}(a - c_2), \tag{22}$$

$$P^B = a - Q^B = \frac{(a + c_2)d - a}{2d - 1} \leqslant c_1, \tag{23}$$

where the inequality follows from (19). Here the newcomer's monopoly price is at or below the oldtimer's marginal cost and the cost reduction is what Arrow (1962) dubbed "drastic." If (19) does not hold, then the newcomer's optimal cost reduction is the corner solution (13) and the firms' profits are given by (14) and (15).

We can summarize the three possible benchmark cases:

Case B.I. Technical advance indecisive

If

$$\frac{4}{3}\frac{a - c_1}{a - 2c_1 + c_2} \leqslant d \quad \text{and} \quad d \geqslant \frac{8}{9}, \tag{24}$$

then ε^B is given by (6), the firms' profits by (9) and (10), the combined output and market price by (11) and (12).

Case B.II: Technical advance virtually decisive

If

$$\frac{a - c_1}{a - 2c_1 + c_2} \leqslant d \leqslant \frac{4}{3}\frac{a - c_1}{a - 2c_1 + c_2} \quad \text{and} \quad d \geqslant \frac{8}{9}, \tag{25}$$

then ε^B is given by (13), the firms' profits by (14) and (15), the combined output and market price by (16) and (17).

Case B.III: Technical advance decisive

If

$$\frac{1}{2} \leqslant d \leqslant \frac{a - c_1}{a - 2c_1 + c_2}, \tag{26}$$

then ε^B is given by (18), the firms' profits by (20) and (21), and the combined output and market price by (22) and (23).

These three benchmark cases may be thought of as the possible types of newcomers the oldtimer might confront.

3. The giving cases

We now turn to the second scenario, denoted by G, in which the oldtimer offers the newcomer access to his superior production technology. In return, the newcomer commits not to conduct R&D. In this case both firms employ the lower marginal cost, c_1, and each produces the symmetric duopoly quantity $q_1^G = q_2^G = q^G = (a - c_1)/3$, and realizes a profit

$$\pi_1^G = \pi_2^G = \left(q^G\right)^2 = \left(\frac{a - c_1}{3}\right)^2. \tag{27}$$

The combined output is

$$Q^G = 2q^G = \frac{2}{3}(a - c_1) \tag{28}$$

and the market price is

$$P^G = a - Q^G = \frac{a + 2c_1}{3}. \tag{29}$$

We compare the present case with the three possible benchmark cases:

Case G.I

Characterized by (24) where the newcomer's technical advance is indecisive. Considering the oldtimer first, we have that $\pi_1^G \geqslant \pi_1^B$ will hold if, by (27) and (9)

$$\left(\frac{a - c_1}{3}\right)^2 \geqslant \left(\frac{a - 2c_1 + c_2 - \varepsilon^B}{3}\right)^2, \tag{30}$$

where ε^B is given by (6). Expression (30) yields

$$c_1 \geqslant c_2 - \varepsilon^B, \tag{31}$$

that is, the oldtimer will offer a deal only if he expects that, in its absence, the newcomer will reduce her marginal cost below his. Substituting ε^B from (6) into (31), we obtain the inequality

$$d \leqslant \frac{4}{9}\frac{a - c_1}{c_2 - c_1}, \tag{32}$$

as the condition necessary for the oldtimer to offer the deal. We now have to check whether or not (32) and (24) are consistent, namely, if

$$\frac{8}{9} \leqslant \frac{4}{9}\frac{a - c_1}{c_2 - c_1} \tag{33}$$

and

$$\frac{4}{3}\frac{a-c_1}{a-2c_1+c_2} \leqslant \frac{4}{9}\frac{a-c_1}{c_2-c_1}. \tag{34}$$

It can be easily shown that both (33) and (34) are equivalent to (4), and hence the oldtimer will offer the deal if both (24) and (32) are satisfied. As for the newcomer, she will accept the offer if $\pi_2^G \geqslant \pi_2^B$. By (10) and (27) if

$$\left(\frac{a-c_1}{3}\right)^2 \geqslant \frac{d}{9d-8}(a-2c_2+c_1)^2. \tag{35}$$

It can be shown that (35) is equivalent to

$$d \geqslant \frac{2}{9}\frac{(a-c_1)^2}{(a-c_2)(c_2-c_1)}. \tag{36}$$

Thus, d must satisfy both (24), (32), and (36). For such a d to exist,

$$\frac{2}{9}\frac{(a-c_1)^2}{(a-c_2)(c_2-c_1)} \leqslant \frac{4}{9}\frac{a-c_1}{c_2-c_1} \tag{37}$$

must hold. This inequality can be shown to be equivalent to (4). It follows that, if (24) and (32) are satisfied, the oldtimer will offer the deal and, unless (36) fails to hold, the newcomer will accept it. Note that when c_2 approaches c_1, the right-hand side of (36) approaches infinity. Under these circumstances, there will be fewer instances when the newcomer accepts the offer. Indeed, in the limiting case, where $c_2 = c_1$, the newcomer possesses the same technology as the oldtimer and no deal will prevent her from conducting R&D. When her initial marginal cost c_2 is sufficiently high, the newcomer might lean towards employing the better technology c_1, rather than conducting R&D.

To examine the effect of a deal on the final product prices, we subtract the symmetric duopoly price, (29), that would obtain in the presence of a deal from the price, (12), that would apply in its absence. It can easily be seen that the difference is negative precisely when the condition for the oldtimer to offer the deal, (31), is satisfied. Moreover, the deal, by its very terms, eliminates any technical advance.

Case G.II

Characterized by (25) where the newcomer's technical advance is virtually decisive. Since the oldtimer's profit would be zero if the newcomer conducts R&D, he would offer her his technology. The newcomer would accept the deal if $\pi_2^G \geqslant \pi_2^B$. By (15) and (27) if

$$\left(\frac{a-c_1}{3}\right)^2 \geqslant (a-c_1)^2 - \frac{d}{2}(a-2c_1+c_2)^2, \tag{38}$$

that is if

$$d \geqslant \frac{16}{9}\left(\frac{a-c_1}{a-2c_1+c_2}\right)^2. \tag{39}$$

Note that the right-hand side of (39) is greater than the left-hand side of (25) if

$$\frac{16}{9}\frac{a-c_1}{a-2c_1+c_2} > 1 \tag{40}$$

holds. Namely, if

$$7(a-2c_2+c_1)+5(c_2-c_1) > 0. \tag{41}$$

The last inequality is satisfied by (4) and $c_2 > c_1$. Hence, it is possible to satisfy both (39) and (25) if

$$\frac{16}{9}\left(\frac{a-c_1}{a-2c_1+c_2}\right)^2 \leqslant d \leqslant \frac{4}{3}\frac{a-c_1}{a-2c_1+c_2}. \tag{42}$$

Thus, the newcomer will accept the deal offered if (42) holds, and will reject it if

$$\frac{a-c_1}{a-2c_1+c_2} \leqslant d \leqslant \frac{16}{9}\left(\frac{a-c_1}{a-2c_1+c_2}\right)^2. \tag{43}$$

By comparing the pre-deal price (17) with the post-deal price, (29), it is clear that implementing the deal will raise the product's price. And, again, the deal will stop technical advance.

Case G.III

Characterized by (26) where the newcomer's technical advance is decisive. As the oldtimer's profit would be zero if the newcomer conducts R&D, he would definitely be better off by offering his technology. The newcomer would accept the offer if $\pi_2^G \geqslant \pi_2^B$. By (21) and (27) if

$$\left(\frac{a-c_1}{3}\right)^2 \geqslant \frac{d}{2(2d-1)}(a-c_2)^2. \tag{44}$$

Expression (44) is equivalent to

$$A = d\left[9(a-c_2)^2 - 4(a-c_1)^2\right] \leqslant -2(a-c_1)^2. \tag{45}$$

Since $c_2 \leqslant (a+c_1)/2$ holds by (4), we obtain that A, defined in (45), satisfies

$$\begin{aligned}\frac{A}{d} &\geqslant 9\left(a-\frac{a+c_1}{2}\right)^2 - 4(a-c_1)^2\\ &= -1.75(a-c_1)^2 > -2(a-c_1)^2.\end{aligned} \tag{46}$$

Hence (44) cannot hold, and the newcomer will reject the deal.

We summarize the above in the following proposition:

PROPOSITION 1. *In the giving scenario, a deal is feasible if the newcomer's technical advance is potentially either indecisive or virtually decisive. In both cases a deal will raise the product's price relative to the counterpart benchmark cases and eliminate technical advance. A deal is infeasible if the newcomer's technical advance is potentially decisive. And in the absence of a deal the price will decline.*

4. The sharing cases

We now turn to the last scenario, denoted by S, in which the oldtimer offers the newcomer access to his superior production technology in return for her sharing her R&D outcomes with him. Hence, in the production stage of the game both firms employ the lower marginal cost, $c_1 - \varepsilon^S$, and produce the symmetric duopoly quantity $q_1^S = q_2^S = q^S = (a - c_1 + \varepsilon^S)/3$. We begin this analysis, by observing that the R&D cost function, employed in the analysis of the benchmark case, should be modified to take into account the reasonable supposition that reducing marginal cost is more difficult when starting with the superior production technology than with the inferior one. In other words, achieving any reduction in marginal cost should depend on its current level. Consequently, we assume that the R&D cost function is now given by

$$\frac{d}{2}(c_2 - c_1 + \varepsilon)^2 - \frac{d}{2}(c_2 - c_1)^2 = \frac{d}{2}\big[\varepsilon^2 + 2\varepsilon(c_2 - c_1)\big]. \tag{47}$$

Note that the above function is consistent with the one $(d\varepsilon^2/2)$ employed in the benchmark case B, as letting $c_2 \to c_1$ in (47) yields the former expression. Also note that the marginal cost of R&D is now $d(\varepsilon + c_2 - c_1)$. The newcomer now solves

$$\max_{\varepsilon}\left(\frac{a - c_1 + \varepsilon}{3}\right)^2 - \frac{d}{2}\big[\varepsilon^2 + 2\varepsilon(c_2 - c_1)\big]. \tag{48}$$

The first order necessary condition yields

$$\varepsilon^S = \frac{2(a - c_1) - 9d(c_2 - c_1)}{9d - 2}, \tag{49}$$

with the second order condition yielding $d \geqslant 2/9$. Note that $\varepsilon^S \geqslant 0$ implies, through (49),

$$d \leqslant \frac{2}{9}\frac{a - c_1}{c_2 - c_1}. \tag{50}$$

If (50) fails to hold, the newcomer will prefer not to conduct R&D under the deal offered, meaning that she either does not conduct R&D or will not share it. Suppose that (50) holds. Substituting (49) into the oldtimer's profit function, we obtain

$$\pi_1^S = \left(\frac{a - c_1 + \varepsilon^S}{3}\right)^2 = \frac{9d^2}{(9d - 2)^2}(a - c_2)^2, \tag{51}$$

and by subtracting the R&D cost, the newcomer's profit

$$\begin{aligned}\pi_2^S &= \pi_1^S - \frac{d}{2}\big(c_2 - c_1 + \varepsilon^S\big)^2 + \frac{d}{2}(c_2 - c_1)^2\\ &= \frac{d}{9d - 2}(a - c_2)^2 + \frac{d}{2}(c_2 - c_1)^2\end{aligned} \tag{52}$$

is obtained. Since each firm's output is given by $(a - c_1 + \varepsilon^S)/3$, total industry output is

$$Q^S = 2q^S = 2\frac{a - c_1 + \varepsilon^S}{3} = \frac{6d}{9d-2}(a - c_2), \tag{53}$$

and the product price is

$$P^S = a - Q^S = \frac{3d(a + 2c_2) - 2a}{9d - 2}. \tag{54}$$

We now compare the results of this case with those of the benchmark cases.

Case S.I

Characterized by (24) where the newcomer's technical advance is indecisive. Considering the oldtimer first, we have that $\pi_1^S \geqslant \pi_1^B$ will hold if, by (51) and (9)

$$\left(\frac{a - c_1 + \varepsilon^S}{3}\right)^2 \geqslant \left(\frac{a - 2c_1 + c_2 - \varepsilon^B}{3}\right)^2, \tag{55}$$

where ε^B is given by (6), and ε^S is given by (49). Inequality (55) holds if

$$c_1 + \varepsilon^S \geqslant c_2 - \varepsilon^B. \tag{56}$$

Recall that when we compared scenarios G and B we observed that in G the oldtimer would offer the deal only if he expected that, in its absence, the newcomer would reduce her initial marginal cost c_2 below his marginal cost c_1. Here, (56) implies that now, in scenario S, the oldtimer will offer the deal even under less threatening circumstances and because he will share in any technical advance. Employing (9) and (51), (55) yields

$$\frac{3d}{9d-2}(a - c_2) \geqslant \frac{3d(a - 2c_1 + c_2) - 4(a - c_1)}{9d - 8}. \tag{57}$$

Inequality (57) is equivalent to

$$J = 27d^2(c_2 - c_1) - 3d(3a - 8c_1 + 5c_2) + 4(a - c_1) \leqslant 0. \tag{58}$$

We will now show that (58) holds for all the relevant values of the parameters. First recall that $c_2 \geqslant c_1$ holds. This lower bound and (50) imply

$$c_1 \leqslant c_2 \leqslant c_1 + \frac{2}{9d}(a - c_1). \tag{59}$$

We now consider J, given by (58), as a function of c_2, and show that it is negative for the two extreme values of c_2 in (59). Indeed, for $c_2 = c_1$, (58) yields

$$J = (-9d + 4)(a - c_1) < 0 \tag{60}$$

for $d \geqslant 8/9$. When $c_2 = c_1 + 2(a - c_1)/(9d)$, we obtain

$$J = \left(-3d - \frac{2}{3}\right)(a - c_1) < 0 \tag{61}$$

for all $d \geqslant 8/9$. Consider now a fixed value of d. For this particular value (60) and (61) imply that J, given by (58), is negative for the two extreme values of c_2. However, (58) also implies that for the given fixed value of d, J is linear in c_2, and hence it must be negative for all intermediate values of c_2. Hence J is negative for all possible values of c_2 and d and (55) holds.

Consider now the newcomer. She will accept the offered deal if $\pi_2^S \geqslant \pi_2^B$. By (10) and (52) if

$$\frac{d}{9d-2}(a-c_2)^2 + \frac{d}{2}(c_2-c_1)^2 \geqslant \frac{d}{9d-8}(a-2c_2+c_1)^2. \tag{62}$$

Inequality (62) is equivalent to

$$\begin{aligned} I = {} & 2(9d-8)(a-c_2)^2 + (9d-8)(9d-2)(c_2-c_1)^2 \\ & - 2(9d-2)(a-2c_2+c_1)^2 \geqslant 0. \end{aligned} \tag{63}$$

Recall now that c_2 must satisfy (59), and consider again the two extreme values. When $c_2 = c_1$, (63) yields $I = -12(a-c_2)^2 < 0$. Hence, as in the former case, the newcomer will not accept a deal if her technology is close to the oldtimer's. If, however, $c_2 = c_1 + 2(a-c_1)/(9d)$, we obtain from (63) following some rearrangement, that (63) holds if and only if

$$81d(d-1) + 4 \geqslant 0. \tag{64}$$

Note that (64) holds when $d \geqslant 1$, and recall that d is bounded from below by (24). Substituting $c_2 = c_1 + 2(a-c_1)/(9d)$ in (24), we obtain

$$d \geqslant \frac{4}{3}\frac{a-c_1}{a-2c_2+c_1} = \frac{4}{3}\frac{9d}{9d+2}. \tag{65}$$

From the last inequality $d \geqslant 10/9$ follows. Hence (64) holds and the deal will be accepted by the newcomer. The intuition for this is clear: when her initial marginal cost c_2 is sufficiently high, the newcomer will be more inclined to accept a deal and use the substantially lower marginal cost c_1 as a better starting point for her R&D, even though she will have to share her findings with the oldtimer.

We now turn to discuss the effect of the deal on the price difference, $P^B - P^S$, which depends on $Q^B - Q^S$. Comparing (11) to (53), we have $Q^B \geqslant Q^S$ if

$$\frac{2a-c_1-c_2+\varepsilon^B}{3} \geqslant 2\frac{a-c_1+\varepsilon^S}{3}, \tag{66}$$

that is, if

$$c_2 - c_1 + 2\varepsilon^S \leqslant \varepsilon^B. \tag{67}$$

By (6) and (49), if

$$c_2 - c_1 + 2\frac{2(a-c_1)-9d(c_2-c_1)}{9d-2} \leqslant \frac{4}{9d-8}(a-2c_1+c_2). \tag{68}$$

Following some rearrangements, it can be shown that (68) holds if

$$f_1(d) = 3\big[27d^2(c_2 - c_1) - 6d(c_2 - c_1) + 8(a - c_2)\big] \geqslant 0. \tag{69}$$

By (4), $f_1(d) \geqslant f_2(d)$, given by

$$\begin{aligned} f_2(d) &= 3(c_2 - c_1)\big[27d^2 - 6d + 8\big] \\ &= 3(c_2 - c_1)\left[27d\left(d - \frac{6}{27}\right) + 8\right]. \end{aligned} \tag{70}$$

Hence $f_2(d) > 0$, and (69) and hence (68) and (65), (66) hold for the relevant range of $d \geqslant 8/9$. So, in this case as well, implementation of a deal will increase prices. Also, by (49), (6), and following some algebraic manipulations, $\varepsilon^B \geqslant \varepsilon^S$ if

$$2(9d - 1)(a - c_1) \geqslant -\big(16 + 18d^2\big)(c_2 - c_1), \tag{71}$$

which is always satisfied. Hence, without a deal there will be more technological advance. The difference between ε^B and ε^S can be attributed to the disincentive created by the oldtimer's free riding on the newcomer's R&D.

Case S.II

Characterized by (25) where the newcomer's technical advance is virtually decisive. Again, as the oldtimer's profit would be zero if the newcomer conducts R&D, he would offer his technology to the newcomer, while she would accept the deal if (50) holds and $\pi_2^S \geqslant \pi_2^B$. By (15) and (52) if

$$\frac{d}{9d-2}(a - c_2)^2 + \frac{d}{2}(c_2 - c_1)^2 \geqslant (a - c_1)^2 - \frac{d}{2}(a - 2c_1 + c_2)^2 \tag{72}$$

holds. Rearranging (72), we obtain that it is equivalent to

$$\begin{aligned} H = 9d^2\big[(c_2 - c_1)^2 + (a - 2c_1 + c_2)^2\big] + 2d\big[(a - c_2)^2 - (c_2 - c_1)^2 \\ - 9(a - c_1)^2 - (a - 2c_1 + c_2)^2\big] + 4(a - c_1)^2 \geqslant 0. \end{aligned} \tag{73}$$

We now turn to show that there are cases in which (73) will not hold. Consider the extreme case where $c_2 = c_1$. Then

$$\frac{H}{(a - c_1)^2} = 9d^2 - 18d + 4. \tag{74}$$

The minimum of this quadratic function is at $d = 1$. Furthermore, (25) yields $1 \leqslant d \leqslant 4/3$, and for both extreme values of d, (74) is negative. Thus, it is negative for all $1 \leqslant d \leqslant 4/3$, and (72) cannot hold in this case.

We now turn to the impact of the deal on prices. Comparing (16) to (53), we have $Q^B \geqslant Q^S$ if

$$a - c_1 \geqslant \frac{6d}{9d-2}(a - c_2), \tag{75}$$

or if,

$$d \geqslant \frac{2}{3} \frac{a - c_1}{a - c_1 + 2(c_2 - c_1)}. \tag{76}$$

Since the right-hand side of (76) is smaller than $2/3$, it follows that $Q^B \geqslant Q^S$ for $d \geqslant 2/3$, in particular for $d \geqslant 8/9$ as implied by the second order conditions. Consequently, a deal is bound to increase the product's price.

Turning now to check for the extent of technological improvement we observe that $\varepsilon^B \geqslant \varepsilon^S$ holds if, by (49) and (13), following some manipulations

$$(9d - 4)(a - c_1) \geqslant -(18d - 2)(c_2 - c_1), \tag{77}$$

which is always satisfied. It follows that the level of technological improvement will be higher without a deal.

Case S.III

Characterized by (26) where the newcomer's technical advance is decisive. As the oldtimer's profit would be zero if the newcomer conducts R&D, he would definitely be better off by offering her his technology. The newcomer, though, would accept the deal offered if (50) and $\pi_2^S \geqslant \pi_2^B$ hold. By (21) and (52) if

$$\frac{d}{9d - 2}(a - c_2)^2 + \frac{d}{2}(c_2 - c_1)^2 \geqslant \frac{d}{2(2d - 1)}(a - c_2)^2. \tag{78}$$

Expression (78) is equivalent to

$$f(d) \leqslant \left(\frac{c_2 - c_1}{a - c_2}\right)^2, \tag{79}$$

where

$$f(d) = \frac{5d}{(2d - 1)(9d - 2)}. \tag{80}$$

The derivative of $f(d)$ is given by

$$f'(d) = 5\frac{-18d^2 + 2}{(2d - 1)^2(9d - 2)^2} < 0 \tag{81}$$

when $D \geqslant 1/2$. That is, f is decreasing in d. Recall now that in the case considered, d is constrained by (50), that is by

$$d \leqslant \hat{d} = \frac{2}{9} \frac{a - c_1}{c_2 - c_1}. \tag{82}$$

Since f is decreasing in d, if we establish that (79) does not hold for $d = \hat{d}$, then it will not hold for all values of d. Indeed, substituting (82) into (80), we obtain that

$$f(\hat{d}) = \frac{5(a - c_1)(c_2 - c_1)}{(4a + 5c_1 - 9c_2)(a - c_2)} > \left(\frac{c_2 - c_1}{a - c_2}\right)^2 \tag{83}$$

if

$$\frac{5(a - c_1)}{4a + 5c_1 - 9c_2} > \frac{c_2 - c_1}{a - c_2}. \tag{84}$$

Expression (84) is equivalent to

$$g(c_2) = 5(a - c_1)^2 - 9(a - c_1)(c_2 - c_1) + 9(c_2 - c_1)^2 > 0. \tag{85}$$

Note that by our assumptions (see (4)), $c_1 \leqslant c_2 \leqslant (a + c_1)/2$. It can be easily verified that, the quadratic function g of c_2 is positive at the two extreme values $c_2 = c_1$, and $c_2 = (a + c_1)/2$, and that it attains its minimum at $c_2 = (a + c_1)/2$. Hence, (85) holds and consequently, (78) cannot hold, implying that the newcomer will reject the deal if she can reduce her marginal cost decisively in its absence.

We summarize the above in the following proposition:

PROPOSITION 2. *In the sharing case, a deal is feasible if the newcomer's technical advance is potentially either indecisive or virtually decisive. In both cases, the deal will raise the product's price and reduce the level of technical improvement as compared to the benchmark case. No deal is feasible if the newcomer's technical advance is potentially decisive. And in the absence of a deal, the product's price will decline.*

5. Conclusions

Our analysis discloses that a newcomer firm will decline an established firm's offer of access to its currently superior production technology in return for her either not conducting R&D or else sharing its results, if she has the R&D capability to drive the oldtimer from the market. In other words, an oldtimer's effort to avert being driven from the market through a cooption strategy will fail against a newcomer able to do so. However, it can succeed against less potent newcomers with only the ability to reduce his market share and even against those just able to drive him from the market. Obviously, the oldtimer is more eager to consummate a deal with the more threatening newcomers. The prospect of the newcomer sharing her technology improvements further heightens the oldtimer's eagerness to make a deal.

As for the newcomer, her receptivity to a deal depends on her relative marginal cost disadvantage. She will reject the oldtimer's offer if her disadvantage is negligible. The prospect of having the oldtimer free-ride on her R&D results also blunts her interest in a deal.

From consumers' standpoint, the bad news is that consummated deals between the oldtimer and the newcomer lead to higher prices and less technical advance than would occur in their absence. The good news is that decisive innovations that lead to lower prices cannot be thwarted by a deal between the oldtimer and the newcomer.

Several further research paths suggest themselves. It might be interesting to analyze the signaling game between the oldtimer and the newcomer, whose type from among the three possible is unknown to the oldtimer. Relaxation of the implicit assumption that any deal between the oldtimer and the newcomer can be costlessly monitored and enforced might lead to some interesting principle-agent type analysis.

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CHAPTER 7

Efficiency of Joint Enterprises with Internal Bargaining

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Abstract

In this paper we take a close look at those strategic incentives arising in a situation where firms share the costs and profits in a multi-firm project, and bargain for their respective (precommitted) split of cost- and profit-shares. We establish that, when each firm's effort contribution to the joint undertaking is mutually observable (which is often the case in closely collaborative operations) and hence can form basis of the contingent cost- and profit-sharing scheme, it is not the gross economic efficiency but the super-/sub-additivity of the nett returns from effort that directly affects the sustainability of a profile of firms' effort contributions. The (in)efficiency result we obtain in this paper is of different nature from so-called "free riding" or "team competition" problems: the set of sustainable outcomes with bargaining over precommitted cost- and profit-shares is generally neither a superset nor a subset of the sustainable set without bargaining.

Keywords: cost sharing, profit sharing, repayment, subgame perfection

JEL classifications: L13, G31, O32

1. Introduction

Cost sharing between multiple economic bodies, such as a *research joint venture* undertaken by multiple firms operating in the same industry, often tends

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to be encouraged from policy- and welfare-points of view.[1] Apparently, the leading reason for such "official" encouragement is the assertion that cost sharing can enhance cost-efficiency, eliminating otherwise wasteful *effort duplication*. A relevant example is the possibility of carrying out joint R&D activities in the development of new products and processes (see Katz, 1986; d'Aspremont and Jacquemin, 1988; Katz and Ordover, 1990; Kamien et al., 1992; Suzumura, 1992). On the other hand, it is well noted that, generally, each participant in any joint project has an incentive to "free ride" the effort exerted by other participants, which tends to entail an inefficient outcome with a suboptimally low level of effort chosen strategically by each participant.

Perhaps one of the most natural and the most spontaneous "solution" to this incentive problem is to allow firms to make their cost- and profit-shares in the joint project *directly contingent upon their exerted effort levels*. In a joint project where participating firms closely collaborate with one another, it is often not at all unrealistic to assume that they can accurately monitor each other's effort levels. In this paper we model such a situation by a simple two-stage game where each firm decides its own effort investment in the first stage, followed by the realisation of their respective nett profit shares in the ensuing stage. By precommitting their nett profit shares *before deciding their respective effort investment*, firms can reward or punish each other's effort decisions and thereby enforce a certain profile of effort investment even if their decisions (in the first stage of the game) are simultaneously and noncooperatively made.

Our main finding in this paper is that, even though the aforementioned contingent profit-sharing scheme serves as a means to circumvent the classical free riding problem, it can harbour a different kind of inefficiency. The gist of the difference between preceding studies and our model is not the mere fact that firms can precommit with their nett profit shares and monitor each other's effort, but that there can be room for *bargaining among firms* when they predetermine their nett profit shares. Essentially, each firm's bargaining power is closely related to its "outside alternative" which, in a game-theoretic context, is largely parallel to the firm's *unilateral deviation incentives*. This inevitably implies that an outcome which is not susceptible to strong unilateral deviation incentives by any of the participating firms, can be sustained as a (subgame perfect) equilibrium whether economically efficient or not.

To summarise, if each firm's cost share is determined independently of their respective contributions, it tends to entail the classical free riding problem. Alternatively, if profit sharing can be made contingent upon each firms' strategic contribution decisions, then the bargaining between participating firms tends to give rise to multiple equilibria, among which the effort levels are *complementary between firms* (i.e., the locus of equilibria is downward-sloping) if nett *joint* returns to effort is *submodular* between firms; or *complementary between firms*

[1] See the National Cooperative Research Act in the US; EC Commission (1990); and Goto and Wakasugi (1988), *inter alia*.

(i.e., the locus of equilibria is upward-sloping) if nett joint returns to effort is *submodular*.

The basic structure of our model, together with its general qualitative features, is laid out in Section 2. We present illustrative examples in Section 3 to develop intuition on how precommitted bargaining can affect the sustainability of economically efficient outcomes. Section 4 concludes the paper. A glimpse of extension to a more quantitative decisions made by each of the participating firms in a joint project, is given in Appendix B.

2. *Basic model*

We start our analysis from a simple model of cost- and profit-sharing between two economic bodies, referred to as "firm 1" and "firm 2" henceforth. Although these two "firms" are to launch a jointly undertaken project, each of them is to decide, simultaneously and noncooperatively, whether or not to make an incremental marginal contribution to the joint project. The *nett joint returns* from their decisions can be summarised in the following table.

		Firm 2	
		Contribute	Not contribute
Firm 1	Contribute	$Y[1, 1]$	$Y[1, 0]$
	Not contribute	$Y[0, 1]$	$Y[0, 0]$

Throughout the paper we assume that contributions are *mutually observable*, so that firms can make their shares of nett profits $y_1[K]$ and $y_2[K]$ *contingent directly upon the profile of their contributions* subject, obviously, to

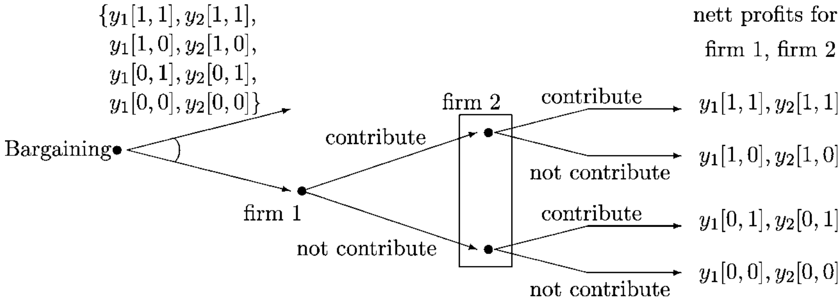
$$y_1[K] + y_2[K] = Y[K], \quad [K] \in \big\{[1, 1], [1, 0], [0, 1], [0, 0]\big\}.$$

Hence, the procedural structure of this game can be summarised by the tree in Figure 1.

At the beginning, the two firms bargain[2] for the complete contingent set of nett profit shares. To retain as much generality as possible we avoid narrowly specifying the procedure of bargaining, other than imposing the following weak regularity requirement which seems plausible in any standard economic sense.

[2] It deserves heightened attention that the presence of bargaining should not be mistaken as if we were invoking any sort of cooperative decision making. As is well known, for instance, Nash bargaining can be viewed as a limiting solution for Rubinstein's bargaining, which is in fact a genuinely noncooperative game and is entirely devoid of any form of cooperative decision making (Rubinstein, 1982).

Figure 1. Cost/profit sharing contingent upon contributions.



DEFINITION. A bargaining function $b[\cdot,\cdot,\cdot] = (b_1[\cdot,\cdot,\cdot], b_2[\cdot,\cdot,\cdot])$ where

$$y_1[k_1,k_2] = b_1\big[y_1[\neg k_1,k_2], y_2[k_1,\neg k_2], Y[k_1,k_2]\big];$$
$$y_2[k_1,k_2] = b_2\big[y_1[\neg k_1,k_2], y_2[k_1,\neg k_2], Y[k_1,k_2]\big];$$
$$\{k_1,\neg k_1\} = \{k_2,\neg k_2\} = \{0,1\},$$

is said to be *regular* if

- b_1 increases in $y_1[\neg k_1,k_2]$, decreases in $y_2[k_1,\neg k_2]$, and increases in $Y[k_1,k_2]$;
- b_2 decreases in $y_1[\neg k_1,k_2]$, increases in $y_2[k_1,\neg k_2]$, and increases in $Y[k_1,k_2]$;
- $b_1 = y_1[\neg k_1,k_2]$ and $b_2 = y_2[k_1,\neg k_2]$ whenever $y_1[\neg k_1,k_2]+y_2[k_1,\neg k_2] = Y[k_1,k_2]$.

Note that our definition of regularity implies

$$\mathrm{sign}\big[y_1[k_1,k_2] - y_1[\neg k_1,k_2]\big] = \mathrm{sign}\big[y_2[k_1,k_2] - y_2[k_1,\neg k_2]\big].$$

This automatically implies the following general feature.

PROPOSITION 1. *For any regular bargaining function* $b[\cdot,\cdot,\cdot]$ *and nett joint profit schedule* $Y[\cdot,\cdot]$, *whenever a solution* $\{\{y_i[k_1,k_2]\}_{k_1\in\{0,1\}}^{k_2\in\{0,1\}}\}_{i=1,2}$ *exists, it sustains the equilibrium outcome such that*:

- *either both firms contribute or neither firm contributes if*

$$Y[1,1] + Y[0,0] \geqslant Y[1,0] + Y[0,1]; \tag{2.1}$$

- *only one of the two firms contributes if*

$$Y[1,1] + Y[0,0] \leqslant Y[1,0] + Y[0,1]. \tag{2.2}$$

In words, {contribute, contribute} and {not contribute, not contribute} are equilibrium outcomes if the nett gains from the two firms' contributions are *superadditive* (as in inequality (2.1)).[3] Otherwise, if the strategic contribution decisions are to yield *subadditive* nett profits (indicated by inequality (2.2)), then {contribute, not contribute} and {not contribute, contribute} are equilibrium outcomes.[4]

Economic implication

Proposition 1 implies that, in the prospect of bargaining between the participant firms inside the joint project, the equilibria resulting from each firm's "selfish" contribution decisions are determined solely on the grounds of super-/sub-additivity of the nett gains from contributions, not on the grounds of efficient outcomes *per se*. This can be illustrated in Figure 2, where the most efficient contribution profiles change across thickened borders. They are sustainable through Nash bargaining where circled, unsustainable where crossed out. For, to the upper-right of the dashed diagonal the equilibrium profiles are $[1, 0]$ and $[0, 1]$, to its lower-left they are $[1, 1]$ and $[0, 0]$.

3. Illustrative examples

Probably the most popularly accepted bargaining solution concept is the Nash solution.[5] Let the ratio of bargaining power between the two firms be $\psi_1 : \psi_2$. The two firms' nett profit shares when both firms contribute are determined as

$$\frac{y_1[1,1] - y_1[0,1]}{\psi_1} = \frac{y_2[1,1] - y_2[1,0]}{\psi_2},$$
$$y_1[1,1] + y_2[1,1] = Y[1,1]. \tag{3.1}$$

In words, firm 1's incentive (or disincentive) to "deviate" from contribution (C) to no contribution (N) should be matched against that for firm 2, weighted by

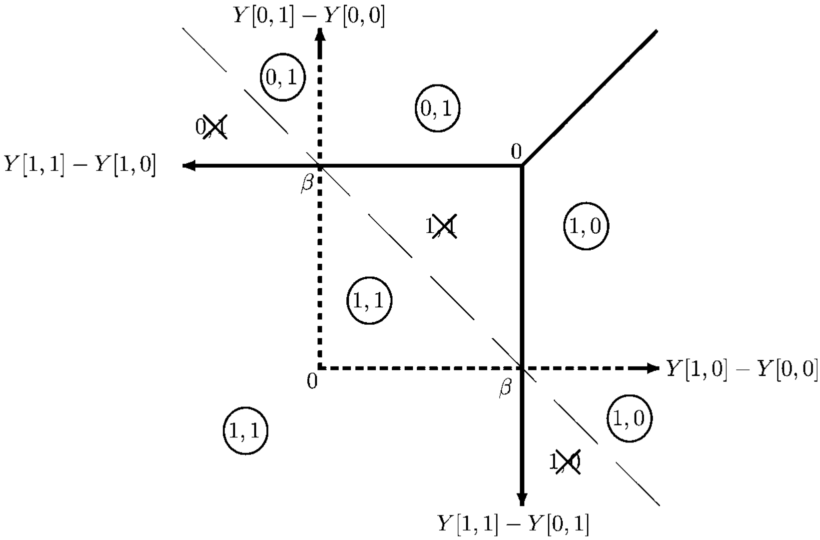
---

[3] Here, we refer to the discrete action version of superadditivity $Y[1,1] - Y[0,1] \geqslant Y[1,0] - Y[0,0]$ and submodularity $Y[1,1] - Y[0,1] \leqslant Y[1,0] - Y[0,0]$. In the former, the incentives for (or against) contribution are *supermodular* between the two firms (i.e., one firm's incentive to contribute is higher when the other firm does likewise than when the other firm does elsewise). In the latter, these incentives are *submodular*.

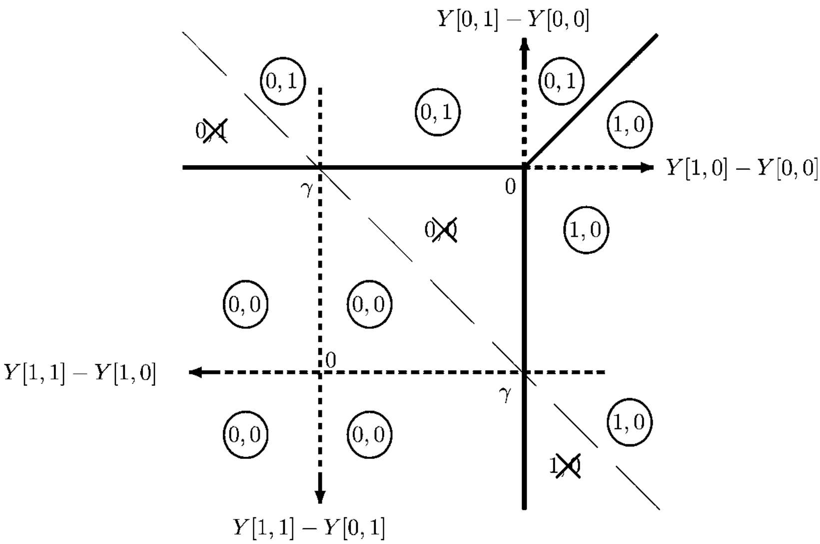
[4] Again, the analysis of R&D activity provides well-known examples of both subadditivity and superadditivity, depending upon whether the choice of R&D efforts is followed by Cournot or Bertrand competition (see Brander and Spencer, 1983; Dixon, 1985; Bester and Petrakis, 1993).

[5] For algebraic simplicity, we treat Nash bargaining as sharing of the *nett excess surplus*, i.e., the nett profit differential in comparison to the "outside option" available to each firm, be the excess surplus positive or negative. The qualitative nature of the game would stand largely unaffected if we interpreted it as sharing of a *positive excess surplus* only, not adopting the same form of solution when the excess surplus is negative. The latter is technically more intricate but can be plausible depending upon what sort of economic circumstance is in question (see Appendix A).

Figure 2.** **Efficient outcomes and their sustainability via Nash bargaining: (a) when $Y[1,1] - Y[0,0] = \beta \geqslant 0$; (b) when $Y[1,1] - Y[0,0] = \gamma \leqslant 0$.



(a)



(b)

their respective bargaining power.[6] Likewise,

$$\frac{y_1[1,0]-y_1[0,0]}{\psi_1}=\frac{y_2[1,0]-y_2[1,1]}{\psi_2},$$
$$y_1[1,0]+y_2[1,0]=Y[1,0], \tag{3.2}$$

$$\frac{y_1[0,1]-y_1[1,1]}{\psi_1}=\frac{y_2[0,1]-y_2[0,0]}{\psi_2},$$
$$y_1[0,1]+y_2[0,1]=Y[0,1], \tag{3.3}$$

$$\frac{y_1[0,0]-y_1[1,0]}{\psi_1}=\frac{y_2[0,0]-y_2[0,1]}{\psi_2},$$
$$y_1[0,0]+y_2[0,0]=Y[0,0]. \tag{3.4}$$

The above system of eight equations with eight unknowns leaves one degree of freedom and gives us the general solution

$$\begin{aligned}
&y_1[0,0]+y_2[0,0]=Y[0,0],\\
&y_1[1,1]=y_1[0,0]+\frac{Y[1,1]-Y[1,0]+Y[0,1]-Y[0,0]}{2},\\
&y_2[1,1]=y_2[0,0]+\frac{Y[1,1]-Y[0,1]+Y[1,0]-Y[0,0]}{2},\\
&y_1[1,0]=y_1[0,0]+\frac{\psi_1(Y[0,1]+Y[1,0]-Y[1,1]-Y[0,0])}{2(\psi_1+\psi_2)},\\
&y_2[0,1]=y_2[0,0]+\frac{\psi_2(Y[1,0]+Y[0,1]-Y[1,1]-Y[0,0])}{2(\psi_2+\psi_1)},\\
&y_1[0,1]=y_1[0,0]\\
&\qquad\qquad+\frac{\psi_2(Y[1,1]-Y[1,0])+(2\psi_1+\psi_2)(Y[0,1]-Y[0,0])}{2(\psi_1+\psi_2)},\\
&y_2[1,0]=y_2[0,0]\\
&\qquad\qquad+\frac{\psi_1(Y[1,1]-Y[0,1])+(2\psi_2+\psi_1)(Y[1,0]-Y[0,0])}{2(\psi_2+\psi_1)}.
\end{aligned}$$

EXAMPLE 1. *A priori* equal bargaining power $\psi_1 = \psi_2$, the private cost of contribution is £8 million per firm whilst the gross benefit from contribution is £10 million if only one firm contributes and £24 million if both contribute.

[6] Again, in our metaphor to Rubinstein's bargaining and its limiting solution, this corresponds to the case where the two firms' degrees of patience, measured in terms of discount rates r_1 and r_2, are in the ratio $r_1 : r_2 = \frac{1}{\psi_1} : \frac{1}{\psi_2}$. As we see hereinafter, we introduce these bargaining power parameters for the sake of completeness, or differently put, to demonstrate that our qualitative results do not hinge upon the distribution of bargaining power between the participating firms.

The nett joint return table becomes:

		Firm 2	
		Contribute	Not contribute
Firm 1	Contribute	$Y[1,1]=8$	$Y[1,0]=2$
	Not contribute	$Y[0,1]=2$	$Y[0,0]=0$

in £ million.

The nett joint return from a sole firm's contribution is £2 million whilst that from an additional firm's contribution is £6 million, whereby nett returns from contribution is *superadditive* between the two firms.

As aforementioned there are a continuum of bargaining solutions, but there is only one *symmetric* solution[7] (in £ million):

$$y_1[0,0] = y_2[0,0] = 0, \qquad y_1[1,0] = y_2[0,1] = -1,$$
$$y_1[0,1] = y_2[1,0] = 3, \qquad y_1[1,1] = y_2[1,1] = 4.$$

This entails two pure strategy subgame perfect equilibria (simply "equilibria" hereinafter unless otherwise specified), in one of which neither firm contributes, in the other both firms contribute and share the profit equally. This reflects the fact that nett returns from contribution are superadditive (see Proposition 1 in Section 2). Obviously, the latter equilibrium entails the most efficient (first best) outcome.

Were there no bargaining, instead if the two firms were to share the gross profit equally irrespective of their contributions, then the unique equilibrium outcome would be for neither firm to contribute. This is due to the classical *free riding problem* leading to underincentives for each firm to contribute. It is hereby concluded that the prospect of bargaining can help sustain the economically efficient outcome.

EXAMPLE 2. *A priori* equal bargaining power $\psi_1 = \psi_2$, the private cost of contribution is £2 million per firm whilst the gross benefit from contribution is £10 million if only one firm contributes and £16 million if both contribute.

The nett joint return table becomes:

		Firm 2	
		Contribute	Not contribute
Firm 1	Contribute	$Y[1,1]=12$	$Y[1,0]=8$
	Not contribute	$Y[0,1]=8$	$Y[0,0]=0$

in £ million.

[7] We list the symmetric solution for nothing but concreteness. The set of equilibrium outcomes would, of course, be the same whether we selected the symmetric bargaining solution or an asymmetric solution.

The nett joint return from a sole firm's contribution is £8 million whilst that from an additional firm's contribution is £4 million, whereby nett returns from contribution is *subadditive* between the two firms.

The unique *symmetric* solution (in £ million) is:

$$y_1[0,0] = y_2[0,0] = 0, \qquad y_1[1,0] = y_2[0,1] = 1,$$
$$y_1[0,1] = y_2[1,0] = 7, \qquad y_1[1,1] = y_2[1,1] = 6,$$

where the equilibria are for only one of the firms to contribute and take £3 million out of the gross profit of £10 million whilst the other firm takes the remainder, £7 million, without making contribution. This is the reflexion of the subadditivity of nett returns from contribution.

Obviously, the nett return from contribution is always positive, hence economically the most efficient outcome would be for both firms to contribute, which is nevertheless unsustainable through bargaining. Without bargaining, if the two firms were to split the gross profit always evenly, then the efficient outcome would indeed be the unique equilibrium outcome. In this case, unlike in our previous example, bargaining hinders the sustainability of economically the most efficient outcome.

EXAMPLE 3. *A priori* equal bargaining power $\psi_1 = \psi_2$, the private cost of contribution is nil for firm 1 and £10 million for firm 2, whilst the gross benefit from contribution is £4 million if only one firm contributes and £12 million if both contribute.

The nett joint return table is:

		Firm 2	
		Contribute	Not contribute
Firm 1	Contribute	$Y[1,1] = 2$	$Y[1,0] = 4$
	Not contribute	$Y[0,1] = -6$	$Y[0,0] = 0$

in £ million.

As this game is *a priori* asymmetric between the two firms, there is no "symmetric" solution. One of the solutions is

$$y_1[0,0] = y_2[0,0] = 0, \qquad y_1[1,0] = y_2[0,1] = -1,$$
$$y_1[0,1] = -5, \qquad y_2[1,0] = 5, \qquad y_1[1,1] = -4, \qquad y_2[1,1] = 6,$$

which accommodates two equilibria, in one of which neither firm contributes, in the other both firms contribute. Obviously in this case firm 1's contribution is uniformly efficient whilst firm 2's contribution is uniformly inefficient, hence the most efficient outcome is only for firm 1 not for firm 2 to contribute. This efficient outcome would be sustainable if gross profits are shared evenly all the time, but is not sustainable with the bargaining for profit sharing schedules.

4. Conclusion

Standard game-theoretic literature has it that, in any jointly undertaken productive activity, if the profit sharing schedule cannot be made contingent upon the level of effort exerted by each participating firm and hence each firm inevitably bears its own effort costs, then there arises systematic underincentives for efforts, entailing lower aggregate effort than economically efficient. This is the classical *free riding problem*.

What we have shown in this paper is that bargaining over a profit sharing schedule that is *contingent upon observed effort exerted by each participating firm* [I] can alleviate the free riding problem, yet [II] tends to entail a profile of effort levels based solely upon the super-/sub-additivity of nett returns to effort, irrespective of the nett joint productivity of effort. The latter inevitably implies that [IIa] when nett returns to effort are subadditive, a firm's low effort tends to be traded for another firm's high effort even when the joint nett returns to effort is uniformly positive (in which case the efficient outcome of all firms' high effort becomes unsustainable) or when the joint nett returns are uniformly negative (where the efficient outcome would be all firms' low effort), and that [IIb] when nett returns to effort are superadditive, a firm's high effort tends to link with another firm's high effort, whereby the system fails to select for an efficient firm against an inefficient firm.

Appendix A

The alternative, technically more intricate, scenario is that firms must follow Nash solution only if each firm's excess surplus share is positive. The system of Equations (3.1) through (3.4) is now replaced with:

$$
\begin{aligned}
&\frac{y_1[1,1]-y_1[0,1]}{\psi_1}=\frac{y_2[1,1]-y_2[1,0]}{\psi_2},\\
&y_1[1,1]+y_2[1,1]=Y[1,1]\geqslant y_1[0,1]+y_2[1,0],\\
&\frac{y_1[1,0]-y_1[0,0]}{\psi_1}=\frac{y_2[1,0]-y_2[1,1]}{\psi_2},\\
&y_1[1,0]+y_2[1,0]=Y[1,0]\geqslant y_1[0,0]+y_2[1,1],\\
&\frac{y_1[0,1]-y_1[1,1]}{\psi_1}=\frac{y_2[0,1]-y_2[0,0]}{\psi_2},\\
&y_1[0,1]+y_2[0,1]=Y[0,1]\geqslant y_1[1,1]+y_2[0,0],\\
&\frac{y_1[0,0]-y_1[1,0]}{\psi_1}=\frac{y_2[0,0]-y_2[0,1]}{\psi_2},\\
&y_1[0,0]+y_2[0,0]=Y[0,0]\geqslant y_1[1,0]+y_2[0,1].
\end{aligned}
$$

It is intuitively clear that this leads to the same equilibrium result as in Proposition 1, although the exact set of sustainable solutions can now have one more degree of freedom than in Section 2 (that is, two degrees of freedom in total).

Appendix B

Our basic analysis in Section 2 can be straightforwardly extended to a discrete contributions space. Assume now that each of the two firms has a *trinary*, as opposed to the previously *binary*, choice of contributing either 0, 1, or 2 units to the jointly undertaken project. The nett joint returns table now becomes as follows.

		Firm 2		
		2 units	1 unit	0 units
Firm 1	2 units	$Y[2,2]$	$Y[2,1]$	$Y[2,0]$
	1 unit	$Y[1,2]$	$Y[1,1]$	$Y[1,0]$
	0 units	$Y[0,2]$	$Y[0,1]$	$Y[0,0]$

Accordingly, our concept of regularity needs to be redefined as follows.

REDEFINITION. A bargaining function $b[\cdot,\cdot,\cdot] = (b_1[\cdot,\cdot,\cdot], b_2[\cdot,\cdot,\cdot])$:

$$y_1[k_1,k_2] = b_1\big[\max y_1[\neg k_1,k_2], \max y_2[k_1,\neg k_2], Y[k_1,k_2]\big],$$
$$y_2[k_1,k_2] = b_2\big[\max y_1[\neg k_1,k_2], \max y_2[k_1,\neg k_2], Y[k_1,k_2]\big],$$

where

$$\max y_1[\neg k_1,k_2] \equiv \max\big\{y_1\big[k_1^\bullet,k_2\big], y_1\big[k_1^\circ,k_2\big]\big\},\ \big\{k_1,k_1^\bullet,k_1^\circ\big\} = \{0,1,2\},$$
$$\max y_2[k_1,\neg k_2] \equiv \max\big\{y_2\big[k_1,k_2^\bullet\big], y_1\big[k_1,k_2^\circ\big]\big\},\ \big\{k_2,k_2^\bullet,k_2^\circ\big\} = \{0,1,2\}$$

is said to be *regular* if

- b_1 increases in $\max y_1[\neg k_1,k_2]$, decreases in $\max y_2[k_1,\neg k_2]$, and increases in $Y[k_1,k_2]$;
- b_2 decreases in $\max y_1[\neg k_1,k_2]$, increases in $\max y_2[k_1,\neg k_2]$, and increases in $Y[k_1,k_2]$;
- $b_1 = \max y_1[\neg k_1,k_2]$ and $b_2 = \max y_2[k_1,\neg k_2]$ whenever $\max y_1[\neg k_1,k_2] + \max y_2[k_1,\neg k_2] = Y[k_1,k_2]$.

Our interest is not in an exhaustive equilibrium comparative statics result on this game, but instead in the following analogue of our foregoing Proposition 1 (see Section 2).[8]

[8] Note that Proposition 2, unlike Proposition 1, does not exhaust the entire feasible range of parameter values $Y[\cdot,\cdot]$. For instance, it is possible that inequality (B.1) may be satisfied whilst inequalities (B.2) and (B.3) may be violated. Our intention here is to focus on those two cases listed specifically on Proposition 2, as these two are the relevant cases hereinafter.

PROPOSITION 2.

- *The two firms' contributing the same number of units, either* 0, 1, *or* 2 *units each, is an equilibrium outcome if*

$$Y[2,2] + Y[1,1] \geqslant Y[2,1] + Y[1,2]; \tag{B.1}$$

$$Y[2,2] + Y[0,0] \geqslant Y[2,0] + Y[0,2]; \tag{B.2}$$

$$Y[1,1] + Y[0,0] \geqslant Y[1,0] + Y[0,1]. \tag{B.3}$$

- *The two firms' contributing two units altogether, be it split* 2–0 *or* 1–1, *is an equilibrium outcome if*

$$Y[2,0] + Y[1,1] \geqslant Y[2,1] + Y[0,1]; \tag{B.4}$$

$$Y[2,0] + Y[0,2] \geqslant Y[2,2] + Y[0,0]; \tag{B.5}$$

$$Y[1,1] + Y[0,2] \geqslant Y[1,0] + Y[1,2]. \tag{B.6}$$

Namely, when the nett gains from the two firms' contributions are *superadditive* in the sense of *positive affiliation* (as in (B.1) through (B.3)) the two firms' equilibrium contributions are *strategically perfectly complementary*; otherwise when the nett gains are *subadditive* (as in (B.1) through (B.4)) the equilibrium contributions are *strategically perfectly substitutable* between the two firms.

The reason why these two "extreme" cases appeal to our interest is because they enable us to extrapolate our analysis further to a continuous contributions space. An analogue of Propositions 1 and 2 is as below.

PROPOSITION 3.

- *The two firms' effort levels* k_1, k_2 *are complementary along the locus of equilibria if* $\frac{\partial^2 Y[k_1,k_2]}{\partial k_1 \partial k_2} > 0$.
- *The two firms' effort levels* k_1, k_2 *are substitutional along the locus of equilibria if* $\frac{\partial^2 Y[k_1,k_2]}{\partial k_1 \partial k_2} < 0$.

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CHAPTER 8

Equilibrium Research Joint Ventures

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Abstract

Research joint ventures (RJVs) avoid duplication of R&D costs and facilitate knowledge diffusion. However, sharing R&D output intensifies post-innovation market competition and hence hampers firms' incentive to join an RJV. In this paper, RJV formation is modeled as a noncooperative sequential game, as in Bloch (1995, "Endogenous structures of association in oligopoly", RAND Journal of Economics 26, 537–556). I show that in equilibrium a unique RJV exists, and it comprises of only a subset of the firms in the industry unless R&D cost is low. Moreover, the equilibrium RJV is larger than the size that maximizes the profit per member firm but smaller than the socially optimal size. When firms initially have different marginal costs, various RJV structures can emerge in equilibrium. For some parameter values of the model, large (low-cost) firms join hands in R&D, leaving small (high-cost) firms as outsiders. For other parameter values, a group of large firms invite small firms, instead of other large firms, to form an RJV.

Keywords: duplicative R&D cost, endogenous research joint venture, asymmetric firms

JEL classifications: L13, O32

1. Introduction

It has been well recognized that R&D rivalry among business firms in general do not generate socially optimal outcomes, due to factors like duplication of R&D costs, technological spillovers, and uncertainty of innovation outcome, etc. Cooperative R&D or research joint ventures (RJVs) is perceived to be an effective way to overcome such market failures in innovation.[2] To promote cooperation in

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[2] See, e.g., Hagedoorn et al. (2000) for a recent survey about the incentive to cooperate in R&D.

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R&D, the US Congress passed the National Cooperative Research Act in 1984 which eased the antitrust treatment of cooperative R&D among competing firms. Similarly, the EUREKA program was created in 1985 as an intergovernmental initiative in order to enhance European competitiveness through its support to R&D activity in Europe.

Advantages of research joint ventures include internalization of technological spillovers, avoidance of wasteful duplication of R&D effort, and utilization of the synergies, or complementaries, among the member firms. RJVs can also increase ex post dissemination of research findings. While these are well understood in the literature, what is less understood is how these various factors affect the structure of an RJV. For example, what are the implications of internalizing spillovers, avoidance of duplication of R&D costs, or utilizing synergies on the structures of RJVs? Are these advantages large enough to draw every firm in an industry to join an RJV?[3]

In this paper, I develop a model that specifically analyzes firms' incentive to avoid duplicative R&D investments. R&D activity in this model incurs a fixed and reduces the unit cost of production by a discrete amount. By forming an RJV, firms can share the fixed costs of R&D and at the same time collectively own the new technology that results from the innovation process. However, having too large an RJV lowers the competitive advantage of the member firms in the post-R&D market as too many firms are entitled to the use of the new technology. The privately optimal RJV structure is thus determined by the trade-off between sharing R&D cost, which favors a larger RJV, and maintaining the market power of the member firms in the post-innovation market, which tends to reduce the size of RJV.

The RJV formation process is modeled as a noncooperative sequential game, as in Bloch (1995). Within this simply framework, several interesting results are derived. First, I show that only one RJV is formed in equilibrium and in general it comprises only a subset of the firms in the industry.[4] The socially optimal arrangement, however, is to have an industry-wide R&D joint venture. Second, it is also shown that relative to independent R&D, cooperative innovation in the form of an RJV leads to a larger number of firms engaging in R&D. This implies that the policy of allowing competing firms to form RJVs is always welfare enhancing in this model. Third, the model also nicely captures the strategic incentive of using RJV as a device to discourage R&D activity by competing firms.

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[3] Early studies of endogenous formation of RJVs include Martin (1994), Bloch (1995), Yi and Shin (1995), and De Bont and Wu (1997).

[4] Closely related to the basic trade-off of the model is that in Matutes and Padilla (1994) who consider formation of competing ATM networks in a spacial model of banking competition. In their model, two basic forces determine the size of ATM networks. First, the larger the network, the more attractive it is to depositors. This *network effect* encourages banks to join the network. Second, compatibility between ATMs makes the services of the banks better substitutes for each other. This *substitution effect*reduces the competitive advantage that a bank has over rivals with which the bank shares its ATM. Matutes and Padilla show that due to the *substitution effect* banks achieve only partial compatibility in their ATM networks.

In fact, in equilibrium the size of the RJV is larger than what would maximize the joint profits of the member firms so that firms in the residual coalition would not find it profitable to launch competing R&D projects, either collectively or individually.

In the later part of the model, I also study RJV formation among asymmetric firms who differ in their initial costs of production, focusing on the equilibrium composition of RJVs. Although the model with asymmetric firms is more difficult to analyze, I identify two general forces that are at work. First, to minimize the degree of competition in the post-innovation market, RJV member firms prefer the nonmembers to be weak (of high-cost). This implies that low-cost firms tend to conduct R&D together. But high-cost firms, if left out, are more desperate and hence more likely to form a competing RJV. It is shown by means of an example (with three firms) that either of those two forces can dominate. In particular, for some parameter values of the model, all nonmember firms of the RJV in equilibrium are of high-cost. For a different set of parameter values, the equilibrium RJV consists of a group of high-cost firms and low-cost firms, leaving other low-cost firms as outsiders.

There has been a growing literature on RJV formations. Bloch (1995) analyzes the endogenous formation of RJVs in a differentiated oligopoly and shows that in equilibrium firms in the industry form two competing RJVs of different sizes. In his model, each firm's R&D investment is fixed and the size of innovation depends on the number of firms in an RJV. In my model, the size of innovation is fixed, as is the R&D cost; but only one RJV is formed in equilibrium. Yi and Shin (1995, 1996) study various membership rules of RJVs and analyze RJV formation when firms have complementary research assets. In a patent race setting, Martin (1994) shows that in equilibrium more than one RJVs may be formed, and the outcome is in general not socially optimal. De Bont and Wu (1997) analyzes RJV formation in an oligopoly model with R&D spillovers. Their model uses the notions of internal stability and external stability to define equilibrium size of RJV which implies that one RJV exists. The present model differs from the existing literature in that it specifically models duplicative R&D costs aspect of R&D competition, and studies its implication in the simplest possible setting. Recently, there are some studies of RJVs among asymmetric firms, e.g., Veugelers and Kesteloot (1996), Roller et al. (1997, 2000), and Navaretti et al. (2000). But most of these studies are limited to duopoly only.[5]

[5] There are also some recent studies in RJVs in vertical settings. For example, Banerjee and Lin (2001) examined the incentives of an input suppliers and downstream users, which use the new technology to produce a final good, to form an RJV. They show that, although this vertical joint venture is beneficial to all the partners, upstream and downstream firms have conflicting interests with respect to the size of the RJV: the former would prefer to have the size of the coalition as large as possible, and the latter the opposite case. Chen and Ross (2003) study input RJVs in a two-tier oligopoly model.

2. The model

An industry has $n \geqslant 2$ firms producing a homogeneous product the demand for which is given by $p = a - Q$. Initially, the firms each have constant marginal cost of production equal to $a - \lambda$, $\lambda > 0$. Every firm in the industry has access to an R&D project. The R&D project, if undertaken, will cost a fixed amount, F, and result (with certainty) a new process with marginal cost of production equal to $a - \lambda - \mu$. The parameter μ measures the size of innovation and is exogenously given. Firms are free to conduct R&D jointly. If a group of firms form an RJV, they equally share the R&D cost, and all are entitled to use the low-cost technology in the post-innovation product market. In the post-innovation product market, all firms compete in the Cournot fashion. We focus only on co-operation in the R&D stage, so the members of an RJV cannot, say for antitrust reasons, coordinate their decisions regarding the product market.

Suppose k of the n firms conduct R&D (jointly or otherwise). In this case, the product market is characterized by the Cournot equilibrium with k low-cost firms and $n - k$ high-cost firms. Let $\Pi_1(k)$ and $\Pi_2(k)$ denote the profits per firm (gross of the R&D cost) of the two groups respectively. For the linear demand specification, the industry output in this case is calculated to be:

$$Q(k) = \left\{ \begin{array}{ll} \frac{n\lambda + k\mu}{n+1}, & \text{if } k < \lambda/\mu, \\ \frac{k(\lambda+\mu)}{k+1}, & \text{if } k \geqslant \lambda/\mu \end{array} \right\}.$$

The corresponding profits are

$$\Pi_1(k) = \left\{ \begin{array}{ll} \frac{[\lambda + (n+1-k)\mu]^2}{(n+1)^2}, & \text{if } k < \lambda/\mu, \\ \frac{(\lambda+\mu)^2}{(k+1)^2}, & \text{if } k \geqslant \lambda/\mu \end{array} \right\}$$

for the low-cost firms and

$$\Pi_2(k) = \left\{ \begin{array}{ll} \frac{(\lambda - k\mu)^2}{(n+1)^2}, & \text{if } k\mu < \lambda, \\ 0, & \text{if } k\mu \geqslant \lambda \end{array} \right\}$$

for the high-cost firms.

The number of firms active in the post-innovation Cournot equilibrium depends on the size of innovation, μ, the market size, λ, as well as the value of k. If more than λ/μ firms conduct R&D and consequently have the new technology, the competition in the product market will be so intense that the high-cost firms will be driven out of business. If the number of firms that conduct R&D is small, in particular if $k < \lambda/\mu$, both the low-cost and the high-cost firms have a positive market share. I allow both major innovation ($\lambda/\mu < n$) and minor innovation ($\lambda/\mu \geqslant n$).

The incentives for R&D are determined by the profit functions $\Pi_1(k)$, $\Pi_2(k)$, and the R&D cost, F. Clearly, both $\Pi_1(k)$ and $\Pi_2(k)$ are decreasing in k, reflecting the fact that whenever one more firm obtains the new technology all the other firms in the industry are hurt. Moreover, $\Pi_1(k) > \Pi_2(k)$ trivially holds for all k.

I assume that the industry-wide RJV is profitable relative to the case of no R&D.

ASSUMPTION 1. *$\Pi_1(n) - \frac{F}{n} > \Pi_2(0)$ (or equivalently, $F/n < \mu(2\lambda + \mu)/(n+1)^2$, for the linear demand specification).*

Before moving to the detailed analysis of the model, it is useful to introduce the following function. Let $G(m; k) \equiv \Pi_1(k+m) - \Pi_2(k)$, $m = 1, 2, \ldots, n-k$. That is, $G(m; k)$ measures the gain per firm from R&D (gross of R&D cost) for a coalition with m firms, given that k firms have already conducted R&D. Clearly, the m-firm RJV is profitable if and only if $G(m; k) > F/m$.

By definition,

$$G(m; k) = \left\{ \begin{array}{l} \frac{\mu}{(n+1)^2}[2\lambda + (n+1-2k-m)\mu](n+1-m), \\ \quad \text{if } m + k < \lambda/\mu, \\ (\lambda+\mu)^2/(k+m+1)^2, \\ \quad \text{if } m + k \geqslant \lambda/\mu \end{array} \right\}$$
$$1 \leqslant m \leqslant n - k.$$

Note that $G(m; k)$ is a decreasing function of k. An increase in k has two effects. First, it intensifies the competition in the post-innovation product market, which makes R&D less attractive to the m-firm coalition. Secondly, since $\Pi_2(k)$ declines with k, it becomes more costly for a firm not to conduct R&D. In this model the first effect dominates the second effect, so $G(m; k)$ decreases with k. The importance of this observation, as we will see, is that the first k-firm RJV can deter R&D by the residual coalition by increasing its size.

3. Independent R&D

As a benchmark, consider the case where firms simultaneously but independently make their R&D investment decisions. A firm that innovates bears the entire R&D cost, F. Obviously, a firm conducts independent R&D if and only if $G(1; k) > F$, where k is the number of its competitors that engage in R&D. The following result obtains by noting that $G(1; k)$ is a decreasing function of k. Let k' denote the (pure strategy) Nash equilibrium number of firms that conduct R&D in the independent R&D game

LEMMA 1.

(i) *If $F < G(1; n-1)$, then $k' = n$ and conducting independent R&D is the dominant strategy of each firm*;
(ii) *if $G(1; n-1) \leqslant F < G(1; 0)$, then $0 < k' < n$, where k' is such that $G(1; k'-1) > F \geqslant G(1; k')$*; *and*
(iii) *if $F \geqslant G(1; 0)$, then $k' = 0$.*

Case (i) is the situation where R&D cost is very low, so no matter what its competitors do, the gain of R&D to an individual firm always exceeds the cost. If the R&D cost is higher, as in case (ii), independent R&D is profitable only when some firms in the industry do not conduct R&D. In case (iii), the R&D cost is so high that no firm wants to innovate even when it is sure that it is the only firm with the new technology.

4. Research joint venture

4.1. Sequential formation of RJV

Following Bloch (1995), I model the process of RJV formation as a noncooperative sequential game. In particular, one of the firms, the initiator, first announces an RJV coalition $S_1 \subseteq \{1, 2, \ldots, n\}$. Since firms are symmetric, it is assumed that firm 1 is the initiator. Each prospective member of S_1 responds in turn to the offer. If all firms in S_1 accept the offer, the RJV S_1 is formed and the process is repeated among the remaining firms, with the firm with the lowest index being the next initiator. If one of the perspective members of S_1 rejects the offer, it is chosen as the initiator in the next round. A firm that intends to do no R&D is modeled as announcing an empty set, and a firm can choose to do independent R&D by announcing a singleton set consisting of itself. An outcome of this RJV formation game is thus a partition of the set of firms into disjoint coalitions, with firms not doing R&D being empty sets. A feature of this RJV formation process is that a firm is not allowed to join an RJV unless all the existing member firms agree.

Given the simple structure of the model, it is clear that there can be at most one RJV formed in equilibrium. Intuitively, if two or more RJVs are formed, the member firms of these two coalitions can do better by merging into a single RJV and thus avoiding duplicating R&D cost. Suppose that more than one RJVs are formed in equilibrium. Let S_A and S_B denote the second last and the last RJVs, respectively, formed along the subgame perfect equilibrium path in the sequential game. By definition, no firms that do not belong to any RJV in this equilibrium would find it profitable to form another RJV among themselves. Given this, the initiator of S_A would find it more profitable to propose $S_A \cup S_B$ instead and thus save on R&D cost. And all members of $S_A \cup S_B$ would subsequently agree to the proposal, anticipating that this would not change the behavior of the firms not belonging to any RJV in the given equilibrium because the number of firms who eventually do R&D after the proposal is accepted is the same as in the original equilibrium. But this contradicts to the assumption that the original partition (with S_A and S_B being separate RJVs) is an equilibrium. This leads to part (i) of the proposition below.

Let k^* denote the equilibrium size of the RJV. Thus, in equilibrium, k^* firms joint hand in R&D and the other $n - k^*$ firms choose not to conduct R&D (jointly or otherwise). The part (ii) of the following result says that R&D cooperation in this model not only leads to avoidance of duplications of R&D cost, but also gives rise to larger number of firms that conduct R&D.

PROPOSITION 1.

(i) *Only one RJV is formed in equilibrium in this model and nonmembers choose not to conduct R&D activity*; *and*
(ii) $k' \leqslant k^*$.

Suppose $k' > k^*$. By definition, in the noncooperative R&D equilibrium $k' - k^*$ firms still find independent R&D profitable, given that k^* firms have conducted R&D. These $k' - k^*$ firms can raise their profits by pooling their R&D resources. But this contradicts the fact that in the RJV equilibrium, no coalition of firms find R&D profitable given that k^* firms have already conducted R&D.

4.2. The profit-maximizing RJV size

Consider what might be the best RJV size that the initiator can announce in the RJV formation game. If there is going to be an RJV established at all in equilibrium, it must be the case that by joining the RJV a firm receives a profit no less than what it would earn by staying outside. Thus, without loss of generality we assume that the announcement of the initiator, S_1, always contains the firm itself. Given this, the incentive for the initiator to invite additional firms to join the RJV is that the R&D cost can be spread over a larger set of firms. However, a larger RJV lowers post-innovation profits Π_1. Ideally, the initiator would like to announce the size of S_1 (or an integer k) that maximizes $\Pi_1(k) - \frac{F}{k}$, the net payoff per member firm of the proposed RJV. The following lemma informs us that the cost saving incentive is never strong enough for the initiator to invite all the firms to form an RJV.

LEMMA 2. *Let* $k^{\max} \equiv \operatorname{Arg\,max}[\Pi_1(k) - \frac{F}{k}]$. *If Assumption* 1 *holds and demand for the final product is linear, then,* $k^{\max} < n$.

PROOF. It suffices to show that $H \equiv [\Pi_1(n) - \frac{F}{n}] - [\Pi_1(n-1) - \frac{F}{n-1}]$ is negative. For the case where $\lambda/\mu \geqslant n$ (minor innovation), Assumption 1 simply says $F/n < \mu(2\lambda+\mu)/(n+1)^2$. Simple algebra shows that $H < 0$ is equivalent to $\frac{F}{n(n-1)} < \frac{\mu(2\lambda+3\mu)}{(n+1)^2}$. The latter inequality is valid under Assumption 1, so the lemma holds for minor innovations. Now if $\lambda/\mu \leqslant n-1$ (major innovation), then $H = [\frac{(\lambda+\mu)^2}{(n+1)^2} - \frac{F}{n}] - [\frac{(\lambda+\mu)^2}{n^2} - \frac{F}{n-1}] = \frac{F}{n(n-1)} - \frac{(\lambda+\mu)^2(2n+1)}{(n+1)^2 n^2}$. But, Assumption 1 implies that $F/n < (\lambda+\mu)^2/(n+1)^2$. Since $(2n+1)(n-1) > n^2$ for $n \geqslant 2$, we have $H < 0$. □

Having the $(k+1)$th firm join the RJV affects the existing members in two ways. It lowers the R&D cost per firm, as the new member contributes to the total R&D investment. At the same time, it reduces each member firm's post-innovation profit because the new firm also shares the new technology. In deciding whether or not to give membership to a new firm, the existing members weigh the corresponding cost savings, which equals $F/k - F/(k+1) =$

$F/[k(k+1)]$, with the reduction in their individual profit, $\Pi_1(k) - \Pi_1(k+1)$. As k become very large, the resulting cost savings become disproportionately small, so it never pays to have all the n firms to join the RJV.

4.3. The equilibrium RJV size

The profit-maximizing size of RJV, $k^{\max}$, reflects firms' *stand-alone incentive* for joining an RJV. By definition, an RJV of size $k^{\max}$ is the best for the member firms *if* the other $n - k^{\max}$ firms do not conduct their own R&D. But any subset of the residual coalition is free to form their own RJV. As discussed earlier, the incentive for m of those firms to do so is given by $G(m; k^{\max})$. If $G(m; k^{\max})$ exceeds the corresponding R&D cost, F/m, then in response to the formation of an RJV by the first $k^{\max}$ firms, another RJV will be formed. If this is the case, the initiator of the first RJV will be better off by announcing an RJV of size $k^{\max} + m$, rather than $k^{\max}$, in the first place. Therefore, the equilibrium size of RJV, k^* must be such that the member firms' payoffs are maximized subject to the condition that the residual coalition finds it unprofitable to form a competing RJV (namely, $G(m; k^*) \leqslant F/m$ for all $m \in \{1, 2, \ldots, n - k^*\}$). The equilibrium RJV size is thus determined by both the *stand-alone* and the *deterrence incentive*.

PROPOSITION 2. *Assume that Assumptions 1 hold. Then,*

(i) $k^{\max} \leqslant k^* \leqslant n$, *and*
(ii) $k^* = n$ *if and only if R&D is the dominant strategy for every firm in the independent R&D game (i.e., if and only if F is very low).*

PROOF. See Appendix A. □

This proposition informs us that the RJV in this model in general does not consist of all n firms in the industry. Despite the incentive to share R&D cost, including all the firms in the RJV is too costly for the member firms as it would intensify post-R&D competition in the product market. An industry-wide RJV is formed only if R&D is the dominant strategy for every firm in the independent R&D game. This basically happens when the R&D cost is very low $(F < G(1, n-1))$ so that no firm can be deterred from doing its own R&D no matter what the other firms' actions are (recall case (i) of Lemma 1). For large F, however, this will no longer be true. Consequently, the size of equilibrium RJV is smaller than n.

It is worthwhile to emphasize that Proposition 2 predicts that an industry-wide RJV will be formed not because R&D cost is so high that firms want to share cost with as many firms as possible. Rather, it is because R&D cost is so low that no firm can be deterred from pursuing individual R&D.

4.3.1. RJV as a means of driving rivals out the market: The case of major innovation: $\lambda/\mu < n$

A conventional wisdom is that RJV can be used to force rivals out of the market. In my model this happens when the equilibrium size of RJV exceeds λ/μ, in which case the nonmember firms shut down in the post-innovation Cournot equilibrium and thus only the member firms are active in the product market. However, due to deterrence incentive, it is possible that k^* well exceeds λ/μ, i.e., the RJV may be larger than necessary to drive the other firms out of business.

To see this, consider the case $\lambda/\mu \leqslant 1$. In this situation, the size of innovation is so big that a single firm can monopolize the product market if it is the only firm to conduct R&D. It is easy to see that the firm would not want to do joint R&D with any other firms just to share cost. By doing R&D alone, a firm receives the monopoly profit and incurs the entire R&D cost, thereby receiving the net gain of $\Pi_1(1) - F$. If it joins hands with $k \geqslant 1$ other firms in R&D, its net profit will be $\Pi_1(k) - F/k$. Since $\Pi_1(1) > k\Pi_1(k)$ (the monopoly profits are greater than the sum of the oligopoly profits), $\Pi_1(1) - F > k[\Pi_1(k) - F/k] \geqslant \Pi_1(k) - F/k$. Thus, if no other firms have access to R&D, this firm would be able to monopoly the industry by conducting individual R&D activity. However, when other firms can also conduct R&D, as in this model, a group of other firms may join hand to form a competing RJV. To deter this from happening, the first firm can invite some of firms to form an RJV in the first place in such a way that no subset of the residual coalition will find it profitable to form a separate RJV. (Recall that function $G(m, k)$ decreases in k.) In this equilibrium, a single RJV is formed and its R&D outcome drives the other firms out of the market who find it not profitable to fight back by forming competing RJVs.

4.4. Welfare

Let $W(k)$ denote the total welfare when k firms conduct joint R&D. That is

$$W(k) = CS(k) + k\Pi_1(k) + (n-k)\Pi_2(k) - F,$$

where $CS(k) = 0.5[Q(k)]^2 = 0.5(\frac{n\lambda + k\mu}{n+1})^2$ is the consumer surplus.

As k increases, the profits of both the nonmember firms and the members decrease. Despite this, it is readily verified that $W(k)$ increases with k. That is, as the RJV becomes larger, the increase in consumer surplus exceeds the reduction in firms' profits. Therefore, the socially efficient R&D arrangement, given that firms compete as Cournot players in the product market, is to have an industry-wide RJV. However, Proposition 2 informs us that the equilibrium RJV is in general smaller than the social optimum.

What kinds of government policies might help in getting the equilibrium RJV closer to the social optimum? R&D subsidy may help increase the equilibrium RJV size k^*. It does so through the deterrence effect. With financial support of the government, the residual coalition is more willing to form a competing RJV. Anticipating this, the first initiator may announce a larger RJV coalition for the purpose of preventing a competing RJV from being formed. If the amount of R&D subsidy is so large that the after-subsidy R&D cost is below $G(1; n-1)$ (see Lemma 1), then it becomes a dominant strategy for each firm to conduct R&D. In this case, the equilibrium RJV will comprise all firms in the industry, as Proposition 2 predicts.

5. *RJV formation among asymmetric firms*

Suppose that the firms in the industry initially have different marginal costs. In this case, a natural question to ask is: What will be the composition of an equilibrium RJV? In particular, do firms tend to conduct joint R&D with more efficient firms so that less efficient firms are left out of RJV in equilibrium?

Sticking with linear demand $p = a - bQ$, the Cournot equilibrium profit of firm i, given the cost configuration $(c_1, c_2, \ldots, c_n)$, is

$$\Pi_i^0 = \left(a - nc_i + \sum_{j \neq i} c_j\right)^2 \Big/ \left[b(n+1)^2\right].$$

If firm i conducts (independent) R&D, it marginal cost is reduced to c, and it's profit will be

$$\Pi_i = \left(a - nc + \sum_{j \neq i} c_j\right)^2 \Big/ \left[b(n+1)^2\right].$$

The net gain of innovation to firm i is thus

$$\Delta\Pi_i \equiv \Pi_i - \Pi_i^0 = \left(2a - nc_i - nc + 2\sum_{j \neq i} c_j\right)(nc_i - nc)/\left[b(n+1)^2\right].$$

Clearly, $\frac{\partial \Delta\Pi_i}{\partial c_i} \propto (a - nc_i + \sum_{j \neq i} c_j) > 0$ and $\frac{\partial \Delta\Pi_i}{\partial c_j} > 0$.

The first inequality says that firms with higher initial cost have a stronger incentive for R&D, whereas the second inequality informs us that R&D is less attractive to a firm after other firms reduce their costs.

There are at least two forces that determine the composition of an RJV. First, to minimize the degree of competition in the post-innovation market, RJV member firms prefer the firms not participating in the RJV to be weak (of high-cost). But high-cost firms, if left out in an RJV, are more desperate and hence have a stronger incentive to form a competing RJV. Analytical results are difficult to obtain, due to technical complexity. The following example shows that either of these two forces can dominate. In certain situations, the first force dominates so that in equilibrium the nonmember firms are all weak. In other situations, some low-cost firms may be invited to join hands with high-cost firms, leaving other low-cost firms as outsiders of the RJV. In the latter case, the low-cost nonmembers would not form an RJV of their own, since they already enjoy a reasonable level of profits. However, the high-cost firms, if left outside, would form a competing RJV as the gain to innovate is higher for them than for the low-cost firms.

5.1. An example

There are three firms in the industry. Initially, the marginal costs of firm 1 and firm 2 (the low-cost firm) are c_L, and the marginal cost of firm 3 (the high-cost firm) is $c_H > c_L > 0$. The firms have access to an R&D project that, if undertaken, will reduce the marginal cost to 0. The cost of R&D is denoted as F. The demand for the good is $p = a - Q/16$. The notation (i, j) in the following proposition (proved in Appendix A) refers to the equilibrium RJV which has firms i and j as members.[6]

PROPOSITION 3. *Assume that* $a \geqslant \frac{10}{3}c_H$ *and* $\frac{a}{6+\sqrt{42}} < c_L < \frac{a}{4+\sqrt{13}}$. *Then* $(1,3)$ *is an equilibrium if* $3c_L(2a + 2c_H - c_L) \leqslant F \leqslant \min\{\Delta, \Delta'\}$, *and* $(1,2)$ *is an equilibrium if* $\Delta \leqslant F \leqslant \min\{6c_H(2a + c_H), 8c_L(a + c_H - c_L)\}$ *where*

$$\Delta \equiv 3c_H(2a - 3c_H), \quad \text{and}$$
$$\Delta' \equiv c_L\big[4a + 6(c_H - c_L)\big] + c_H\big[4a - 10(c_H - c_L)\big].$$

For F falling between $3c_L(2a + 2c_H - c_L)$ and $\min\{\Delta, \Delta'\}$, firm 3 will conduct independent R&D if firm 1 and 2 join hands in R&D. But if firms 1 and 3 form an RJV, firm 2 will not do R& D by itself because its initial cost is already low relative to that of firm 3, so the gain from innovation is not as high. Since firm 3 cannot be deterred by a two-firm RJV but firm 2 can, firm 1 invites the weaker competitor, firm 3, to join the RJV, leaving firm 2 as an outsider.

However, for F larger than Δ, neither firm 3 nor firm 2 will find individual R&D to be profitable if the other two firms have already formed an RJV. In this case, two strong firms, firms 1 and 2 form an RJV in equilibrium. If the R&D cost is too high, in particular if $F > 6c_H(2a + c_H)$, firms 1 and 2 will invite firm 3 to join the coalition in order to share the cost.

6. Conclusion

This paper analyzes the basic trade-off that competing firms face in forming a research joint venture: RJVs enable firms to avoid duplication of R&D costs, but member firms also compete in the post-innovation product market with the jointly discovered technology. For the case with symmetric firms and linear demand function, it is shown that the incentive to share R&D cost is never strong enough as to induce all the firms in the industry to form an RJV, unless R&D cost is very low. The equilibrium RJV is thus smaller than the socially optimal arrangement which entails an industry-wide RJV. When R&D costs are very low, an industry-wide RJV is formed because competing RJVs cannot be deterred.. Moreover, due to the incentive to deter competing RJVs, RJV members

[6] As in the previous section, firm 1 is the first initiator and R&D costs are shared equally among member firms.

tend to invite additional firms over and above the point that maximizes members (myopic) profits.

For the case with asymmetric firms, the model identifies two basic forces that are at work. To minimize the degree of competition in the post-R&D market, member firms of an RJV prefer the nonmember (and none-innovating) firms to be of high-cost, thereby more tempted to invite low-cost firms to joint the RJV. However, high-cost firms are also more likely to form their own RJVs assuming the have the technical capability. While general results cannot be obtained for asymmetric firms, the example in this paper indicates that either of the two forces can dominate. I believe that the above-mentioned basic forces should be present in any general setting with asymmetric firms.

Appendix A

A.1. Proof of Proposition 2

(i) Suppose $k^* < k^{\max}$. The residual coalition finds R&D unprofitable given that this k^*-firm RJV is formed. By the definition of $k^{\max}$, the RJV can raise its profit per member firm by inviting additional $k^{\max} - k^*$ firms to joint. Doing so will not trigger the residual coalition (of the $n - k^{\max}$ firms) to form another RJV; because $G(m; k)$ decreases with k, R&D is not profitable either for the residual coalition as more firms conduct R&D. This contradicts k^* being the equilibrium RJV size.

(ii) Now suppose that R&D is the dominant strategy for every firm in the independent R&D game. In this case, no matter what size the first initiator announces, no firm in the residual coalition can be deterred from R&D. Realizing this, the first initiator will invite all the n firms to form an RJV. Thus, $k^* = n$.

If R&D is not the dominant strategy for every firm in the independent R&D game, then there exits a k^{**}, such that it does not pay a firm to conduct independent R&D if k^{**} firms have already undertaken R&D. That is, $G(1; k^{**}) \leqslant F$. Since $G(1; \cdot)$ is a decreasing function, as noted earlier, it must be that $G(1; n-1) \leqslant G(1; k^{**}) \leqslant F$. Based on this, we next prove that $k^* < n$. Consider what would happen if the initiator announces an RJV, $S_1 \subset N \equiv \{1, 2, \ldots, n\}$ with size $k^{\max}$. If $G(m; k^{\max}) \leqslant F/m$ for all $m \in \{1, 2, \ldots, n - k^{\max}\}$, then $k^* = k^{\max}$ is the equilibrium size of RJV. If $G(m; k^{\max}) > F/m$ for some $m \in \{1, 2, \ldots, n - k^{\max}\}$, then it is profitable for some firms in the residual coalition to form a competing RJV. Thus, following the initiator's announcement, either the proposal will be rejected by some firms in S_1, or another RJV will be proposed by the next initiator who is in $N - S_1$. To assure itself to be in the equilibrium RJV, the first initiator can announce $k^{\max} + 1$ in the first place. If an RJV with $k^{\max} + 1$ firms cannot prevent the residual coalition from establishing another RJV, the initiator can try $k^{\max} + 2$. Since $G(1; \cdot)$ is a decreasing function and $G(1; n-1) \leqslant F$, it takes at most $n-1$ firms for them to prevent a competing RJV from being formed. Therefore, $k^* < n$.

Finally, it is easy to see that after the initiator announces the RJV of size k^*, no will-be member firm will (unilaterally) leave the proposed RJV. By joining the RJV, a firm receives a payoff of $\Pi_1(k^*) - F/k^*$. If a firm refuses to join, its payoff will be $\Pi_2(k^*)$ in equilibrium. As shown above, $\Pi_1(k^*) - F/k^* > \Pi_1(n) - F/n$ (otherwise the first initiator would have announced $k = n$). On the other hand, Assumption 1 together with the fact that Π_2 decreases with k implies that $\Pi_1(n) - F/n > \Pi_2(k^*)$. Therefore, $\Pi_1(k^*) - F/k^* > \Pi_2(k^*)$.

A.2. Proof of Proposition 3

In the absence of R&D by any firm, the Cournot profit of firm i is given by $\pi_0^i \equiv (a - 4c_i + \sum_{j=1}^{3} c_j)^2$, $c_1 = c_2 = c_L$, $c_3 = c_H$, $i = 1, 2, 3$.

Let π_S^i denote firm i's profit in the product market when S is the set of firms that conduct R&D, $S \subseteq \{1, 2, 3\}$. The condition $a \geqslant \frac{10}{3} c_H$ ensures that firm 3 (the high-cost producer) will still be active if RJV $(1, 2)$ is formed. This in turn implies that, no matter what are the identities of the R&D firms, the non-R&D firm(s) will not be driven out of business.

We now show that $(1, 3)$ is an equilibrium.

First, note that $3c_L(2a + 2c_H - c_L) = \pi_{(1)}^1 - \pi_0^1$. So, for $F \geqslant 3c_L(2a + 2c_H - c_L)$, it does not pay firm 1 to conduct R&D alone.

Second, by definition,

$$\pi_0^1 + \pi_0^3 = (a - 2c_L + c_H)^2 + (a - 3c_H + 2c_L)^2, \quad \text{and}$$
$$\pi_{(1,3)}^1 + \pi_{(1,3)}^3 = 2(a + c_L)^2.$$

Thus, after algebraic simplification,

$$\pi_{(1,3)}^1 + \pi_{(1,3)}^3 - \left(\pi_0^1 + \pi_0^3\right) = c_L\left[4a + 6(c_H - c_L)\right] + c_H\left[4a - 10(c_H - c_L)\right] \equiv \Delta_2'.$$

Thus, $(1, 3)$ is profitable for $F < \min\{\Delta, \Delta'\}$.[7]

Now suppose that $(1, 3)$ is formed. Then, by pursuing independent R& D, firm 2's profit would increase by the amount $\pi_{(1,2,3)}^2 - \pi_{(1,3)}^2 = 3c_L(2a - 3c_L)$. Since $3c_L(2a - 3c_L) < 3c_L(2a + 2c_H - c_L)$, independent R&D by firm 2 is deterred by the formation of $(1, 3)$ for $F \geqslant 3c_L(2a + 2c_H - c_L)$.

Lastly, $F \leqslant \Delta$ implies that $F \leqslant \Delta'' \equiv 6c_L(2a + c_L)$,[8] i.e., $\pi_{(1,2,3)}^1 - F/3 \leqslant \pi_{(1,3)}^1 - F/2$. Since firm 1 is the initiator, it will not invite firm 2 to join $(1, 3)$ to share R&D costs.

This proves that $(1, 3)$ is an equilibrium RJV under the assumed conditions. That $(1, 2)$ is an equilibrium can be similarly proved.

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[7] Simple algebra shows that $3c_L(2a + 2c_H - c_L) < \Delta'$ under the condition $a > \frac{10}{3} c_H$, and that $3c_L(2a + 2c_H - c_L) < \Delta < \Delta'' \equiv 6c_L(2a + c_L)$ under the condition $\frac{a}{6+\sqrt{42}} < c_L < \frac{a}{4+\sqrt{13}}$.

[8] See footnote 7.

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PART III

Delegation and R&D incentives

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CHAPTER 9

Product and Process Innovation in Differential Games with Managerial Firms

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Abstract

We take a differential game approach to study the optimal choices of managerial firms concerning efforts in product a process innovation. We find the Nash equilibria under the open-loop and closed-loop information structure, and we compare the steady state allocations with the corresponding equilibria of markets populated by standard profit-maximising firms. We find that the managerial incentive leads firm to underinvest in product differentiation and to overinvest in process innovation, as compared to standard profit-maximising firms.

Keywords: differential games, process innovation, product innovation, delegation

JEL classifications: C73, D43, D92, L13, O31

1. Introduction

In the vein of the long-standing debate between Schumpeter (1942) and Arrow (1962), the interplay between market structure (or market power) on the one side and the intensity of R&D activities and the resulting pace of technical progress on the other has received a huge amount of attention in the existing literature.[2]

Here, we study the optimal decisions of managerial oligopolistic firms concerning investment in product innovation and investment in process innovation.

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1 Fax: +39 051 2092664.
2 So much so that listing all the relevant contributions is indeed impossible. See Reinganum (1989) and Martin (2001) for exhaustive overviews.

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Specifically, we consider a dynamic Cournot setting with N firms, where all of them are managerial, with the incentive scheme being as in Vickers (1985),[3] so that the maximand of any manager takes into account the profit and the amount of production. Our analysis will be carried out under the assumption that firms' behaviour is strictly non-cooperative, i.e., any form of R&D cooperation is ruled out, so that our interest will solely focus upon the interplay between market power (or market structure) and the R&D performance.

Product innovation consists in investments aimed at reducing the degree of substitutability among differentiated goods; process innovation consists in investments aimed at reducing the marginal cost of production (as in the literature stemming from the seminal contribution of d'Aspremont and Jacquemin, 1988).

In order to study these processes, we take a differential game approach. We find the Nash equilibria under the open-loop and the closed-loop information structure; then, we focus on the steady state allocations, which are stable in the saddle point sense.

The comparison of the steady state outcomes in the case of managerial firms with the corresponding equilibria in the case of profit-maximising firms provides clearcut results: the structure of the managerial incentives leads firms to invest more in process innovation, and less in product innovation, as compared to standard profit-maximising firms. Therefore, if we keep in mind that here 'managerial' is equivalent to 'more aggressive' or 'more competitive', the present analysis yields a mixed contribution to the aforementioned debate, since it reaches an Arrovian conclusion concerning process innovation and a Schumpeterian one concerning instead process innovation.

The outline of the paper is as follows. Section 2 investigates the case of product innovation. Section 3 presents the case of process innovation. Concluding remarks are in Section 4.

2. *Product innovation*

Consider a market where N single-product firms sell differentiated products over $t \in [0, \infty)$. Market competition takes place *à la* Cournot. The demand structure is

$$p_i(t) = A - Bq_i(t) - D(t)\sum_{j \neq i} q_j(t) \tag{1}$$

where $D(t) \in [0, B]$ measures product substitutability, i.e., it is an inverse measure of product differentiation between any pair of varieties. At any time t, the output level $q_i(t)$ is produced at constant returns to scale, for a given $D(t)$, and

[3] For analogous investigations of strategic delegation, see Fershtman and Judd (1987) and Fershtman et al. (1991), *inter alia*.

operative costs are

$$C_i(t) = cq_i(t) \tag{2}$$

where c is a positive parameter.

We assume that, at the initial instant $t = 0$, $D(0) = B$, so that firms may produce the same homogeneous good through a technology which is public domain.[4] Product differentiation may increase (that is, $D(t)$ may decrease) through firms' R&D investment according to:

$$\begin{aligned}\frac{dD(t)}{dt} &= -\frac{K(t)}{1+K(t)} \cdot D(t) \\ &\equiv -\frac{k_i(t) + \sum_{j \neq i} k_j(t)}{1 + [k_i(t) + \sum_{j \neq i} k_j(t)]} \cdot D(t); \quad k_i(t) \geqslant 0 \; \forall i.\end{aligned} \tag{3}$$

The above dynamics of product differentiation, borrowed from Cellini and Lambertini (2002), can be interpreted as follows. The aggregate (industry) R&D expenditure is $K(t)$, while $k_i(t)$ is individual investment. Given the symmetric nature of product differentiation in this model, there exists a complete spillover effect in the R&D process. Notice that the externality effect we consider here entails that the outcome of R&D activity is public domain via the demand function. On the contrary, the externality effects usually considered in the literature are associated with information leakage or transmission (see, *inter alia*, d'Aspremont and Jacquemin, 1988). The R&D technology defined by (3) exhibits decreasing returns to scale. As a result, $D(t)$ is non-increasing over time, and would approach zero if $K(t)$ tended to infinity.

The instantaneous profit is $\pi_i(t) = (p_i(t) - c)q_i(t) - k_i(t)$. The instantaneous payoff to manager i is $M_i(t) = \pi_i(t) + \theta q_i(t)$, where θ captures the extent of the managerial incentive (see Vickers, 1985). In the intertemporal framework, each manager aims at maximizing the discounted value of its flow of payoffs $J_i = \int_0^\infty e^{-\rho t} M_i(t)\, dt$ under the dynamic constraint (3) concerning the state variable $D(t)$. The control variables are $q_i(t)$ and $k_i(t)$.

This problem is formally equivalent to Cellini and Lambertini (2002, 2004), where marginal production cost, as perceived by managers, is $\hat{c} = c - \theta$. Since c and θ are both constant parameters, it suffices to rewrite the entire game and results by replacing c with $\hat{c}$. Accordingly, the game is as follows. We present the solution both (i) under the open-loop information structure, that is, each firm computes its optimal plan at the beginning of time, and then stick to it forever, and (ii) under the closed-loop information structure, that is, firms takes into account the level of state variable(s) in each instant of time, when they decide the level of control variables.

[4] The idea that the degree of substitutability depends upon the behaviour of firms has been investigated in static models by Harrington (1995); Lambertini and Rossini (1998); Lambertini et al. (1998).

2.1. The open-loop solution

Let firms choose non-cooperatively both R&D efforts and output levels. The discounted flow of payoffs accruing to firm i's manager is:

$$J_i = \int_0^{\infty} e^{-\rho t}\left\{q_i(t)\cdot\left[A - Bq_i(t) - D(t)\sum_{j\neq i} q_j(t) - \hat{c}\right] - k_i(t)\right\} dt \quad (4)$$

to be maximised w.r.t. $q_i(t)$ and $k_i(t)$, under (3). The corresponding Hamiltonian function is:

$$\mathcal{H}_i(t) = e^{-\rho t}\cdot\left\{(A-\hat{c})q_i(t) - B\big(q_i(t)\big)^2 - D(t)q_i(t)\sum_{j\neq i} q_j(t) - k_i(t) + \lambda_i(t)\left[-\frac{k_i(t)+\sum_{j\neq i} k_j(t)}{1+[k_i(t)+\sum_{j\neq i} k_j(t)]}\cdot D(t)\right]\right\}, \quad (5)$$

where $\lambda_i(t) = \mu_i(t)e^{\rho t}$, $\mu_i(t)$ being the co-state variable associated to $D(t)$. Necessary and sufficient conditions for a path to be optimal are:

$$\frac{\partial\mathcal{H}_i(t)}{\partial q_i(t)} = A - 2Bq_i(t) - D(t)\sum_{j\neq i} q_j(t) - \hat{c} = 0; \quad (6)$$

$$\frac{\partial\mathcal{H}_i(t)}{\partial k_i(t)} = -1 - D(t)\lambda_i(t)\frac{1}{(1+k_i(t)+\sum_{j\neq i} k_j(t))^2} = 0; \quad (7)$$

$$-\frac{\partial\mathcal{H}_i(t)}{\partial D(t)} = \frac{\partial\mu_i(t)}{\partial t} \quad \Rightarrow$$

$$\frac{\partial\lambda_i(t)}{\partial t} = q_i(t)\sum_{j\neq i} q_j(t) + \lambda_i(t)\left(\frac{k_i(t)+\sum_{j\neq i} k_j(t)}{1+[k_i(t)+\sum_{j\neq i} k_j(t)]} + \rho\right); \quad (8)$$

$$\lim_{t\to\infty} \mu_i(t)\cdot D(t) = 0. \quad (9)$$

We introduce the usual symmetry assumption, involving no loss of generality: $q_i(t) = q_j(t) = q(t)$, and $k_i(t) = k_j(t) = k(t)$. This implies $\sum_{j\neq i} q_j(t) = (N-1)q(t)$ and $\sum_{j\neq i} k_j(t) = (N-1)k(t)$.

From (6) we get the individual equilibrium output[5]:

$$q(t) = \frac{A-\hat{c}}{2B+(N-1)D(t)}. \quad (10)$$

Hence, (7) rewrites as

$$-\lambda(t) = \frac{[1+Nk(t)]^2}{D(t)}. \quad (11)$$

[5] Which coincides with the standard outcome of Cournot models with product differentiation (Singh and Vives, 1984; Majerus, 1988).

Likewise, (8) simplifies as follows:

$$\frac{\partial\lambda(t)}{\partial t} = (N-1)\big[q(t)\big]^2 + \frac{N\lambda(t)k(t)}{1+Nk(t)} + \lambda(t)\rho. \tag{12}$$

From (11) we obtain $k(t)$, which can be differentiated w.r.t. t. Then, plugging (12) into $dk(t)/dt$, one obtains:

$$\frac{dk(t)}{dt} = \frac{1}{2N}\sqrt{\frac{D(t)}{-\lambda(t)}} \cdot \big\{-\lambda(t)\rho - (N-1)\big[q(t)\big]^2\big\}. \tag{13}$$

This can be further simplified by substituting the co-state variable with (11), to get:

$$\frac{dk(t)}{dt} = \frac{1}{2N(1+Nk(t))} \cdot \left\{\frac{\rho}{D(t)}\big[1+Nk(t)\big]^2 - (N-1)\big[q(t)\big]^2\right\}, \tag{14}$$

which obviously holds for all $D(t) \in (0, B]$. If $D(t) = 0$, optimal instantaneous investment is $k(t) = 0$.

We are now in a position to assess the overall dynamic properties of the model, fully characterised by (14) and $dD(t)/dt = -Nk(t)D(t)/(1+Nk(t))$. The latter equation establishes that $dD(t)/dt < 0$ for all $k(t) \in (0, \infty)$ and for all $D(t) \in (0, B]$; while $dD(t)/dt = 0$ if $k(t) = 0$ or $D(t) = 0$. In the latter case, it is immediate to verify that $dq(t)/dt$ is also nil. Moreover,

$$\operatorname{sign}\left\{\frac{dk(t)}{dt}\right\} = \operatorname{sign}\left\{\frac{\rho}{D(t)}\big[1+Nk(t)\big]^2 - (N-1)\big[q(t)\big]^2\right\}. \tag{15}$$

Thus, using equilibrium output (10), we have:

$$\frac{dk(t)}{dt} > 0 \quad \text{iff} \quad k(t) > \frac{1}{N}\left[\frac{(A-\hat{c})\sqrt{(N-1)D(t)}}{[2B+(N-1)D(t)]\sqrt{\rho}} - 1\right]. \tag{16}$$

Clearly,

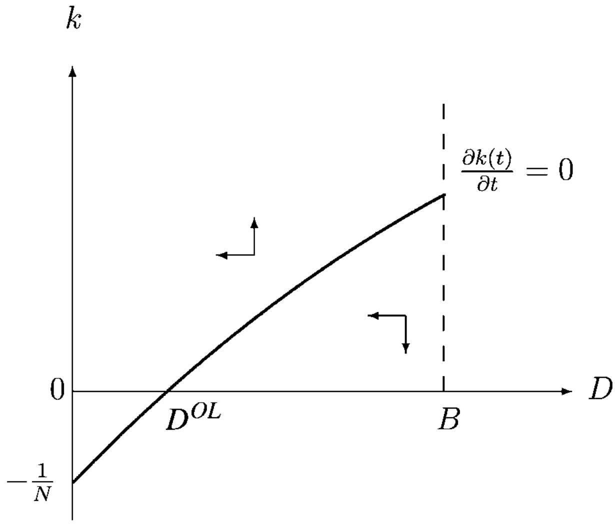
$$\frac{dk(t)}{dt} = 0 \quad \text{at} \quad k^{OL} = \frac{1}{N}\left[\frac{(A-\hat{c})\sqrt{(N-1)D(t)}}{[2B+(N-1)D(t)]\sqrt{\rho}} - 1\right]. \tag{17}$$

We are interested in investigating the dynamics of the system in the positive quadrant of the space $\{D, k\}$, which is described in Figure 1. The locus $dD(t)/dt = 0$ corresponds to the axes. The locus $dk(t)/dt = 0$ draws a curve over the admissible range of parameter D, which may or may not cross the horizontal axis within the same range, i.e., $D \in (0, B]$. If it does, the resulting degree of substitutability in steady state is

$$D^{OL} = \frac{(A-\hat{c})^2 - 4B\rho - (A-\hat{c})\sqrt{(A-\hat{c})^2 - 8B\rho}}{2(N-1)\rho}. \tag{18}$$

A set of parameter conditions ensure that $D^{OL} \in (0, B]$—see Cellini and Lambertini (2002) for the details. When no steady state exists, the model becomes trivial, in that the only admissible strategy is $k(t) = 0$ at every t, implying that firms are stuck with homogeneous products forever.

Figure 1. Dynamics in the space (D, k).



As to the stability of the system, it remains to be stressed that, whenever $D^{OL} \in (0, B]$, it is a saddle, and it can obviously be approached only along the north–east arm of the saddle path.

We now proceed to the comparative statics on D^{OL} w.r.t. all parameters.

From (18), it is immediately verified that, *ceteris paribus*, D^{OL} is decreasing, i.e., steady state product differentiation is increasing, in the number of firms. This result can be interpreted in the light of the debate between the polar positions of Schumpeter (1942) and Arrow (1962), concerning the relationship between the intensity of market competition and the incentives to invest in R&D (for a survey, see Reinganum, 1989). Here, R&D efforts are aimed at increasing product differentiation. In general, any increase in the number of firms lowers profits, and this tendency can be counterbalanced by investing a larger amount of resources in order to decrease the degree of substitutability among products. Notice that the anti-Schumpeterian flavour of these considerations is evident, in the limit case $N = 1$, when the monopolist has no incentive at all to invest.

Not surprisingly, $\partial D^{OL}/\partial(A - \hat{c}) > 0$ and $\partial D^{OL}/\partial B < 0$. Given that $(A - \hat{c})/B$ yields a measure of market size and profitability, any increase in this ratio induces firms to reduce their expenditure in product differentiation.

Now consider that $\hat{c} = c - \theta$. Consequently, we can write:

$$\frac{\partial k^{OL}}{\partial \theta} = \frac{\partial k^{OL}}{\partial \hat{c}} \cdot \frac{\partial \hat{c}}{\partial \theta} < 0. \tag{19}$$

This, in turn, entails

$$\frac{\partial D^{OL}}{\partial \theta} = \frac{\partial D^{OL}}{\partial \hat{c}} \cdot \frac{\partial \hat{c}}{\partial \theta} > 0. \tag{20}$$

Therefore, we may claim the following:

LEMMA 1. *Any increase in the extent of delegation entails a decrease in the open-loop equilibrium investment, which in turn brings about a decrease in the steady state level of product differentiation.*

The economic meaning of Lemma 1 can be spelled out in intuitive terms. For any given level of product differentiation, managerial firms prefer a larger level of production, as compared to profit-maximising firms. When the degree of differentiation is endogenous, managerial firms devote a smaller amount of resources to investment in product innovation, consistently with their lower level of profits, as compared to standard profit-maximising firms.

Finally, $\partial D^{OL}/\partial\rho < 0$ can be interpreted in the following terms. As ρ becomes higher, the present value of future profits shrinks. This can be balanced by a higher investment in product differentiation. More explicitly, an increase in ρ seemingly reduces, *ceteris paribus*, firms' capability to spend as measured by the incoming profit flows. However, a reduction in D^* does indeed restore endogenously firms' profitability and, consequently, their incentive to invest so as to offset the negative effects produced by higher discounting. This amounts to saying that, in this model, the income effect outweighs the intertemporal substitution effect.

2.2. The closed-loop solution

The Hamiltonian of a manager i is the same as in (5). However, under closed-loop information, firms take into account the feedback effects at any instant. Hence, the first order conditions for the closed-loop equilibrium are now:

$$\frac{\partial \mathcal{H}_i(t)}{\partial q_i(t)} = A - 2Bq_i(t) - D(t)\sum_{j\neq i} q_j(t) - \hat{c} = 0; \quad \Rightarrow \tag{21}$$

$$q_i^*(t) = \frac{A - \hat{c} - D(t)\sum_{j\neq i} q_j(t)}{2B};$$

$$\frac{\partial \mathcal{H}_i(t)}{\partial k_i(t)} = -1 - D(t)\lambda_i(t)\frac{1}{(1 + k_i(t) + \sum_{j\neq i} k_j(t))^2} = 0, \tag{22}$$

$$k_i^*(t) = -1 - \sum_{j\neq i} k_j(t) + \sqrt{-D(t)\lambda_i(t)};$$

$$-\frac{\partial \mathcal{H}_i(t)}{\partial D(t)} - \sum_{j\neq i}\frac{\partial \mathcal{H}_i(t)}{\partial q_j(t)}\frac{\partial q_j^*(t)}{\partial D(t)} - \sum_{j\neq i}\frac{\partial \mathcal{H}_i(t)}{\partial k_j(t)}\frac{\partial k_j^*(t)}{\partial D(t)} = \frac{d\mu_i(t)}{dt} \quad \Rightarrow \tag{23}$$

$$\frac{d\lambda_i(t)}{dt} = q_i(t)\sum_{j\neq i} q_j(t) - \left[\sum_{j\neq i} D(t)q_j(t)\sum_{m\neq j}\frac{q_m(t)}{2B}\right.$$

$$+\sum_{j\neq i}\frac{\lambda_i(t)\sqrt{\lambda_i(t)D(t)}}{2[1+k_i(t)+\sum_{j\neq i}k_j(t)]^2}\Bigg]$$
$$+\lambda_i(t)\left(\frac{k_i(t)+\sum_{j\neq i}k_j(t)}{1+[k_i(t)+\sum_{j\neq i}k_j(t)]}+\rho\right);$$

$$\lim_{t\to\infty}\mu_i(t)\cdot D(t)=0. \tag{24}$$

We introduce the following:

ASSUMPTION. $q_i(t)=q_j(t)=q(t)$, and $k_i(t)=k_j(t)=k(t)$.

This is a usual symmetry assumption involving no loss of generality as long as one adopts the Nash equilibrium as the solution concept. In particular, it implies $\sum_{j\neq i}q_j(t)=(N-1)q(t)$ and $\sum_{j\neq i}k_j(t)=(N-1)k(t)$.

Then, from (21) we derive the equilibrium per firm output:

$$q(t)=\frac{A-\hat{c}}{2B+(N-1)D(t)} \tag{25}$$

which again coincides with the standard outcome of Cournot models with product differentiation (see Singh and Vives, 1984; Majerus, 1988; Cellini and Lambertini, 1998, *inter alia*). Hence, given the implied symmetry condition $\lambda_i(t)=\lambda(t)\ \forall i$, (22) rewrites as

$$-\lambda(t)=\frac{[1+Nk(t)]^2}{D(t)}. \tag{26}$$

By symmetry, and using (26), (23) simplifies as follows:

$$\frac{d\lambda(t)}{dt}=\frac{D(t)(N-1)[q(t)]^2[2B-D(t)(N-1)]}{2BD(t)}-\frac{B(1+Nk)[2Nk+N-1+2\rho(1+Nk)]}{2BD(t)}. \tag{27}$$

From (26) we obtain $k(t)$, which can be differentiated w.r.t. t:

$$\frac{dk(t)}{dt}=\frac{1}{2n\sqrt{-\lambda(t)D(t)}}\left[-\frac{d\lambda(t)}{dt}D(t)-\lambda(t)\frac{dD(t)}{dt}\right]. \tag{28}$$

Then, plugging (27) and (26) into $\partial k(t)/\partial t$ and rearranging, one obtains:

$$\frac{dk(t)}{dt}\propto B\big[1+Nk(t)\big]\big[2\rho\big(1+Nk(t)\big)+N-1\big]-D(t)(N-1)\big[q(t)\big]^2\big[2B-D(t)(N-1)\big], \tag{29}$$

since

$$\frac{1}{2n\sqrt{-\lambda(t)D(t)}}>0 \tag{30}$$

always. The expression in (13) is valid for all $D(t) \in (0, B]$. If $D(t) = 0$, optimal per-period investment is $k(t) = 0$. Likewise, one can also exclude the monopoly case ($N = 1$), where strategic interaction between goods is absent by definition. Therefore, in the remainder we focus on $N \geqslant 2$.

We are now in a position to assess the overall dynamic properties of the model, fully characterised by (28) and $dD(t)/dt = -nk(t)D(t)/(1 + Nk(t))$. The latter equation establishes that $dD(t)/dt < 0$ for all $k(t) \in (0, \infty)$ and for all $D(t) \in (0, B]$; while $dD(t)/dt = 0$ if $k(t) = 0$ or $D(t) = 0$. In the latter circumstance, it is immediate to verify that $dk(t)/dt$ is also nil.

Moreover, from (13), using the equilibrium value of the output level from (25), we obtain that

$$\begin{aligned}
&\frac{dk(t)}{dt} = 0 \quad \text{iff} \\
&2B\rho N^2\big[\alpha(t)\big]^2\big[k(t)\big]^2 + NB\big[\alpha(t)\big]^2(4\rho + N - 1)k(t) \\
&\quad + B\big[\alpha(t)\big]^2(2\rho + N - 1) - (N-1)(A - \hat{c})^2 D(t) \\
&\quad \times \big[2B - (N-1)D(t)\big] = 0,
\end{aligned} \tag{31}$$

where

$$\alpha(t) \equiv 2B + (N-1)D(t). \tag{32}$$

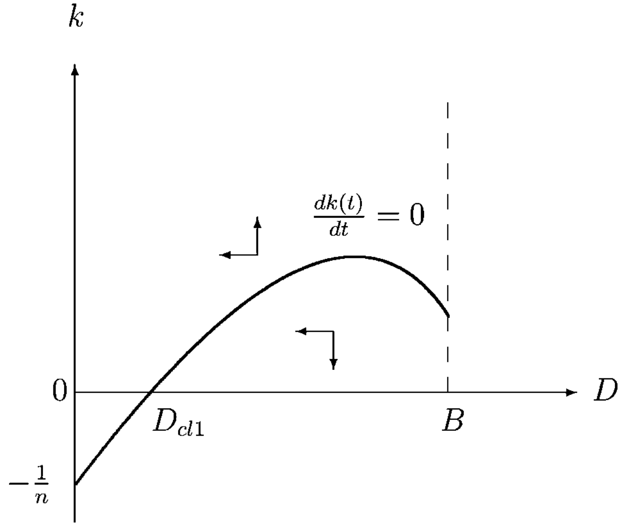
The roots of (31) are:

$$\begin{aligned}
&k(t) = \frac{-B \cdot \alpha(t) \cdot (4\rho + N - 1) \pm \sqrt{\Omega}}{4NB\rho\alpha(t)}, \\
&\Omega \equiv 8(A - \hat{c})^2 D(t)\alpha(t)\rho - B^2(N-1)\big[2B - D(t)\big]^2 \\
&\qquad + BN\big\{4B\big[B + (N-2)D(t)\big] + \big[D(t)\big]^2\big(N^2 - 3N + 3\big)\big\}.
\end{aligned} \tag{33}$$

The smaller root corresponds to a locus where k has always negative values, and can therefore obviously be disregarded, being economically meaningless. Then, considering the larger root, we are interested in investigating the dynamics of the system in the positive quadrant of the space $\{D, k\}$, which is described in Figure 1. The locus $dD(t)/dt = 0$ corresponds to the axes. The locus $dk(t)/dt = 0$ draws a curve over the admissible range of parameter D, which may or may not cross the horizontal axis within the same range, i.e., $D \in (0, B]$. If it does, the resulting candidate degree of substitutability in steady state is either

$$\begin{aligned}
D_{cl1} = {} & \frac{1}{(N-1)[(A - \hat{c})^2 + B(2\rho + N - 1)]} \\
& \times \Big(B\Big[(A - \hat{c})^2 - 2B(2\rho + N - 1) - (A - \hat{c}) \\
& \times \sqrt{(A - \hat{c})^2 - 8B(2\rho + N - 1)}\Big]\Big),
\end{aligned} \tag{34}$$

***Figure 2.* Dynamics in the space (D, k) for $n = 2$ and $B \in (0, \widehat{B})$.**



or

$$D_{cl2} = \frac{1}{(N-1)[(A-\hat{c})^2 + B(2\rho + N - 1)]} \times \Big(B\Big[(A-\hat{c})^2 - 2B(2\rho+N-1) + (A-\hat{c}) \times \sqrt{(A-\hat{c})^2 - 8B(2\rho+N-1)}\Big]\Big), \tag{35}$$

with $D_{cl1,2} \in \mathbb{R}$ iff $B \in (0, \overline{B})$, $\overline{B} \equiv (A-\hat{c})^2/[8(2\rho+N-1)]$. Subscript *cl* stands for closed-loop.

Comparing D_{cl1}, D_{cl2} and B, one may identify the conditions ensuring that the following inequalities hold:

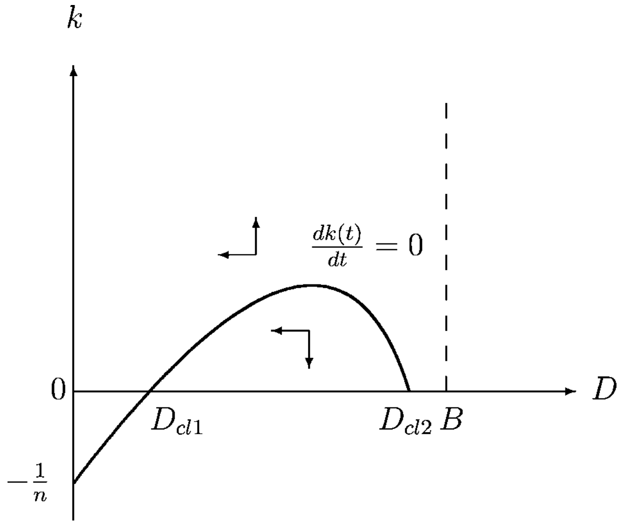
$$D_{cl2} > D_{cl1} > 0; \tag{36}$$

$$B > D_{cl2}. \tag{37}$$

The first relationship holds true over the whole admissible parameter range, while the second one is subject to specific conditions,[6] such that we can formulate the following claim. If $N = 2$ and $B \in (0, \widehat{B})$, there exists only one steady state at D_{cl1}. If $N = 2$ and $B \in (\widehat{B}, \overline{B})$, there exist two steady state levels of product substitutability, D_{cl1} and D_{cl2}, with $B > D_{cl2} > D_{cl1} > 0$. For all $N \geqslant 3$ and all $B \in (0, \overline{B})$, there exist two steady state levels of product substitutability, D_{cl1} and D_{cl2}, with $B > D_{cl2} > D_{cl1} > 0$. The alternative situations are illustrated in Figures 2–3.

[6] We omit the details for brevity. See Cellini and Lambertini (2004).

***Figure 3.* Dynamics in the space (D, k) for either (i) $n = 2$ and $B \in (\widehat{B}, \overline{B})$, or (ii) $n \geqslant 3$ and all $B \in (0, \overline{B})$.**



Concerning the stability analysis, the system of dynamic equations (3) and (28) can be linearised around steady state points $(D_{cl1}, 0)$ (whenever $D_{cl1} \in (0, B)$) and $(D_{cl2}, 0)$ to prove that the sign of the determinant of the Jacobian matrix is the sign of $3D(N-1) - 2B$ which: (i) in $(D_{cl1}, 0)$ is negative for all $B \in (0, \overline{B})$; (ii) in $(D_{cl2}, 0)$ is positive for all $B \in (0, \overline{B})$. Since in $(D_{cl2}, 0)$ the trace of the Jacobian matrix is positive over the whole admissible range of parameters, we can state the following[7]:

PROPOSITION 2. *The steady state* $(D_{cl1}, 0)$ *is always a saddle point. The steady state* $(D_{cl2}, 0)$*, whenever it exists, is an unstable focus.*

It remains to be stressed that the saddle point $(D_{cl1}, 0)$ can obviously be approached only along the north–east arm of the saddle path.

As far as the comparative statics is concerned, it is worth noting that the sign of $\partial D_{cl1}/\partial\theta$ is quite involved to be computed algebraically. However, numerical simulations show that it is positive over acceptable ranges of parameter values, while $\partial k/\partial\theta < 0$, so that the same qualitative considerations holding for the open-loop information case apply also in the case of the closed-loop information structure.

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[7] The detailed calculations involved in the assessment of the stability properties are omitted for the sake of brevity. They are available from the authors upon request.

3. Process innovation

Relying on Cellini and Lambertini (2003), in this section we present a dynamic version of the d'Aspremont and Jacquemin (1988) model, with managerial firms.[8] To this regard, it is also worth stressing that a relatively small but growing literature investigates the incentives of managerial firms towards process R&D using multistage static games, with mixed results (see Zhang and Zhang, 1997; Kräkel, 2004; Kopel and Riegler, 2006).

For the sake of simplicity, we consider an oligopoly with homogeneous goods.[9] The game takes place over continuous time, $t \in [0, \infty)$. At every instant, the market demand function writes as follows:

$$p(t) = A - q_i(t) - Q_{-i}(t), \tag{38}$$

where $Q_{-i}(t)$ is the output supplied by all firms other than i.

Each firm i supplies the market through a technology characterised by a constant marginal cost. Accordingly, her instantaneous cost function is $C_i(c_i, q_i) = c_i(t)q_i(t)$. The marginal cost borne by firm i evolves over time as described by the following dynamic equation:

$$\frac{dc_i(t)}{dt} \equiv \dot{c}_i = c_i(t)\Big[-k_i(t) - \beta \sum_{j \neq i} k_j(t) + \delta\Big], \tag{39}$$

where $k_i(t)$ is the R&D effort exerted by firm i at time t, while parameter $\beta \in [0, 1]$ measures the positive technological spillover that firm i receives from the R&D activity of any other firm j. Parameter $\delta \in [0, 1]$ is a constant depreciation rate measuring the instantaneous decrease in productive efficiency due to the ageing of technology. Equation (39) can be rewritten as follows:

$$\frac{\dot{c}_i}{c_i(t)} = -k_i(t) - \beta \sum_{j \neq i} k_j(t) + \delta, \tag{40}$$

so as to highlight that the rate of change of firm i's marginal cost over time is linear in the instantaneous investment efforts. That is, (39) is indeed a dynamic version of the linear R&D technology employed by d'Aspremont and Jacquemin (1988) in the static model.

The instantaneous cost of setting up a single R&D laboratory is:

$$\Gamma_i\big(k_i(t)\big) = b\big[k_i(t)\big]^2, \tag{41}$$

where b is a positive parameter. Throughout the game, firms discount future payoffs at the common and constant discount rate $\rho > 0$.

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[8] See also Kamien et al. (1992) and Suzumura (1992), *inter alia*.

[9] The introduction of a given degree of product differentiation would have no relevant bearings on the main conclusions.

The instantaneous profit function is:

$$\pi_i(t) = \left[p(t) - c_i(t)\right]q_i(t) - \Gamma_i\left(k_i(t)\right) \tag{42}$$

and each firm delegates control of its activities to a manager characterised by a preference for output expansion, whereby his objective function at any time t is:

$$M_i(t) = \pi_i(t) + \theta q_i(t). \tag{43}$$

In (43), parameter θ measures the extent of delegation; as in the previous section, any $\theta > 0$ allows for output expansion on the part of the manager. Accordingly, the Hamiltonian of manager i is:

$$\begin{aligned} \mathcal{H}_i(\mathbf{q}, \mathbf{k}, \mathbf{c}) = e^{-\rho t}\Bigg\{ & \Bigg[A - q_i(t) - \sum_{j \neq i} q_j(t) - c_i(t) + \theta\Bigg]q_i(t) - b\left[k_i(t)\right]^2 \\ & - \lambda_{ii}(t)c_i(t)\left[k_i(t) + \beta k_j(t) - \delta\right] \\ & - \sum_{j \neq i} \lambda_{ij}(t)c_j(t)\left[k_j(t) + \beta k_i(t) - \delta\right]\Bigg\}. \end{aligned} \tag{44}$$

Cellini and Lambertini (2005) show that a particular case of the present model—the case in which firms are profit-maximising units, i.e., $\theta = 0$—benefits from the property that the closed-loop solution coincides with the open-loop one. It can be quickly ascertained that this property holds also in the more general case where $\theta > 0$. Thus, in what follows, we focus on the open-loop solution, which is analytically easier to characterise, and, in the present setup, benefits from the property of being subgame perfect.[10]

The relevant first order conditions (FOCs) for the optimum are:

$$\frac{\partial \mathcal{H}_i(\cdot)}{\partial q_i(t)} = A - 2q_i(t) - \sum_{j \neq i} q_j(t) - c_i(t) + \theta = 0; \tag{45}$$

$$\frac{\partial \mathcal{H}_i(\cdot)}{\partial k_i(t)} = -2bk_i(t) - \lambda_{ii}(t)c_i(t) - \beta \sum_{j \neq i} \lambda_{ij}(t)c_j(t) = 0. \tag{46}$$

As a first step, observe that (45) only contains firm i's state variable, so that in choosing the optimal output at any time during the game firm i may disregard the current efficiency levels of the rivals. That is, there is no feedback effect in the output choice. Conversely, at first sight there seem to be a feedback between the R&D decisions, as (46) indeed contains all state variables, at least for any positive spillover effect.[11] Proving that the open-loop solution is subgame perfect amounts in fact to showing that no feedback effect are actually present, even for positive spillover levels.

[10] For more on differential games where open-loop equilibria are degenerate feedback ones, see Başar and Olsder (1982, 1995[2]), Mehlmann (1988) and Dockner et al. (2000).

[11] Intuitively, if $\beta = 0$, then the investment plans are completely independent and therefore it is apparent that no feedback effect operates.

Taking the above considerations into account, the adjoint or co-state equations are:

$$-\frac{\partial \mathcal{H}_i(\cdot)}{\partial c_i(t)} - \sum_{j\neq i} \frac{\partial \mathcal{H}_i(\cdot)}{\partial k_j(t)} \cdot \frac{\partial k_j(t)}{\partial c_i(t)} = \frac{\partial \lambda_{ii}(t)}{\partial t} - \rho\lambda_{ii}(t) \quad \Leftrightarrow \tag{47}$$

$$\begin{aligned}\frac{\partial \lambda_{ii}(t)}{\partial t} = {} & q_i(t) + \lambda_{ii}(t)\Big[k_i(t) + \beta \sum_{j\neq i} k_j(t) + \rho - \delta\Big] \\ & - \frac{\beta}{2b} \sum_{j\neq i} \lambda_{ji}(t)\Big[\beta\lambda_{ii}(t)c_i(t) + \lambda_{ij}(t)c_j(t) \\ & + \beta \sum_{l\neq i,j} \lambda_{il}(t)c_l(t)\Big],\end{aligned} \tag{48}$$

$$\begin{aligned}& -\frac{\partial \mathcal{H}_i(\cdot)}{\partial c_j(t)} - \frac{\partial \mathcal{H}_i(\cdot)}{\partial k_i(t)} \cdot \frac{\partial k_i(\cdot)}{\partial c_j(t)} - \sum_{l\neq i,j} \frac{\partial \mathcal{H}_i(\cdot)}{\partial k_l(t)} \cdot \frac{\partial k_l(\cdot)}{\partial c_j(t)} \\ & = \frac{\partial \lambda_{ij}(t)}{\partial t} - \rho\lambda_{ij}(t) \quad \Leftrightarrow\end{aligned} \tag{49}$$

$$\begin{aligned}\frac{\partial \lambda_{ij}(t)}{\partial t} = {} & \lambda_{ij}(t)\Big[k_j(t) + \beta k_i(t) + \beta \sum_{l\neq i,j} k_l(t) + \rho - \delta \\ & - \frac{\beta}{2b}\Big(2bk_i(t) + \lambda_{ii}(t)c_i(t) + \beta \sum_{j\neq i} \lambda_{ij}(t)c_j(t)\Big)\Big] \\ & - \frac{\beta}{2b} \sum_{l\neq i,j} \lambda_{lj}(t)\Big[\beta\lambda_{ii}(t)c_i(t) + \lambda_{il}(t)c_l(t) \\ & + \beta \sum_{j\neq i,l} \lambda_{ij}(t)c_j(t)\Big]\end{aligned} \tag{50}$$

where each term

$$\frac{\partial \mathcal{H}_i(\cdot)}{\partial k_j(t)} \cdot \frac{\partial k_j(t)}{\partial c_i(t)} \tag{51}$$

captures the feedback effect from j to i, and partial derivatives $\partial k_j(t)/\partial c_i(t)$ are calculated using the optimal values of investments as from FOC (46):

$$k_j(t) = -\frac{\lambda_{jj}(t)c_j(t) + \beta \sum_{j\neq i} \lambda_{ji}(t)c_i(t)}{2b}. \tag{52}$$

These conditions must be evaluated along with the initial conditions $\{c_i(0)\} = \{c_{0,i}\}$ and the transversality conditions

$$\lim_{t\to\infty} e^{-\rho t}\lambda_{ij}(t) \cdot c_j(t) = 0, \quad i, j = 1, 2. \tag{53}$$

Note that, on the basis of *ex ante* symmetry across firms, $\lambda_{lj}(t) = \lambda_{ij}(t)$ for all l. Accordingly, from (50), we have $\partial\lambda_{ij}(t)/\partial t = 0$ in $\lambda_{ij}(t) = 0$. Then, using this piece of information, we may rewrite the expression for the optimal investment of firm i as follows:

$$k_i(t) = -\frac{\lambda_{ii}(t)c_i(t)}{2b}, \tag{54}$$

which entails that $\partial k_i(t)/\partial c_j(t) = 0$ for all $j \neq i$, i.e., feedback (cross-)effects are nil along the equilibrium path. Accordingly, the open-loop equilibrium is a degenerate closed-loop one, and it is strongly time consistent, or equivalently, subgame perfect. It is also worth observing that this procedure shows that FOCs are indeed unaffected by initial conditions as well. The property whereby the FOCs on controls are independent of states and initial conditions after replacing the optimal values of the co-state variables is known as *state-redundancy*, and the game itself as *state-redundant* or *perfect*.[12]

In order to characterise the equilibrium solution, we proceed as follows. First, note that (45) is indeed equivalent to the static condition for the maximisation of the managerial objective function (43). Imposing symmetry on both individual quantities and marginal production costs and solving, one obtains:

$$q(t) = \frac{A - c(t) + \theta}{N + 1}. \tag{55}$$

While (45) has the usual appearance of a static FOC, the optimal R&D effort in (54) depends upon i's co-state variable. Such expression can be differentiated w.r.t. time to get the dynamic equation of $k_i(t)$:

$$\frac{dk_i(t)}{dt} \equiv \dot{k}_i = -\frac{1}{2b}\left[c_i(t)\dot{\lambda}_{ii}(t) + \lambda_{ii}(t)\dot{c}_i(t)\right] \tag{56}$$

with $\dot{\lambda}_{ii}(t)$ obtaining from (48). Then, (56) can be further simplified by using

$$\lambda_{ii}(t) = -\frac{2bk_i(t)}{c_i(t)} \tag{57}$$

which obtains from (46). This yields:

$$\dot{k}_i = -\frac{1}{2b}\left[c_i(t)q_i(t) - 2bk_i(t)\right]. \tag{58}$$

Then, imposing symmetry and using (55), one obtains:

$$\dot{k} = \rho k(t) - \frac{c(t)[A - c(t) + \theta]}{2b(N + 1)}. \tag{59}$$

Imposing stationarity:

$$k^*(t) = \frac{c(t)[A - c(t) + \theta]}{2b(N + 1)\rho}.$$

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[12] A more detailed proof, although limited to the case of pure profit-seeking behaviour, can be found in Cellini and Lambertini (2005).

Over the parameter region where the solution is real, the corresponding steady state is stable in the saddle sense (see Cellini and Lambertini, 2005, Proposition 2).

A simple comparative statics exercise reveals that:

$$\frac{\partial k^*}{\partial \theta} > 0 \tag{60}$$

which clearly entails

$$\frac{\partial c^*}{\partial \theta} < 0. \tag{61}$$

Accordingly, we can state our main result as follows:

PROPOSITION 3. *The optimal R&D effort is monotonically increasing in the extent of delegation. Consequently, managerial firms are more efficient than their entrepreneurial counterparts.*

From the expression of k^*, one can also detect that, as either N or θ increases, the market becomes more competitive, but while an increase in N has a negative impact on the optimal R&D effort, an increase in the extent of delegation exerts a positive one. Therefore the present model delivers mixed answers to the longstanding Arrow vs Schumpeter debate.

It is also interesting to explain the reason why the presence of managerial incentive leads firms to increase their optimal efforts in process innovation as compared to what they would do if they were standard profit-maximising firms. The economic meaning is clear, as managers are keen on expanding output, and this in turn is easier, the lower are production costs. Therefore, the aggressiveness of managerial firms is ultimately responsible for their attitude towards process innovation projects.

4. Conclusions

We have taken a differential game approach to investigate the behaviour of managerial firms concerning investment in product differentiation and process innovation. Our core result is that firms with managerial incentives *à la* Vickers (1985) tend to underinvest in product innovation, and to overinvest in process innovation, as compared to standard profit-maximising firms. The intuition behind this result is clear. The separation between ownership and control leads firms to increase production levels, given the structure of managerial incentives. If the (constant) operative costs are given, this means lower profit levels and lower amount of resources devoted to product innovation. On the contrary, if the operative costs are endogenous, and depend on the efforts in process innovation, a manager has further reasons to aim at attaining a lower marginal cost, since this permits him to further increase the output level.

We have shown that our results are robust to different assumptions concerning the information set in the differential game framework under consideration. In particular, the product differentiation game provides two different steady state equilibria, under open- and closed-loop information structure respectively, but the qualitative conclusions obtained by comparative statics exercises are the same under both information structures. In the case of process innovation, the steady state equilibrium coincides under the different information structures, since the closed-loop equilibrium collapses into the open-loop equilibrium, with clearcut implications on the optimal R&D performance of firms.

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CHAPTER 10

Delegation in an R&D Game with Spillovers

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Abstract

This paper considers a strategic delegation setting with R&D spillovers in a Cournot market. The game we analyze has four stages. First, owners have the option to hire a manager. If they decide to delegate, then in the contracting stage they have to determine the optimal incentives for the managers. In the R&D stage, the levels of investments in research and development are chosen which reduce production costs. Finally, in the production stage quantities offered on the market are selected. We characterize the sub-game perfect outcomes of this game depending on the level of R&D spillovers and derive the following main insights. First, in a case where no spillovers exist, both owners have the incentive to delegate R&D and production decisions to managers. This leads to higher outputs, higher R&D activities, but lower profits for the firms in comparison with an entrepreneurial (owner-managed) firm. These results still hold if the basic production unit costs are high, independent of the existence of spillovers. In these cases delegation leads to an increase in social welfare. Second, we demonstrate that when spillovers exist and basic unit production costs are low, then there are situations where owners delegate but discourage managers from being aggressive. This "soft" commitment leads to lower outputs, lower R&D, but higher profits for the firms in comparison with an entrepreneurial firm. Here, however, delegation results in lower welfare.

Keywords: strategic delegation, research and development, incentives, strategic commitment

JEL classifications: L13, L2, O31

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1. Introduction

In this paper we consider the effects of delegating decisions on R&D expenditures and production quantities to managers when firms compete in a Cournot market with homogeneous products and when R&D spillovers exist. Zhang and Zhang (1997) were the first to introduce a model which combines elements from the two distinct streams of literature: strategic delegation initiated by Vickers (1985), Fershtman (1985), Fershtman and Judd (1987), and Sklivas (1987) and R&D incentives and efforts under spillovers considered by Spence (1984), d'Aspremont and Jacquemin (1988), Suzumura (1992), and Kamien et al. (1992). Zhang and Zhang consider a 3-stage game, where the owners of the firms delegate the choices of R&D investment and production quantities to managers (managerial firm). Managerial compensation is based on the performance measures profits and sales. Each of the two managers can make investments in R&D. These investments reduce their own production costs, but due to spillover effects, they also lower production costs of the rival firm. The goal of Zhang and Zhang's analysis was to give a comparison of the optimal levels of R&D expenditures, production quantities, firm profits, and welfare achieved under managerial and owner-managed (entrepreneurial) firms. However, as has been demonstrated recently by Kopel and Riegler (2006), the key results of their work are incorrect due to an improper handling of the first order conditions at the contracting stage. Therefore, in this paper we reconsider their setup and provide a characterization of the equilibrium outcome of the game.

After the initial work of Zhang and Zhang (1997), several papers dealing with R&D incentives and delegation have been published. Kräkel (2004) and Lambertini (2004) are both based on the Zhang and Zhang setup. However, instead of Cournot competition, Kräkel assumes that a contest between the firms determines the market outcome. Lambertini, on the other hand, uses a different performance measure for the managerial compensation contract, a linear combination of profits and sales.[1] Moreover, Lambertini studies only the asymmetric case, where an entrepreneurial firm competes with a managerial firm in the product market with Cournot competition. Both authors compare their insights with the (incorrect) results of Zhang and Zhang. Therefore, we will reconsider this discussion and make references to the findings of Kräkel and Lambertini. The issue of strategic delegation and R&D incentives has been also addressed in Lambertini and Primavera (2000), Zhang (2002), Bárcena-Ruiz and Olaizola (2006), and Kopel and Löffler (2008). In these papers spillover effects are not considered, however.

[1] Lambertini and Trombetta (2002) show that contracts which are based on the performance measures sales and profits are equivalent to contracts which are based on quantities and profits in a two-stage framework. However, the same does not hold if the game includes an additional R&D stage. The reason is that investments in R&D reduce costs and this changes the incentives for the manager on subsequent stages.

We start from the model introduced by Zhang and Zhang (1997), but add a stage where owners have to decide whether to delegate or not. This results in a game that comprises of four stages. In the first stage the delegation decision of the owner is considered. In the second stage of the game, the contracting stage, the managerial compensation contract is designed, given that the owner has decided to hire a manager. In stage 3 of the game, the R&D investment decision is made, and in stage 4 the production quantity is determined. This richer setup enables us to analyze if delegation is in fact an equilibrium solution of the game. The main findings of our analysis can be summarized as follows. In a case where no spillovers exist, both owners have the incentive to delegate R&D and production decisions to managers. This leads to higher outputs, higher R&D activities, but lower profits for the firms in comparison with an entrepreneurial firm. This demonstrates that the incentives to overinvest described by, e.g., Brander and Spencer (1983) for owner-managed firms in a set-up without spillovers are even stronger for managerial firms. These results still hold, if the basic production unit costs are high, independent of the existence of spillovers. In all these cases social welfare increases. However, if spillovers exist and the basic unit production costs are low, then there are situations where owners delegate, but *discourage* managers from being aggressive. This leads to lower outputs, lower R&D, but higher profits for the firms in comparison with an entrepreneurial firm. Here social welfare decreases due to delegation. This effect has to our knowledge not been described before in the literature on R&D incentives.

The paper is organized as follows. In the next section we present the four stages of the game. In Section 3 we analyze the subgames of the whole game and discuss the solutions. It will turn out that in most cases a closed form solution for the optimal incentive contract cannot be derived due to the complexity of the first order conditions. Hence, in order to gain some insight into the solution of the game we assume discrete values of the incentive parameter and the level of spillovers and characterize the equilibria of the game in Section 4. We then check the robustness of the qualitative features of the equilibrium for the discrete case by solving the general game numerically in Section 5. Extensions of our model are discussed in Sections 6 and Section 7 concludes our paper.

2. *The model*

Two firms with homogeneous products compete in a market with Cournot competition. Each firm has the same production unit costs of A. These unit costs can be reduced by investing in R&D, where x_i denotes the investment of firm i. Due to spillovers, the R&D expenditures not only lead to a decrease in the production unit costs for the investing firm, but also reduce the unit costs of the rival firm. Given the R&D expenditures x_j of firm j ($j = 1, 2$ and $i \neq j$), firm i's effective production unit costs are $C_i = A - x_i - \theta x_j$, where $\theta \in [0, 1]$ is a measure of the intensity of the spillover effect. There is no uncertainty concerning the effect of the R&D expenditures on the production unit costs. Investing in R&D is costly however, and the R&D cost function is represented by $\frac{1}{2}rx_i^2$, with the R&D cost parameter $r > 0$.[2] The inverse demand function is given by $p = a - bQ$, with $a > A$ and $Q = q_i + q_j$ as the industry output. We consider the following sequential-move game.

- Stage 1: Owner i wants to maximize the firm's profit

$$\pi_i = pq_i - (A - x_i - \theta x_j)q_i - \frac{1}{2}rx_i^2, \tag{1}$$

  and has the option to hire a manager to make the decisions in the R&D *and* production stage.[3] If no manager is hired, then the owner determines both the R&D level x_i and the production quantity q_i. If the owner decides to hire a manager to run the firm, then the manager determines both the R&D level and the production quantity. In this case the total compensation TC to be paid to the manager has to be deducted from the (gross) profit given in (1); see below. The same holds for owner j.
- Stage 2: If an owner decides to delegate the tasks, the choices at the R&D and the production stage of the game are made by the manager. A managerial compensation contract is designed to compensate the manager for the effort. The performance-related part of this compensation contract is based on a linear combination of profits and sales,[4]

$$U_i = \alpha_i \pi_i + (1 - \alpha_i)R_i,$$

  where the incentive parameter $\alpha_i \geqslant 0$, profits π_i are determined according to (1) and sales R_i are given by $R_i = pq_i$. In order to guarantee that the manager accepts this contract, total compensation given by $TC = s + U_i$, with s representing a salary component, has to be at least as large as manager i's reservation value. Clearly the owner as the residual claimant wants to keep total compensation as small as possible. Since each variation in the performance-based part of the payment can be adjusted by the salary s, total compensation exactly meets the reservation utility requirement (see for a discussion, e.g., Kräkel, 2004). For the following analysis it is sufficient to focus on the performance related part of the managerial compensation and we will not discuss the effects of salary adjustments. Furthermore, for simplicity, we will assume that the reservation value of the manager is zero. Consequently,

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[2] For work where uncertainty of R&D outcomes is considered, see Dawid et al. (2005) and the references given there. Note that the R&D costs of owner and manager might be different, since the manager might, e.g., posses task-specific know-how or the owner might simply be too busy to carry out the activities. We discuss this possibility later.

[3] In assuming that both tasks, R& D and production, are carried out by the manager in the delegation case, we follow Zhang and Zhang (1997), Kräkel (2004), and Lambertini (2004).

[4] In accordance with the majority of the strategic delegation literature we are considering only (linear) contracts based on profits and sales. Note that the market parameters a or b might be ex ante unknown to both partners, and then only revealed to the manager after the contract has been signed (see Fershtman and Judd, 1987). In this case forcing contracts are infeasible.

Figure 1. The stage 1 normal form R&D game.

	D	N
D	π_i^{DD}, π_j^{DD}	π_i^{DN}, π_j^{DN}
N	π_i^{ND}, π_j^{ND}	π_i^{NN}, π_j^{NN}

in stage 2 the owner has to determine the incentive parameter α_i, which in turn influences the behavior of the manager at subsequent stages. Observe that $\alpha_i = 1$ replicates the profit maximization calculus of the owner managed firm. Choosing $\alpha_i < 1$ ($\alpha_i > 1$) motivates the manager to act more (less) aggressively in the product market.

- Stage 3: If a manager is hired, the components of the compensation contract are already given at this stage. In the delegation case the R&D expenses x_i of each firm are determined noncooperatively by the managers such that the performance measure U_i is maximized. In the non-delegation case the owners select the R&D expenditures such that the profit π_i is maximized.
- Stage 4: In the final stage of the game, the output quantities are selected. Given the values of the incentive parameters (α_i and α_j) and the effective production costs $A - x_i - \theta x_j$, quantities are determined noncooperatively (either by the managers or the owners). The production quantities are determined such that the performance measure U_i or the profit π_i is maximized.

Obviously, our game possesses four different subgames. In the first subgame both owners delegate R&D and production decisions. We will denote this case by *DD*. In the second subgame both owners take all decisions themselves (denoted by *NN*). In the third and fourth subgame only one owner delegates the decisions whereas the R&D and quantity decision of the other firm is made by the owner (denoted by *DN* and *ND*). In what follows we will solve these subgames by backwards induction. The solution concept we will use is subgame perfection. Note that in analyzing these four subgames we will be able to answer the question if delegation is each firm's dominant strategy. Clearly, the owners will only hire a manager if they can benefit from it. The equilibrium of the first stage of the whole game can then be derived by comparing the entries of the normal form game depicted in Figure 1, where owner i is the row-player and owner j the column-player. The entries π_i^{kl} and π_j^{kl} where $k, l \in \{D, N\}$ denote the profits for the owners obtained in the corresponding subgame (neglecting the costs of delegation).

3. The outcomes of the four subgames

3.1. Subgame DD: both owners delegate

If both owners choose delegation, we have to solve the corresponding subgame by backwards induction. We start with the production and R&D stage and work ourselves backwards towards the contracting stage, where the optimal value of the incentive parameter is selected.

The production and the R&D stage

Given that the incentive parameters α_i and α_j have been selected and the R&D expenses x_i and x_j have been chosen, the managers noncooperatively make a decision about the production quantities q_i and q_j such that the performance measure $U_i(\alpha_i, \alpha_j, x_i, x_j, q_i, q_j)$ is maximized. Solving the first-order conditions yields for the optimal output of firm i (j is the index of the respective rival firm)

$$q_i(\alpha_i, \alpha_j, x_i, x_j) = \frac{a - A(2\alpha_i - \alpha_j) + (2\alpha_i - \alpha_j\theta)x_i + (2\theta\alpha_i - \alpha_j)x_j}{3b}. \tag{2}$$

The corresponding second-order condition $\partial^2 U_i/\partial q_i^2 = \partial^2 U_j/\partial q_j^2 = -2b < 0$ guarantees that we are dealing with a maximum. In the R&D stage of the game, the managers choose the R&D expenditures. Taking the optimal choice of output (2) in the production stage into account, the solution is derived (for given values of α_i and α_j) by maximizing the performance measure $U_i(\alpha_i, \alpha_j, x_i, x_j)$ of manager i. From the first-order conditions we get the following R&D reaction function (for firm j the indices must be swapped):

$$x_i(x_j) = \max\left[0, \frac{2(2\alpha_i - \theta\alpha_j)(a + A(\alpha_j - 2\alpha_i))}{9\alpha_i br - 2(2\alpha_i - \theta\alpha_j)^2} + \frac{2(2\alpha_i - \theta\alpha_j)(2\theta\alpha_i - \alpha_j)}{9\alpha_i br - 2(2\alpha_i - \theta\alpha_j)^2} x_j\right]. \tag{3}$$

The second-order condition for the optimal x_i is $\partial^2 U_i/\partial x_i^2 = (2(2\alpha_i - \theta\alpha_j)^2 - 9br\alpha_i)/9b$, which shows that for a maximum the following condition must be satisfied

$$9br\alpha_i - 2(2\alpha_i - \theta\alpha_j)^2 > 0. \tag{4}$$

In addition to this condition, later on we will provide further parameter requirements which guarantee positivity of quantities, R&D expenditures, and price. Solving the system of R&D reaction functions yields the optimal R&D expenditures as functions of the incentive parameters, i.e., $x_i^{DD}(\alpha_i, \alpha_j)$ and $x_j^{DD}(\alpha_i, \alpha_j)$. The optimal R&D expenditures together with (2) then give the optimal quantities $q_i^{DD}(\alpha_i, \alpha_j)$ and $q_j^{DD}(\alpha_i, \alpha_j)$. Inserting all these expressions into the profit functions would yield the profits of the owners solely as functions of the incentive parameters α_i and α_j, i.e., $\pi_i^{DD}(\alpha_i, \alpha_j)$ and $\pi_j^{DD}(\alpha_i, \alpha_j)$.[5]

[5] Although all these expressions can be calculated in closed form, they are rather complicated and we abstain from presenting them here.

We now briefly look at the properties of the symmetric equilibrium of the subgame obtained for $\alpha_i = \alpha_j = \alpha$. It can be deduced from (2) that for $\alpha_i = \alpha_j$ an increase in firm i's R&D expenditures always increases the production quantity due to the cost reducing effect of R&D, whereas an increase in the R&D expenditures of firm j only results in an increase of the production quantity of firm i when $\theta > 1/2$, i.e., when spillovers are sufficiently high. Moreover, from (3) it follows for $\alpha_i = \alpha_j$ that the R&D efforts of the two firms are strategic complements for spillovers sufficiently high ($\theta > 1/2$), and they are strategic substitutes for $\theta < 1/2$. From the general solutions of the subgame we get for the symmetric case (see also Zhang and Zhang, 1995, 1997)

$$\begin{aligned}
q_i^{DD} &= q_j^{DD} = q^{DD} = \frac{3r(a - A\alpha)}{9br - 2\alpha(2-\theta)(1+\theta)},\\
x_i^{DD} &= x_j^{DD} = x^{DD} = \frac{2(a - A\alpha)(2-\theta)}{9br - 2\alpha(2-\theta)(1+\theta)},\\
\pi_i^{DD} &= \pi_j^{DD} = \pi^{DD}\\
&= \frac{1}{(9br - 2\alpha(2-\theta)(1+\theta))^2}\\
&\quad \times \big[(a - A\alpha)r\big(A\big(-27br + 2\alpha\big(9br + (2-\theta)^2\big)\big)\\
&\quad + a\big(4 + 9br + 14\theta - 8\theta^2 - 6\alpha(2-\theta)(1+\theta)\big)\big)\big]
\end{aligned} \tag{5}$$

In order to guarantee that the price, quantities, R&D expenses, and effective production unit costs are non-negative, the possible set of values of the parameters a, A, b and r has to be restricted. From (5) we can see that the following conditions guarantee that quantities and R&D expenditures are positive in the symmetric equilibrium:

$$a > A\alpha, \tag{6}$$

$$9br - 2\alpha(2-\theta)(1+\theta) > 0. \tag{7}$$

Moreover, using (5) it is easy to prove that the effective production costs $A - x_i - \theta x_j$ in a symmetric equilibrium are positive if

$$9brA - 2a(2-\theta)(1+\theta) > 0 \tag{8}$$

holds. Taken together, conditions (6) and (8) imply condition (7). Therefore, if the parameters fulfill the inequalities

$$\frac{2a(2-\theta)(1+\theta)}{9br} < A < \frac{a}{\alpha}, \tag{9}$$

then production quantities, R&D expenditures, effective production costs, and prices in the symmetric equilibrium are positive. Note, however, that the non-negativity of profits still needs to be checked. From the second order condition for a maximum at the R&D stage (4), we can derive the following condition for the symmetric delegation case:

$$br > \frac{2\alpha(2-\theta)^2}{9}. \tag{10}$$

Taken together, these restrictions are useful to select appropriate values of the parameters.

The contracting stage

To determine the optimal values of the incentive parameters α_i and α_j, we use the reduced profit functions of the owners,

$$\begin{aligned}
&\pi_i^{DD}(\alpha_i,\alpha_j)\\
&\quad = \pi_i^{DD}\big(q_i^{DD}(\alpha_i,\alpha_j), q_j^{DD}(\alpha_i,\alpha_j), x_i^{DD}(\alpha_i,\alpha_j), x_j^{DD}(\alpha_i,\alpha_j)\big),\\
&\pi_j^{DD}(\alpha_i,\alpha_j)\\
&\quad = \pi_j^{DD}\big(q_i^{DD}(\alpha_i,\alpha_j), q_j^{DD}(\alpha_i,\alpha_j), x_i^{DD}(\alpha_i,\alpha_j), x_j^{DD}(\alpha_i,\alpha_j)\big).
\end{aligned} \tag{11}$$

Considering only symmetric equilibria, the optimal values of the incentive parameters for the managers are then determined by solving the following system of first order conditions

$$\left.\frac{\partial\pi_i^{DD}(\alpha_i,\alpha_j)}{\partial\alpha_i}\right|_{\alpha_i=\alpha_j=\alpha} = 0; \qquad \left.\frac{\partial\pi_j^{DD}(\alpha_i,\alpha_j)}{\partial\alpha_j}\right|_{\alpha_i=\alpha_j=\alpha} = 0 \tag{12}$$

where only those values are considered where the second order conditions for a maximum are fulfilled. Unfortunately, it turns out that a closed-form solution for the optimal values of α at the contracting stage cannot be derived, not even under the assumption of a symmetric equilibrium. The reason is that these values are given by the solutions of a fourth degree polynomial (see Kopel and Riegler, 2006). As a consequence, from an analytical point of view it seems impossible to provide a general characterization of the optimal solution of the subgame where both owners delegate. In the following section, we consider two simplifications. First, we assume discrete values for the spillover parameter θ and for the incentive parameter α and derive the corresponding solutions of the subgames.[6] This enables us to gain insights into the qualitative features of the optimal strategies and has the additional advantage that we can also include the possibility of asymmetric equilibria. Second, we check the robustness of the results obtained for this discrete game by solving the first- and second-order conditions at the contracting stage numerically for various sets of parameter values.

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[6] See for a similar approach Kräkel (2004). Note however, that Kräkel's analysis focuses on a different type of market structure.

3.2. Subgames DN and ND: only one owner delegates

If owner i ($i = 1, 2$) delegates the R&D and production decisions to a manager, but owner j ($j = 1, 2$ and $i \neq j$) does not delegate, the game becomes asymmetric. Nevertheless, we can use the results obtained for the R&D and the production stage of subgame *DD*. Recall in this context that letting $\alpha_j = 1$ replicates the profit maximization calculus of the owner-managed firm j. Hence, the optimal R&D expenditures and quantity choices can be simply obtained by using (2) and (3) with $\alpha_j = 1$. Of course, the corresponding solutions for subgame *ND* are obtained from the results obtained for subgame *DN* by swapping the indices i and j.

The production and the R&D stage

The optimal outputs of the firms are given by

$$q_i(\alpha_i, x_i, x_j) = \frac{a - A(2\alpha_i - 1) + (2\alpha_i - \theta)x_i + (2\theta\alpha_i - 1)x_j}{3b},$$
$$q_j(\alpha_i, x_i, x_j) = \frac{a - A(2 - \alpha_i) + (2 - \alpha_i\theta)x_j + (2\theta - \alpha_i)x_i}{3b},$$

and the corresponding second-order conditions for a maximum are again fulfilled. Furthermore, from the analysis above, we get the following R&D reaction functions:

$$x_i(x_j) = \max\left[0, \frac{2(2\alpha_i - \theta)(a + A(1 - 2\alpha_i))}{9\alpha_i br - 2(2\alpha_i - \theta)^2} + \frac{2(2\alpha_i - \theta)(2\theta\alpha_i - 1)}{9\alpha_i br - 2(2\alpha_i - \theta)^2}x_j\right],$$
$$x_j(x_i) = \max\left[0, \frac{2(2 - \theta\alpha_i)(a + A(\alpha_i - 2))}{9br - 2(2 - \theta\alpha_i)^2} + \frac{2(2 - \theta\alpha_i)(2\theta - \alpha_i)}{9br - 2(2 - \theta\alpha_i)^2}x_i\right].$$

The second-order conditions at the R&D stage are satisfied if

$$9br\alpha_i - 2(2\alpha_i - \theta)^2 > 0,$$
$$9br - 2(2 - \alpha_i\theta)^2 > 0. \qquad (13)$$

Solving the system of the R&D reaction functions above yields the R&D expenditures $x_i^{DN}(\alpha_i)$ and $x_j^{DN}(\alpha_i)$. Using these expressions, the optimal quantity choices can then be obtained as $q_i^{DN}(\alpha_i)$ and $q_j^{DN}(\alpha_i)$.

The contracting stage

Using the expressions for the R&D expenditures and the quantities derived above, the reduced profits of the firms are obtained as $\pi_i^{DN}(\alpha_i)$ and $\pi_j^{DN}(\alpha_i)$. Owner i now has to determine the value of the incentive parameter α_i such that the profit $\pi_i^{DN}(\alpha_i)$ is maximized. It turns out that, as in subgame *DD*, the resulting first order condition

$$\frac{\partial \pi_i^{DN}(\alpha_i)}{\partial \alpha_i} = 0 \tag{14}$$

cannot be solved for a closed form solution of α_i, since the optimal values in the asymmetric case are given by the solutions of a seventh-degree polynomial. Again from an analytical point of view it seems impossible to provide a general characterization of the optimal solution. Therefore, we proceed along the same lines as for subgame *DD*.

3.3. Subgame NN: both owners do not delegate

This subgame coincides with the case studied by d'Aspremont and Jacquemin (1988) and will be considered as a benchmark for comparison. The results obtained for subgame *DD* (delegation case) can be used to get the solutions and parameter restrictions for this much simpler subgame *NN* (the non-delegation case). We just simply set $\alpha_i = \alpha_j = 1$. Then from (4) we get the condition $9br - 2(2-\theta)^2 > 0$, which guarantees a maximum at the R&D stage. The quantities, R&D expenditures and profits in equilibrium for the non-delegation case are:

$$\begin{aligned}
q_i^{NN} &= q_j^{NN} = \frac{3(a-A)r}{9br + 2(\theta-2)(\theta+1)},\\
x_i^{NN} &= x_j^{NN} = \frac{2(a-A)(2-\theta)}{9br + 2(\theta-2)(\theta+1)},\\
\pi_i^{NN} &= \pi_j^{NN} = \frac{(a-A)^2 r(9br - 2(\theta-2)^2)}{(9br + 2(\theta-2)(\theta+1))^2}.
\end{aligned} \tag{15}$$

4. The discrete case

As pointed out above, a rigorous analytical characterization of the equilibrium outcomes for subgames *DD*, *DN* and *ND*, in particular for the contracting stage, seems impossible. In this section we investigate the discrete case, i.e., we assume discrete values for the incentive parameters and the level of spillovers and characterize the equilibria of the resulting game.[7] First, we assume that $\alpha_i, \alpha_j \in \{1/2, 1, 3/2\}$. This specification allows us to analyze three different settings. First, setting $\alpha_i = 1$ and $\alpha_j = 1$ reflects profit maximization of both firms and coincides with the owner's solution of subgame *NN*. Secondly, $\alpha_i = 1/2$ directs the manager away from pure profit maximization and awards the manager for higher sales revenues. This gives an incentive to the manager to behave "tough" in the product market. Thirdly, $\alpha_i = 3/2$ puts more weight on the profit

[7] See for a similar assumption Kräkel (2004).

as compared to the situation of pure profit maximization and punishes for sales. This leads to a "softer" behavior of the manager in the market. Note that by setting $\alpha_i = 1$ and $\alpha_j \in \{1/2, 3/2\}$ we obtain the equilibrium solutions of subgames *DN* and *ND*. Second, the spillover parameter θ is restricted to values from the set $\{0, 1/4, 1/2, 3/4, 1\}$. By this it is possible to look at the extreme cases of no spillovers ($\theta = 0$) and maximum spillovers ($\theta = 1$), and also to consider the case of "small," "medium," and "large" spillovers. By comparing the equilibrium outcomes of the subgames for different values of the incentive parameters and spillovers, we can identify which contract (if any) works best as a strategic delegation device for the owners.

4.1. Equilibrium outcomes of the subgames

In what follows we will focus on the analysis of the equilibrium outcome of subgame *DD*. The reason is that if we solve subgame *DD*, where both owners delegate, for all values $\alpha_i, \alpha_j \in \{1/2, 1, 3/2\}$ and $\theta \in \{0, 1/4, 1/2, 3/4, 1\}$, the solutions for the other subgames are easily obtained. For $\alpha_i = 1$, $\alpha_j = 1$ we get the outcome of subgame *NN*, and for $\alpha_j = 1$ (only owner i delegates) and $\alpha_i = 1$ (only owner j delegates) we get the outcomes of subgames *DN* and *ND*, respectively.

- *No spillovers* ($\theta = 0$).

  The optimal choices of R&D expenses and production quantity by the manager of firm i are given by

$$x_i^{DD}(\alpha_i, \alpha_j) = \max\left[0, \frac{-16\alpha_j(a - \alpha_i A) + 12br(a + A(\alpha_j - 2\alpha_i))}{16\alpha_i\alpha_j - 24(\alpha_i + \alpha_j)br + 27b^2r^2}\right],$$

$$q_i^{DD}(\alpha_i, \alpha_j) = \frac{3r}{4}x_i^{DD}(\alpha_i, \alpha_j). \tag{16}$$

  The profits of the owners for the nine combinations of the incentive parameters α_i, α_j are given in Table A.1 (see Appendix A). The values below the diagonal are obtained from the upper entries by swapping the profits of owners i and j. The expressions for the resulting profits in the other subgames can be obtained directly from Table A.1 by using the corresponding entries. For example, the profits for subgame *NN* can be found in Table A.1 as the entry where the ($\alpha_j = 1$)-column and the ($\alpha_i = 1$)-row intersect, since $\pi_i^{DD}(1, 1) = \pi_i^{NN}$.
- *Small spillovers* ($\theta = 1/4$).

  The optimal choices of R&D expenses and production quantity by the manager of firm i are given by

$$x_i^{DD}(\alpha_i, \alpha_j) = \max\left[0, \frac{4(8\alpha_i - \alpha_j)((\alpha_i - 8\alpha_j)(a(\alpha_i - 4\alpha_j) + 3\alpha_i\alpha_j A) - 24\alpha_j(a + A(\alpha_j - 2\alpha_i))br)}{5\alpha_i\alpha_j(\alpha_i - 8\alpha_j)(8\alpha_i - \alpha_j) + 8(\alpha_i + \alpha_j)(\alpha_i^2 + 47\alpha_i\alpha_j + \alpha_j^2)br - 576\alpha_i\alpha_j b^2r^2}\right],$$

$$q_i^{DD}(\alpha_i, \alpha_j) = \frac{6\alpha_i r}{8\alpha_i - \alpha_j}x_i^{DD}(\alpha_i, \alpha_j).$$

The profits of the owners for the nine combinations of the incentive parameters α_i, α_j are given in Table A.2 (see Appendix A).

- *Medium spillovers* ($\theta = 1/2$).

  The optimal choices of R&D expenses and production quantity by the manager of firm i are given by

$$x_i^{DD}(\alpha_i, \alpha_j)$$
$$= \max\left[0, \frac{2(4\alpha_i - \alpha_j)((\alpha_i - 4\alpha_j)(a(\alpha_i - 2\alpha_j) + \alpha_i\alpha_j A) - 6\alpha_j(a + A(\alpha_j - 2\alpha_i))br)}{3\alpha_i\alpha_j(\alpha_i - 4\alpha_j)(4\alpha_i - \alpha_j) + 6(\alpha_i + \alpha_j)(\alpha_i^2 + 7\alpha_i\alpha_j + \alpha_j^2)br - 108\alpha_i\alpha_j b^2 r^2}\right],$$
$$q_i^{DD}(\alpha_i, \alpha_j) = \frac{3\alpha_i r}{4\alpha_i - \alpha_j} x_i^{DD}(\alpha_i, \alpha_j).$$

  The profits of the owners for the nine combinations of the incentive parameters α_i, α_j are given in Table A.3 (see Appendix A).

- *Large spillovers* ($\theta = 3/4$).

  The optimal choices of R&D expenses and production quantity by the manager of firm i are given by

$$x_i^{DD}(\alpha_i, \alpha_j)$$
$$= \max\left[0, \frac{4(8\alpha_i - 3\alpha_j)((3\alpha_i - 8\alpha_j)(a(3\alpha_i - 4\alpha_j) + \alpha_i\alpha_j A) - 24\alpha_j(a + A(\alpha_j - 2\alpha_i))br)}{7\alpha_i\alpha_j(3\alpha_i - 8\alpha_j)(8\alpha_i - 3\alpha_j) + 24(\alpha_i + \alpha_j)(9\alpha_i^2 + 7\alpha_i\alpha_j + 9\alpha_j^2)br - 1728\alpha_i\alpha_j b^2 r^2}\right],$$
$$q_i^{DD}(\alpha_i, \alpha_j) = \frac{6\alpha_i r}{8\alpha_i - 3\alpha_j} x_i^{DD}(\alpha_i, \alpha_j).$$

  The profits of the owners for the nine combinations of the incentive parameters α_i, α_j are given in Table A.4 (see Appendix A).

- *Maximal spillovers* ($\theta = 1$).

  The optimal choices of R&D expenses and production quantity by the manager of firm i are given by

$$x_i^{DD}(\alpha_i, \alpha_j)$$
$$= \max\left[0, \frac{2(2\alpha_i - \alpha_j)(2a(\alpha_i - 2\alpha_j)(\alpha_i - \alpha_j) - 3\alpha_j(a + A(\alpha_j - 2\alpha_i))br)}{3br(2(\alpha_i^3 + \alpha_j^3) - 9\alpha_i\alpha_j br)}\right],$$
$$q_i^{DD}(\alpha_i, \alpha_j) = \frac{3\alpha_i r}{4\alpha_i - 2\alpha_j} x_i^{DD}(\alpha_i, \alpha_j).$$

  The profits of the owners for the nine combinations of the incentive parameters α_i, α_j are given in Table A.5 (see Appendix A).

4.2. Viability of the outcomes

In the case of $\alpha_i = \alpha_j = \alpha \in \{1/2, 1, 3/2\}$ and $\theta \in \{0, 1/4, 1/2, 3/4, 1\}$, conditions (9) and (10) yield

$$\frac{2}{3}a > A > \frac{1}{2br}a,$$
$$br > \frac{4}{3}. \tag{17}$$

In selecting the parameter values we have to take the following economic trade-off into account. On the one hand, the basic production costs A have to be small enough (in comparison to the reservation price a) such that production is economically viable.[8] On the other hand, the effective production costs have to be positive too. This can be guaranteed only if the basic production costs A are sufficiently large.

It is easy to see, that the conditions in (17) do not ensure the positivity of profits, however (e.g., for $\theta = 0$ the profits of the owners for $\alpha_i = \alpha_j = 1/2$ are positive if and only if $A < a/2$; see Table A.1). Of course, they also do not ensure, e.g., positivity of quantities, R&D expenses and profits in the non-symmetric cases. Therefore, in the following proposition we give refined conditions such that all decision variables, costs and profits are positive.

PROPOSITION 1. *Let $br > 2$. Then for $\alpha_i, \alpha_j \in \{1/2, 1, 3/2\}$ and $\theta \in \{0, 1/4, 1/2, 3/4, 1\}$, production quantities and prices, R&D expenditures, effective production costs, and profits of the owners are positive if*

$$A_L = \frac{110br - 50}{4br(54br - 25)}a < A < \frac{6br - 4}{15br - 6}a = A_U. \tag{18}$$

PROOF. The proof of this proposition is based on straightforward—although tedious—calculations. One has to derive the set of conditions such that all expressions for quantities, prices, effective production costs, etc. are positive and then check which inequality gives the tightest bounds. The only two cases which deserve particular attention are (i) $\theta = 3/4, \alpha_i = 1/2, \alpha_j = 3/2$ and (ii) $\theta = 1, \alpha_i = 1/2, \alpha_j = 3/2$. In case (i) the R&D reaction functions given in (3) assume the form

$$x_i = \max\left[0, -\frac{8a + 4A}{144br - 1} + \frac{6}{144br - 1}x_j\right],$$
$$x_j = \max\left[0, \frac{28(2a - 5A)}{3(48br - 49)} + \frac{7}{3(48br - 49)}x_i\right]$$

and the resulting intersection point is

$$x_i = 0; \qquad x_j = \frac{28(2a - 5A)}{3(48br - 49)}.$$

The profits, quantities and effective production costs have to be calculated using these expressions for the R&D expenditures in this particular case. Similarly, in

[8] This becomes even more obvious if we take the profits along the diagonal in Tables A.1–A.5 into account.

case (ii) the R&D reaction functions given in (3) assume the form

$$x_i = \max\left[0, -\frac{2a+A}{9br-1} + \frac{1}{9br-1}x_j\right],$$
$$x_j = \max\left[0, \frac{5(2a-5A)}{27br-25} + \frac{25}{27br-25}x_i\right]$$

and the resulting intersection point is

$$x_i = 0; \qquad x_j = \frac{5(2a-5A)}{27br-25}.$$

Again, the profits, quantities and effective production costs have to be calculated using these expressions for the R&D expenditures. □

4.3. Solutions of the R&D game with spillovers in the discrete case

From the previous subsection we know for which values of the model parameters the decision variables and payoffs for all subgames are non-negative. We can now determine which selection of the incentive parameter is optimal for the owners if they decide to delegate. Each owner can pick the incentive parameter from the set $\{1/2, 1, 3/2\}$ and depending on the spillover parameter $\theta \in \{0, 1/4, 1/2, 3/4, 1\}$ the combination of the strategy choices of the owners leads to the profits given in Tables A.1–A.5. If it turns out that $\alpha_i = 1$ is optimal, then this is equivalent to the fact that the owner of firm i prefers non-delegation instead of delegation (provided delegation costs are positive). As explained before, the profit tables contain the payoffs of all the subgames and we just have to determine which strategy combination (α_i, α_j) yields the highest payoff for the corresponding restriction of the subgame. Together with the expressions for production quantities and R&D efforts this then yields the equilibrium outcome of the corresponding subgame. After having filled in the equilibrium payoffs for each of the four subgames in Figure 1, we can determine the overall equilibrium of the R&D game with spillovers from this normal form game. We first consider the benchmark case of no spillovers,[9] i.e., $\theta = 0$. We can give the following general result for subgame *DD* where both owners delegate.

PROPOSITION 2. *Consider the case where no spillovers exist, $\theta = 0$. Let $br > 2$ and let condition (18) hold. Then, the choice of $\alpha_i = 1/2$ ($\alpha_j = 1/2$) is a dominant strategy for owner i (owner j). Hence, $(\alpha_i = 1/2, \alpha_j = 1/2)$ is the unique equilibrium of subgame DD. In this equilibrium the profits achieved by the managerial firms are less than the profits of an owner-managed firm.*

[9] It should be mentioned that for the model without spillovers, a closed-form solution can be derived. However, since the expressions are quite complicated, we decided to present the results for the discrete case.

PROOF. The proof is straightforward. All that has to be shown is that no matter what owner i does, owner j selects $\alpha_j = 1/2$. This can be proven by checking that the profit differences between equilibrium play and deviations are negative. A comparison of the profits for $\alpha_i = 1/2, \alpha_j = 1/2$ and $\alpha_i = 1, \alpha_j = 1$ shows that the payoffs are higher for an entrepreneurial firm. □

Using Proposition 2 it is easy to derive the equilibrium for the whole game. In subgame *DD* both owners optimally choose $\alpha_i = 1/2, \alpha_j = 1/2$. For subgame *DN*, where only owner i delegates, $\alpha_i = 1/2$ is the optimal choice (since delegation with $\alpha_i = 1/2$ is a dominant strategy). The same holds for subgame *ND*. Accordingly, the payoffs of the normal form game in Figure 1 correspond to the upper-left 2×2-submatrix in Table A.1. Obviously then, in the unique equilibrium of the whole game without R&D spillovers both owners delegate and select $\alpha_i = 1/2, \alpha_j = 1/2$ (cf. the result in Lambertini, 2004). However, in terms of profits, owners would be better off if they would run the firms on their own. This result has been obtained before in a game without R&D and without spillovers (Fershtman and Judd, 1987), where it has been demonstrated that each owner of a firm tries to achieve a Stackelberg-leader position in the market by delegating production to a manager. The manager serves as a self-committing device for the owner and more aggressive behavior on the market is induced by choosing the incentive parameter of the manager's contract $\alpha_i < 1$. On the other hand, if both firms delegate, they both induce their managers to act aggressively on the market and this leads to a situation where profits in equilibrium are smaller than the profits would be without delegation ($\alpha_i = \alpha_j = 1$). The owners are in some sort of prisoner's dilemma situation. Brander and Spencer (1983) report a similar effect in an R&D model with owner-managed firms.

Our results can be compared to the findings of Kräkel (2004), who uses a contest game to model oligopolistic competition. He shows that in the no-spillovers case no symmetric equilibria exist in his model. As Proposition 2 demonstrates, under Cournot competition and no spillovers, the equilibrium of the whole game is symmetric and both firms are active. On the other hand, our result that delegation is a dominant strategy is in line with Kräkel's findings.

We can additionally compare the R&D expenses in the resulting equilibrium with the level of investments in R&D of owner-managed firms. Proposition 3 provides the comparison for the no-spillovers case.

PROPOSITION 3. *Consider the case where no spillovers exist,* $\theta = 0$*. Let* $br > 2$ *and let condition (18) hold. Then, in the unique equilibrium* ($\alpha_i = 1/2$, $\alpha_j = 1/2$) *of the R&D game, R&D expenses and production quantities are higher than for owner-managed firms.*

PROOF. This result follows from a straight-forward comparison of the resulting expressions for the R&D expenses and the production quantities derived by using (16). □

The bottom line of this result is the following. Hiring managers, and—as a result—more competitive behavior on the market, leads to higher R&D activity and higher output, but to a reduction in firms' profits. If spillovers exist, then one can reason that the outcome might be different. The existence of spillovers reduces the player's incentive of investing in R&D, since every player wants to free ride on the R&D expenditures of the competitor (see De Bondt, 1996). Lower R&D expenditures keep production costs high and this results in less aggressive behavior on the market. The question remains how strong this countervailing effect is and if it dominates the competition effect. We find that for high values of the base costs A the competition effect still dominates the incentives for the owners. In other words, if base costs are high and, therefore, the potential for cost reduction through investments in R&D is high, aggressive behavior is a dominant strategy despite the existence of spillovers. The next proposition demonstrates our results.

PROPOSITION 4. *Let $br > 2$ and let condition (18) hold. Then for $A = A_U$, we have for all levels of spillovers $\theta \in \{1/4, 1/2, 3/4, 1\}$:*

(i) *The choice of $\alpha_i = 1/2$ ($\alpha_j = 1/2$) is a dominant strategy for owner i (owner j). Hence, ($\alpha_i = 1/2, \alpha_j = 1/2$) is the unique equilibrium of subgame DD.*
(ii) *The profits for an owner-managed firm are higher than for a managerial firm with ($\alpha_i = 1/2, \alpha_j = 1/2$).*
(iii) *In the unique equilibrium ($\alpha_i = 1/2, \alpha_j = 1/2$) of the R&D game, R&D expenses and production quantities are higher than for owner-managed firms.*

PROOF. In order to show the claim of the proposition, the first step is to evaluate the expressions for the profits for $A = A_U$. Then to prove (i) it has to be shown that no matter what value of α_i owner i selects, owner j chooses $\alpha_j = 1/2$. That is, no other choice would give owner j a higher profit. To prove (ii) the resulting expressions for the equilibrium payoffs (which now depend on the parameters a, b, and r) have to be compared. To prove (iii) the same has to be done for the quantities and the R&D investments. □

According to this result, delegation and choice of $\alpha_i = 1/2, \alpha_j = 1/2$ is the unique equilibrium of the R&D game and we get the same type of commitment for aggressive behavior as before. Again, the profits for the owners are smaller than for the owner-managed firm and quantities and R&D investments are higher.

We can again compare this result with the insights obtained by Kräkel (2004), who just studies the cases of no spillovers and maximal spillovers. He finds that for maximal spillovers ($\theta = 1$), where investments in R&D are a pure public good, there are multiple equilibria. Our Proposition 4 shows that under Cournot competition there is just one equilibrium, which leads to an equal sharing of the market. Moreover, in this equilibrium the profits earned by a managerial firm are strictly smaller than the profits of an entrepreneurial firm. The latter result somehow contrasts with the findings of Kräkel's Proposition 2, where it is shown that under both governance regimes profits are identical. Moreover, in our model delegation is a strictly dominant strategy if spillovers are maximal and basic production unit costs are sufficiently large. Kräkel, however, finds that for maximal spillover each owner never delegates.

We now turn to a situation where spillovers exist, but basic unit production costs are small. Interestingly, in this case equilibria can be found where the opposite result holds. Since the potential for cost reduction through investments in R&D is now restricted, the owners try to avoid aggressive behavior. They could do that by running the firms on their own. However, they could also use the manager as a commitment device again, but punish the manager for aggressive behavior and induce an even "softer" behavior on the market. In what follows we illustrate the type of outcome which can be obtained for the discrete model. As an example, we consider the case of medium spillovers. Then for subgame *DD* the following result can be shown:

PROPOSITION 5. *Consider the case of medium spillovers* ($\theta = 1/2$). *Let* $br > 2$ *and let condition* (18) *hold. Then for* $A = A_L$, *we have*:

(i) *Subgame DD has* 3 *equilibria, namely* ($\alpha_i = 1/2, \alpha_j = 1/2$), ($\alpha_i = 1$, $\alpha_j = 1$)*, and* ($\alpha_i = 3/2, \alpha_j = 3/2$).
(ii) *In the equilibrium* ($\alpha_i = 3/2, \alpha_j = 3/2$) *the profits for the owners are higher than in the other two equilibria.*
(iii) *In the equilibrium* ($\alpha_i = 3/2, \alpha_j = 3/2$), *R&D expenses and production quantities are smaller than for owner-managed firms.*

PROOF. In order to show the claim of the proposition, the first step is to evaluate the expressions for the profits in Table A.3 for $A = A_L$. Then to prove (i) it has to be shown that given owner i selects a certain value for the parameter α_i owner j has no incentive to choose a different value for α_j. That is, no other choice would give owner j a higher profit. To prove (ii) the resulting expressions for the equilibrium payoffs (which now depend on the parameters a, b, and r) have to be compared. The results for the R&D investments and production quantities follows from a straight-forward comparison of the resulting expressions previously derived. □

Given that subgame *DD* has multiple equilibria, an equilibrium selection problem arises. We solve this problem by assuming that the equilibrium with the highest profits for the owners serves as a focal point and will be selected (cf. Schelling, 2003). Under this assumption, we can again easily determine the payoffs of the normal form game in Figure 1 and derive the equilibrium of the whole R&D game. First, if both owners delegate, then they select $\alpha_i = 3/2, \alpha_j = 3/2$. Therefore, for the entries in the upper-left field of the normal form in Figure 1 we obtain $\pi_i^{DD} = \pi_i^{DD}(3/2, 3/2)$ and $\pi_j^{DD} = \pi_j^{DD}(3/2, 3/2)$. If owner i delegates and owner j does not (subgame DN), then owner i sets $\alpha_i = 1$ (since $\alpha_i = 1, \alpha_j = 1$ has been identified as an equilibrium in Table A.1 of subgame DD). This leads to the same profits as non-delegation, i.e., $\pi_i^{DN} = \pi_i^{DD}(1, 1)$, $\pi_j^{DN} = \pi_j^{DD}(1, 1)$ in Figure 1. Analogously, we obtain $\pi_i^{ND} = \pi_i^{DD}(1, 1)$, $\pi_j^{ND} = \pi_j^{DD}(1, 1)$. Finally, $\pi_i^{NN} = \pi_i^{DD}(1, 1)$, $\pi_j^{NN} = \pi_j^{DD}(1, 1)$. Considering now the normal form of the whole game we realize that we also obtain 2 equilibria for the whole game. In one equilibrium both owners delegate with $\alpha_i = 3/2, \alpha_j = 3/2$ and in the other equilibrium both owners do not delegate ($\alpha_i = 1, \alpha_j = 1$). According to Proposition 5 the former equilibrium yields a higher payoff for the owners. This result demonstrates that either owners delegate R&D and production decisions or they determine R&D expenses and quantities for themselves. However, if they delegate, they punish (not encourage) the managers for higher sales to avoid aggressive market behavior. Not unexpectedly, this disincentive for higher sales results in reductions of both the production quantity and R&D expenses, and consequently lead to higher profits.

4.4. Welfare and First Best solution

We now turn to the question if the increase in R&D and output through delegation leads to an overall increase in welfare where welfare W is measured in the usual way as the sum of consumer rent and firms' profits in equilibrium. Moreover, we compare the investments in R&D and the output levels in the resulting equilibria with the "First Best" choices.[10] It is easy to see that in this case the R&D level is x_{FB} and the industry output level is Q_{FB},

$$Q_{\mathrm{FB}} = \frac{2r(a-A)}{2br-(1+\theta)^2},$$
$$x_{\mathrm{FB}} = \frac{(a-A)(1+\theta)}{2br-(1+\theta)^2},$$

which are obtained by equating price and marginal costs. A comparison now yields the following results. In the case where no spillovers exist ($\theta = 0$), so that ($\alpha_i = 1/2, \alpha_j = 1/2$) is a dominant strategy (see Propositions 2 and 3), industry output in equilibrium is smaller than Q_{FB}. More interestingly, however, is the fact that for high basic production costs A the incentive for firms to invest in R&D is so strong that the R&D investment levels are even higher than it would be optimal from a First Best perspective. Hence, firms not only invest more than an owner-managed firm, they even overinvest compared to the First Best level. In the cases with positive spillovers and high basic unit production

[10] For the sake of comparison, we use the same expressions as derived by Zhang and Zhang (1997), who assume that both firms are kept active by the social planner. One might argue, however, that this assumption does not yield the First Best level, since a social planner would prefer to keep only one firm active if production is less costly.

costs (see Proposition 4), industry output and R&D levels in equilibrium are always smaller than the First Best levels. As far as welfare is concerned it turns out that delegation is welfare-enhancing in all these cases. That is, by delegating the R&D and production decisions to managers, although firm's profits are reduced, overall welfare is higher than for the case of entrepreneurial firms. The situation is different for small basic unit production costs (see Proposition 5), when owners delegate decisions and select $\alpha_i = 3/2, \alpha_j = 3/2$. In this case industry output and R&D levels are smaller than First Best. However, overall welfare is reduced. Recall that in this case owners use the possibility to delegate decisions and write incentive contracts as a commitment device in order to reduce the quantity offered in the market. This keeps prices high and results in higher profits than for an owner-managed firm, but leads to a reduction in welfare.

5. *The continuous case: a numerical analysis*

In the previous section we have gained some insights into the qualitative properties of the equilibrium outcomes of the R&D game by characterizing the equilibria for discrete values of the incentive parameters and the level of spillovers. We now use this increased understanding of the model to check the validity of the results for the general case. Recall that closed-form solutions of the R&D game cannot be derived for subgames *DD*, *DN*, and *ND*, since the optimal values of the incentive parameter at the contracting stages of these subgames are given by the solutions of high-degree polynomials. Therefore, the equilibrium choices for the incentive parameter can only be caclulated numerically for given parameter values (see also, e.g., Aggarwal and Samwick, 1999; Kopel and Riegler, 2006).

To be more precise, in this section for given values of the market parameters a and b, for given basic production unit costs A, and for a given value of the R&D cost parameter r, we solve the first order conditions given in (12) and (14) for a particular value $\theta \in [0, 1]$ (starting with $\theta = 0$) to obtain candidate solutions $\alpha^*(\theta)$ for the optimal values of the incentive parameter.[11] We then check

(i) which of the candidate solutions for α is real-valued,
(ii) using the real-valued solutions, if the second order condition for a profit maximum at the contracting stage is fulfilled,
(iii) for subgame *DD* if the inequalities (9) and (10) are satisfied guaranteeing that we are dealing with a maximum at the R&D stage and that production quantities, prices, R&D expenditures, and effective production costs are positive; for subgame *DN* if conditions (13) are satisfied and if production quantities, prices, R&D expenditures, and effective production costs are positive,
(iv) if profits are positive.

[11] The values of the parameters were chosen to satisfy the inequalities given in Proposition 1.

If these questions were answered affirmatively, we keep the solutions $\alpha^*(\theta)$, together with the profits $\pi(\alpha^*(\theta))$, the R&D expenditures $x(\alpha^*(\theta))$, and the production quantities $q(\alpha^*(\theta))$. We repeat this procedure for n values of $\theta \in [0, 1]$.[12] As for the discrete game we will encounter the problem of multiple equilibria. In these cases we will additionally check the stability properties of the corresponding equilibria in order to see if one of them can be ruled out by this refinement criterion (see also, e.g., Amir and Wooders, 1998; Henriques, 1990). For stability of an equilibrium the reaction functions have to cross "correctly," or, more precisely, the slopes of the reaction functions R_1 and R_2 have to fulfill the condition

$$\left|R_1' R_2'\right| < 1.$$

To give an example, for the R&D stage of subgame *DD*, where the reaction functions are given by (3), the stability condition is

$$\left|\frac{2(2\alpha_i - \theta\alpha_j)(2\theta\alpha_i - \alpha_j)}{9\alpha_i br - 2(2\alpha_i - \theta\alpha_j)^2} \frac{2(2\alpha_j - \theta\alpha_i)(2\theta\alpha_j - \alpha_i)}{9\alpha_j br - 2(2\alpha_j - \theta\alpha_i)^2}\right| < 1.$$

For the contracting stage we can use the equivalent criterion (see, e.g., Vives, 1999)

$$\left|\frac{\partial^2\pi_i}{\partial\alpha_i^2}\frac{\partial^2\pi_j}{\partial\alpha_j^2}\right| > \left|\frac{\partial^2\pi_i}{\partial\alpha_i\partial\alpha_j}\frac{\partial^2\pi_j}{\partial\alpha_i\partial\alpha_j}\right|.$$

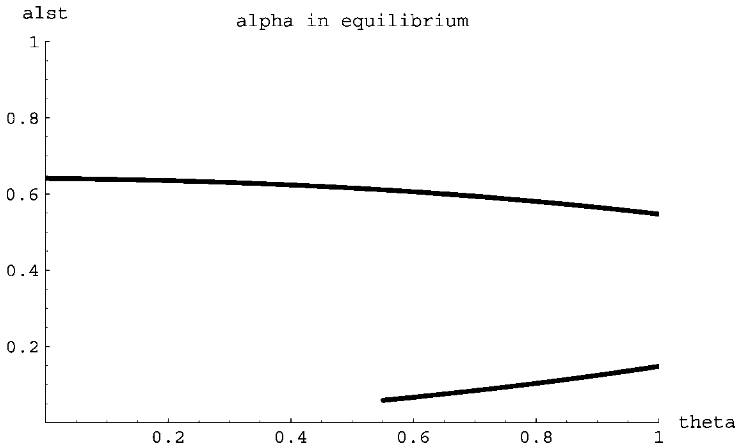
Based on the results for the discrete case, in what follows we focus on two different situations, one where basic production unit costs are relatively high (see Proposition 4) and the other one where basic production unit costs are relatively low (see Proposition 5). The market parameters and the R&D cost parameter were set in both cases to $a = 100$, $b = 1$, and $r = 10$ respectively. The basic production unit costs in the high-cost case were either chosen to be $A = 38$, which is only slightly smaller than the value of $A_U = 38.889$, or $A = 5.1$, which is only slightly larger than $A_L = 5.097$ (see Proposition 1).

5.1. Equilibria of the R&D game for large A

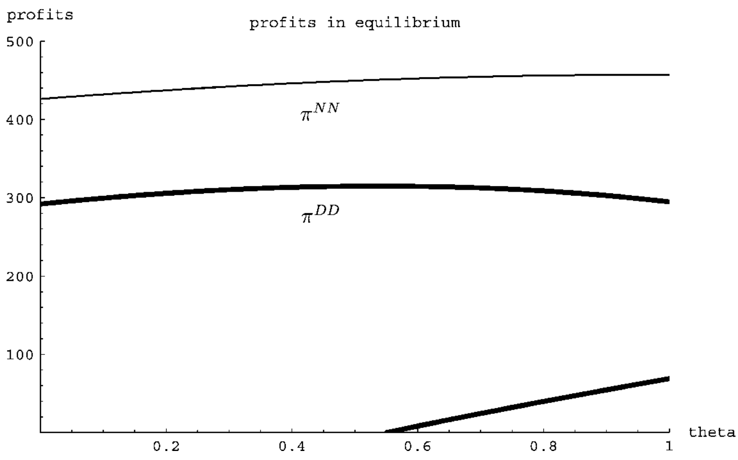
We first consider the case where basic production unit costs are large ($A = 38$). Recall that in the discrete game delegation is a dominant strategy. In the symmetric and unique equilibrium both owners delegate and incentivate the managers to act aggressively on the market. As a result R&D expenditures and production quantities are higher, but profits of both firms are lower than in the owner-managed case (subgame *NN*). As our numerical results will demonstrate, this finding also characterizes a possible outcome of the continuous R&D game for large A.

[12] The number of points for $\theta \in [0, 1]$ was typically chosen $n = 1000$ to obtain an accurate graph for the equilibrium solutions.

Figure 2. $a = 100$, $b = 1$, $r = 10$, $A = 38$. ***(a) Optimal values of α; (b) profits in equilibrium; (c) R&D expenditures in equilibrium; (d) quantities in equilibrium ($q_{\mathrm{FB}} = Q_{\mathrm{FB}}/2$).***



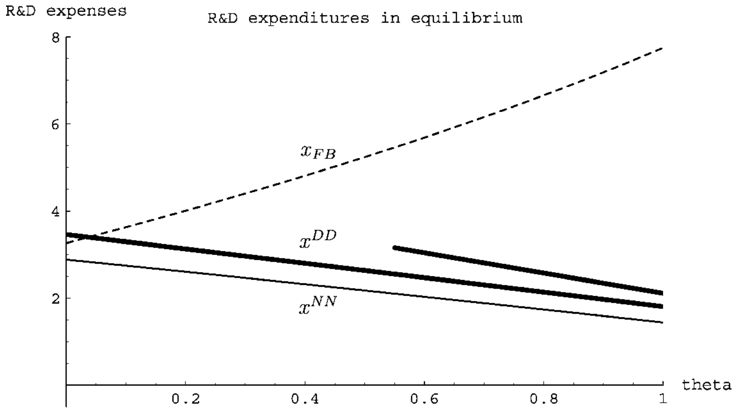
(a)



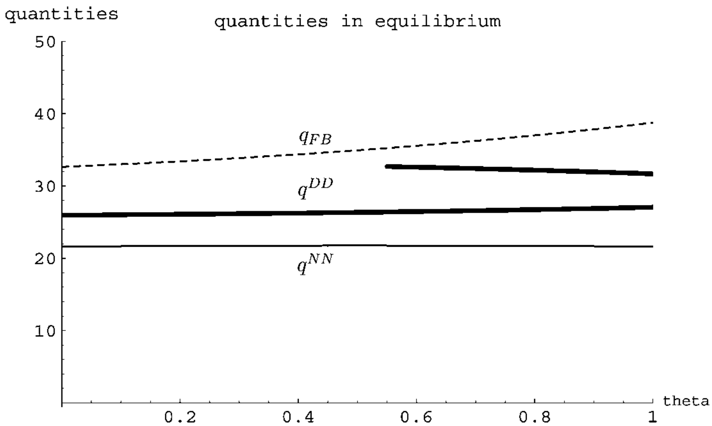
(b)

Panel (a) of Figure 2 shows the optimal value(s) of the incentive parameter for subgame *DD* depending on the spillovers (alst denotes the optimal values α^*). In the figures the bold lines indicate the equilibrium outcomes for subgame *DD* and the thin lines the outcomes of the owner-managed case (subgame *NN*). The dashed lines show the First Best choices of R&D expenditures and production quantities respectively. Up to a spillover level of about 0.55 the optimal α^* is unique, for higher spillovers there are two optimal solutions for the incentive contract. By employing the stability criterion as a refinement, we find that only the values on the upper branch yield equilibria which are stable. Therefore, it

Figure 2. (Continued.)



(c)

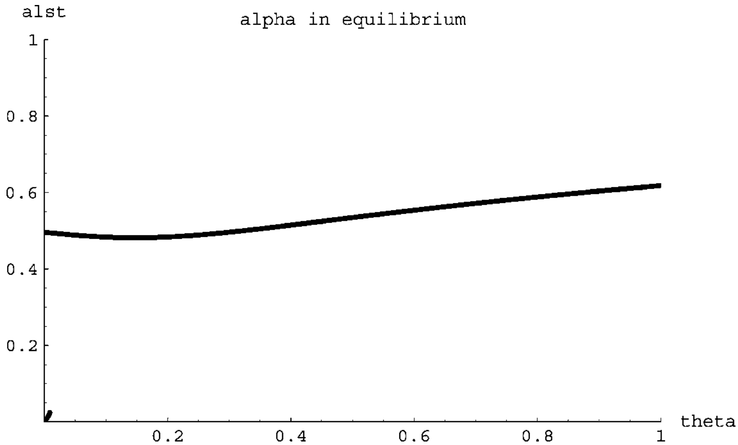


(d)

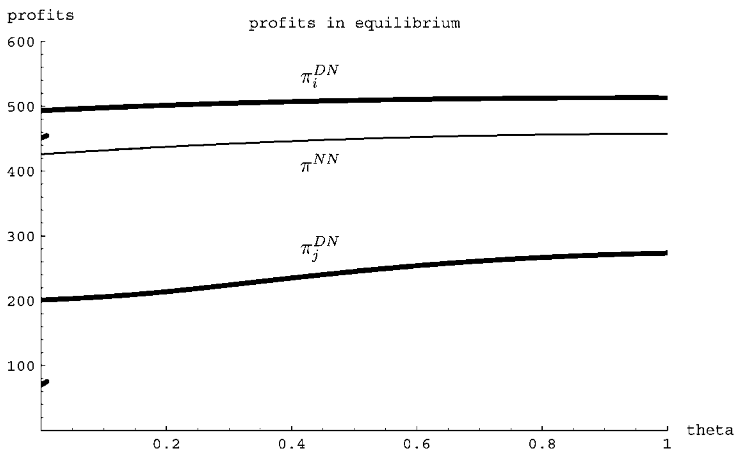
can be argued that the equilibrium is unique for a given level of the spillovers. Observe that the values of α^* are smaller than 1 meaning that the owners write the contracts such that the managers act aggressively in the market stage. However, if both owners follow this strategy, then the resulting profits are smaller than for an entrepreneurial firm. In Panel (b) we depict the corresponding profits for the managerial firm and contrast them with the profits of an owner-managed firm. The figure confirms that the owners are better off by not delegating the R&D and production decisions, i.e., we have $\pi_i^{DD} = \pi_j^{DD} < \pi_i^{NN} = \pi_j^{NN}$.

We now turn to the outcome of subgame *DN* if basic unit production costs are large ($A = 38$) and compare it to subgames *DD* and *NN* to obtain the equilibrium of the overall game. Panel (a) of Figure 3 shows that the equilibrium values of the incentive parameter are again smaller than 1, and therefore the delegating firm incentivates the manager to act aggressively on

Figure 3.* Subgame DN, $a = 100$, $b = 1$, $r = 10$, $A = 38$. *(a) Optimal values of α; (b) profits in equilibrium.



(a)



(b)

the product market to gain a leadership position. Panel (b) reveals that as a result the delegating firm i indeed achieves a larger profit than the owner-managed firm j. A comparison with the profits obtained in subgame *NN* yields $\pi_i^{DN} = \pi_j^{ND} > \pi_i^{NN} = \pi_j^{NN} > \pi_j^{DN} = \pi_i^{ND}$.

From the comparison of the profits obtained in subgames *DN* and *NN*, we know that each owner has an incentive to delegate and to achieve a leadership position since $\pi_i^{DN} = \pi_j^{ND} > \pi_i^{NN} = \pi_j^{NN}$. In order to demonstrate that delegation is a dominant strategy for the owners in the whole game, it remains to show that also the non-delegating firm in subgame *DN* has an incentive to delegate, i.e., $\pi_j^{DD} > \pi_j^{DN}$. A comparison of the profits depicted in Figures 2(b) and 3(b) proves that this is indeed the case and, therefore, delegation is a dominant strategy for the owners. As in the discrete case, the owners find themselves in a prisoners dilemma where the individual incentives lead to an overall equilibrium in which every firm is worse off.

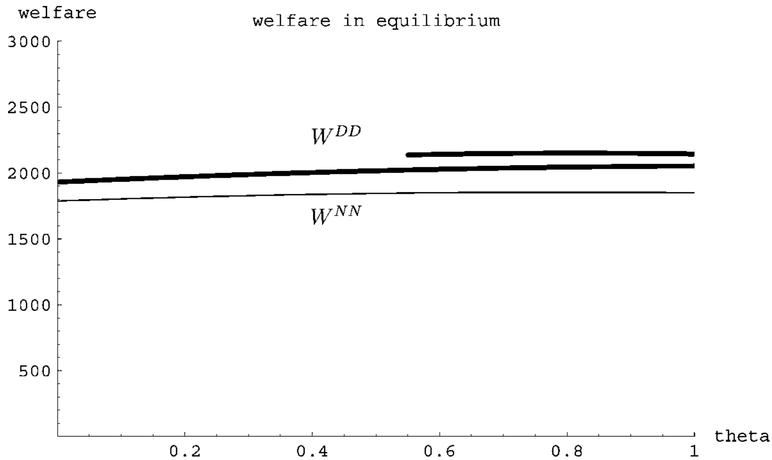
Panels (c) and (d) of Figure 2 show the corresponding optimal R&D expenditures and optimal production quantities in the equilibrium of the whole game respectively when the spillover level θ varies.[13] Some important insights can be gained from these graphs. First, observe that the R&D expenditures decrease for increasing spillovers levels. Intuitively, this is due to the fact that with increasing spillovers the incentive to invest in R&D gets weaker since the rival firm j benefits more and more from firm i's R&D expenditures, see, e.g., De Bondt (1996). Second, if there are no spillovers or spillovers are very small, then managerial firms overinvest in R&D in the sense that they invest more than would be socially optimal (see Panel (c)), $x^{DD} > x_{\mathrm{FB}}$. Such an effect has been observed by Suzumura (1992) (see Theorem 3 on p. 1314) and Brander and Spencer (1983), where in contrast to our set-up they do not consider strategic delegation, i.e., in their models it is assumed that firms are managed by owners. Finally, managerial firms invest more in R&D and produce more than owner-managed firms independent of the level of spillovers, $x^{DD} > x^{NN}, q^{DD} > q^{NN}$. This result can be related to earlier papers on spillovers, e.g., d'Aspremont and Jacquemin (1988), and Suzumura (1992). They show that cooperation of owner-managed firms (at the R&D and/or production stage) leads to higher investments in R&D and output *if spillovers are sufficiently high* (see also the survey by De Bondt, 1996). Our result demonstrates that the same outcome can be achieved by delegating R&D and production decisions to managers, however *independent of the spillover level*. Finally, we briefly look at the welfare effects of delegation. Figure 4 shows the welfare in equilibrium and the welfare if owners determine R&D and production. Obviously, delegation has a beneficial effect in terms of overall welfare, $W^{DD} > W^{NN}$.

5.2. Equilibrium of the R&D game for small A

A quite different qualitative result is obtained if the basic production unit costs are low and close to A_L, namely $A = 5.1$. In Panel (a) of Figure 5 we show the resulting equilibrium values α^* for subgame *DD*. In contrast to a situation where A is high, feasible contracts exist only for spillover levels $\theta \in I_1 = [0.1076, 0.1808]$ and $\theta \in I_2 = [0.4539, 0.7935]$. Note that the equilibrium values of the incentive parameter are larger than 1, which means that—as in the discrete game—the manager is punished for high sales. Profits in equilibrium are higher than in the non-delegation case, $\pi_i^{DD} = \pi_j^{DD} > \pi_i^{NN} = \pi_j^{NN}$; see Panel (b) of Figure 5.

[13] Since delegation is a dominant strategy, the payoffs and actions in the equilibrium of the whole game obviously coincide with the payoffs and actions of subgame *DD*.

Figure 4. ***$a = 100$, $b = 1$, $r = 10$, $A = 38$. Welfare in equilibrium.***



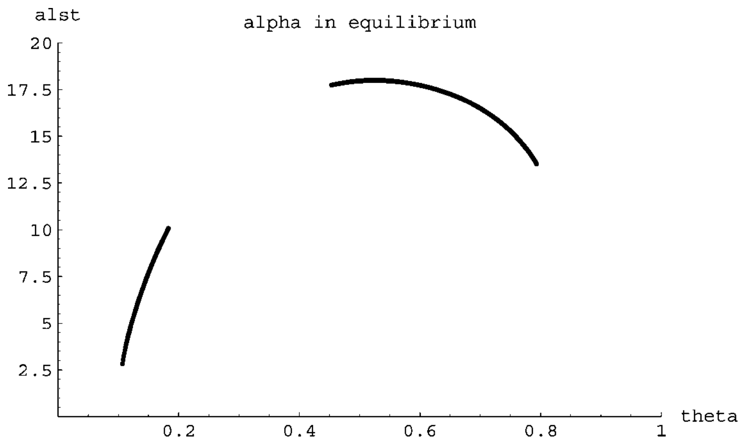
In Figure 6 we show the optimal values of the incentive parameter and the profits for subgame *DN* for $\theta \in [0, 1]$. Since we are interested in the equilibrium of the whole game, we focus on the intervals I_1 and I_2 where an equilibrium of subgame *DD* exists. For spillover levels in I_1 we have two equilibria in subgame *DN*. In one equilibrium the leading firm optimally sets $\alpha^* > 1$ and this results in $\pi_j^{DN} > \pi_i^{DN} > \pi_i^{NN} = \pi_j^{NN}$ and $\pi_j^{DD} > \pi_j^{DN}$. In other words, no matter what firm i does, firm j prefers to delegate. Delegation is a strictly dominant strategy. In the other equilibrium in I_1 the owner of the leading firm incentivates the manager to be aggressive on the market ($\alpha^* < 1$). A comparison of the profits in this equilibrium with the profits of subgames *DD* and *NN* reveals that $\pi_i^{DN} = \pi_j^{ND} > \pi_i^{NN} = \pi_j^{NN} > \pi_j^{DN}$ and $\pi_j^{DD} > \pi_j^{DN}$. Therefore, delegation is again a dominant strategy for player j. It is easy to see that the same logic holds for $\theta \in I_2$.

Taken together these arguments show that for spillovers $\theta \in I_1 \cup I_2$, in the equilibrium of the whole game both owners hire managers and punish their managers for high sales revenues. The qualitative behavior of the outcome coincides again with the results obtained for the discrete game. The manager is used by the owners as a commitment device to “soften” the behavior in comparison to the outcomes achieved by an entrepreneurial firm. As a result of this commitment profits are higher (Panel (b) of Figure 5), and R&D expenditures and production quantities are lower (Figure 5, Panels (c) and (d) respectively) than the payoffs and quantities for the non-delegation case. Furthermore, as Figure 7 shows that this leads to lower welfare than in the owner-managed case.

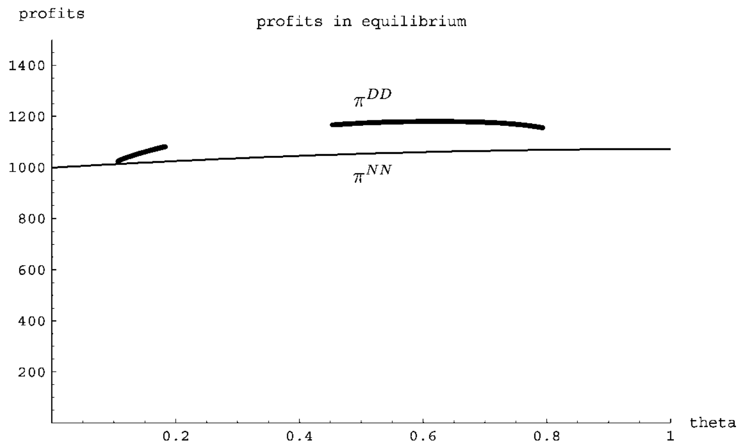
6. Further results and extensions of the model

In this section we are discussing further results and possible extensions of the model.

Figure 5. $a = 100$, $b = 1$, $r = 10$, $A = 5.1$. ***(a) Optimal values of α; (b) profits in equilibrium; (c) R&D expenditures in equilibrium; (d) quantities in equilibrium.***



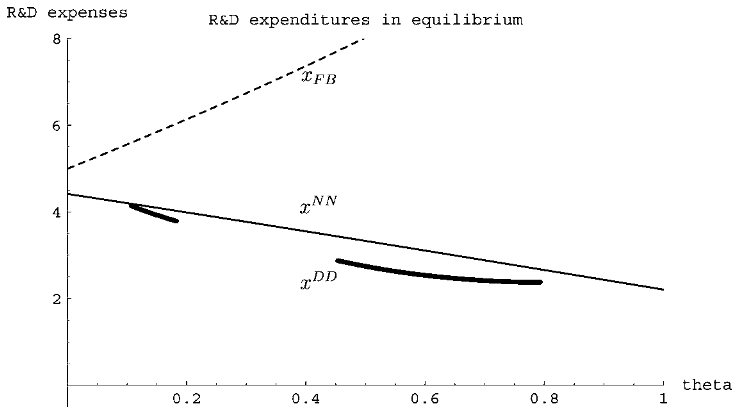
(a)



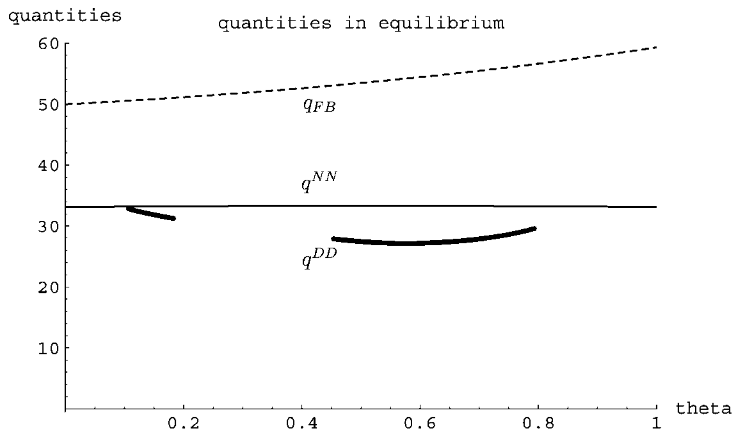
(b)

- *Asymmetric R&D costs*: It has been demonstrated for the discrete case that delegation is never beneficial for the owners when no spillovers exist. In situations where spillovers do exist and basic unit production costs are high, the same result holds. However, if the manager has some characteristics which differ from those of the owner of the firm, then delegation might be even beneficial for the firms if both owners delegate. To give an example, manager and owner might have different costs in carrying out R&D. That is, the R&D cost function is $\frac{1}{2}r\tau x_i^2$, where $\tau = 1$ for the manager and $\tau > 1$ for the owner. We illustrate this situation with a numerical example. Consider the case of maximal spillover ($\theta = 1$) and let $a = 100$, $b = 1$, $r = 10$ and $A = 10$. In

Figure 5. (Continued.)



(c)

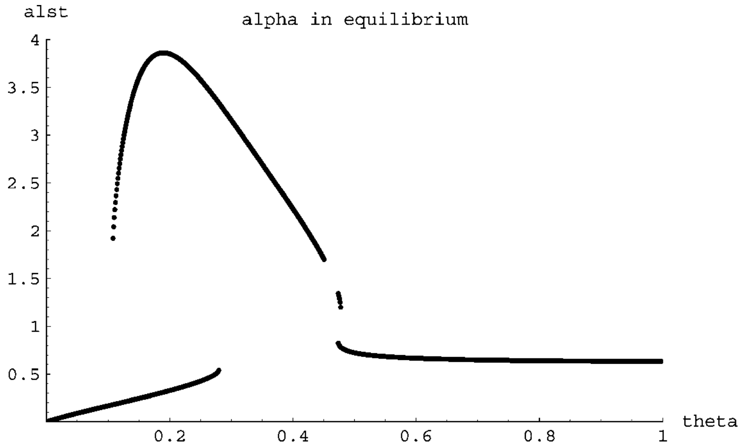


(d)

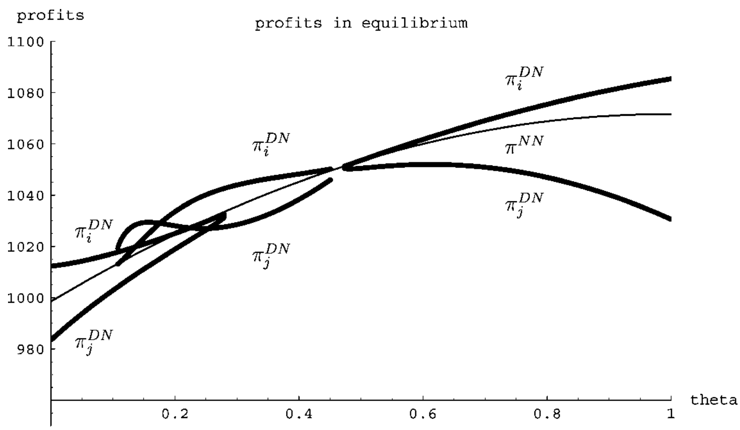
this situation the payoff table (Table A.5) shows that the unique equilibrium is $(\alpha_i = 1/2, \alpha_j = 1/2)$ and the profits for the owners in equilibrium are $\pi_i^D = \pi_j^D = \pi^D \approx 933.56$. Calculating the profits if the owners carry out R&D and production themselves (see the last line in (15)) for the same values of the parameters reveals that $\pi^{ND} < \pi^D \approx 933.56$ if $\tau > 1.847$. Hence, if R&D costs of the owners are more than about 85% higher, then delegation yields a higher payoff for the owners than non-delegation. Observe that the same formulation can be used to capture the difference in types (abilities) of managers with respect to R&D.

- *Asymmetric spillovers*: Another difference between manager and owner may arise in the size of the spillover parameter θ. A manager who is in charge of the R&D task certainly has accumulated an expertise which enables the manager to make better use of the R&D knowledge which spills over from

Figure 6.* Subgame DN, $a = 100$, $b = 1$, $r = 10$, $A = 5.1$. *(a) Optimal values of α; (b) profits in equilibrium.



(a)

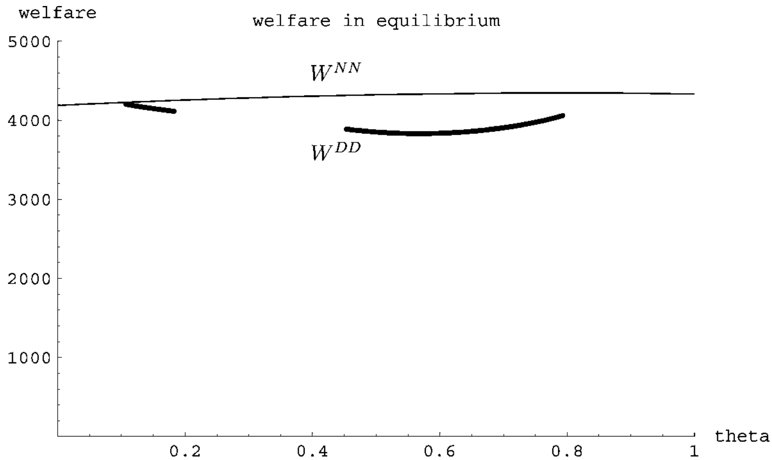


(b)

the rival firm. This could be imagined as switching from a profit table with lower θ to a profit table with higher θ. The point that the manager is more able to absorb and use knowledge spilled over from the rival firm is somehow reminiscent of the notion of absorption capacity (see Cohen and Levinthal, 1989). In order for firms being able to use knowledge from other firms, they have to expend resources to build up capacity which then allows to absorb and use this knowledge to their advantage (see Kaiser, 2002 or Grünfeld, 2003).

- *R&D set up costs*: In our model the marginal costs of R&D are linear. This certainly is a simplification, in particular when one thinks of the set-up costs involved when firms start R&D activities. A different type of R&D

Figure 7. $a = 100$, $b = 1$, $r = 10$, $A = 5.1$. ***Welfare in equilibrium.***



cost function, e.g., $x + x^2$, takes such an effect into account. The positive marginal costs for R&D at $x = 0$ provide some kind of entry barrier.

- *Different performance measures*: In our model we assume that incentive contracts are based on sales revenues and profits. In doing that we followed the majority of papers on strategic delegation. However, other authors study the effect of other (additional) performance measures, e.g., relative profits, market shares, output, etc. For work along these lines see Vickers (1985), Aggarwal and Samwick (1999), Zitzewitz (2001).[14]
- *Organizational and Job design*: In this paper it is assumed that either the manager or the owner carries out both tasks, production and R&D, see also Zhang and Zhang (1997), Kräkel (2004), and Lambertini (2004). On the other hand, the character of the two tasks differs significantly: R&D is of strategic importance for the firm, whereas quantity setting takes place on an operational level. Therefore, additional cases can be studied where owners only partially delegate the decisions (see Kopel and Lambertini, 2005). Here owners have the option of delegating only the quantity choice (short term decision) and determine the R&D expenditures themselves (strategic decisions). Alternatively, the owner might want to hire a different manager for each task (an innovation expert and a production line manager) with different compensation contracts for the two agents. In the literature on job design (see, e.g., Holmstrom and Milgrom, 1991) questions like these have been studied.

[14] Surprisingly, the game considered here is fully solvable if contracts are based on a performance measure which includes profits and quantities as in Vickers (1985). For results on this setup, see Kopel and Lambertini (2005).

- *Market structure*: From the industrial organization literature we know that market structures and the characteristics of the decision variables, e.g., prices or quantities, have a strong influence on the outcomes and performance, see, e.g., Sklivas (1987). It might be interesting to consider the effects of delegation in an R&D model where the manager is responsible for setting prices instead of production quantities. Miller and Pazgal (2001) show an interesting equivalence result for price and quantity competition. In the context of R&D this issue has been analyzed in Bárcena-Ruiz and Olaizola (2006) in a setting different from the one studied in our paper.

7. Conclusions

The question of strategic delegation has attracted much attention since the seminal papers of Vickers (1985), Fershtman (1985), Fershtman and Judd (1987), and Sklivas (1987). Recently several papers have focused on the effects of strategic delegation in the context of R&D decisions, e.g., Zhang and Zhang (1997), Zhang (2002), Kräkel (2004), Lambertini (2004), and Bárcena-Ruiz and Olaizola (2006). In this paper we reconsider the Zhang and Zhang setup, and correct and characterize the solution of the R&D game with spillovers. Additionally, we introduce a delegation stage to the model and study the question if it is beneficial for the owner to hire a manager or not. Our analysis shows that delegation can be an equilibrium outcome of the game. In a case where no spillovers exist, both owners delegate R&D and production decisions to managers and provide incentives for aggressive behavior on the market. This leads to higher outputs, higher R&D activities, but lower profits for the firms in comparison with an entrepreneurial firm. These results still hold, if the basic production unit costs are high, independent of the existence of spillovers. Social welfare increases due to delegation as the decrease in firm profits is overcompensated by an increase in the consumer rent. If spillovers exist and the basic unit production costs are low, then there are situations where owners prefer to delegate but select the incentives such that managers are behaving "soft" on the market. This leads to lower outputs, lower R&D, but higher profits for the firms in comparison with an entrepreneurial firm. Here, however, social welfare decreases due to delegation as the increase in firm profits is smaller than the decrease in the consumer rent.

In addition to these main results, we have also discussed how different characteristics of owners and managers, e.g., different costs of carrying out R&D or different abilities to absorb R&D spillovers, affect the benefits of delegation. Since we find the combination of strategic delegation and R&D a fruitful field for future research, we have also discussed several open topics which we find worth pursuing.

Appendix A

This appendix presents Tables A.1–A.5.

Table A.1. Owner's profits π_i^{DD} and π_j^{DD} for $\theta = 0$

	$\alpha_j = \frac{1}{2}$	$\alpha_j = 1$	$\alpha_j = \frac{3}{2}$
$\alpha_i = \frac{1}{2}$	$\frac{(a-2A)(2a-A)r}{18br-4}$, $\frac{(a-2A)(2a-A)r}{18br-4}$	$\frac{r(2A+a(3br-4))(2a(3br-4)(9br-2)+A(9br(16-9br)-32))}{2(8+9br(3br-4))^2}$, $\frac{r(9br-8)(A(4-9br)+a(6br-4))^2}{4(8+9br(3br-4))^2}$	$\frac{r(-4a+2A+(2a+A)br)(a(br-2)(9br-2)+A(br(32-9br)-8))}{2(4+br(9br-16))^2}$, $\frac{r(3A(2-5br)+a(6br-4))(a(3br-2)(9br-14)-3A(8+br(9br-20)))}{18(4+br(9br-16))^2}$
$\alpha_i = 1$		$\frac{(a-A)^2 r(9br-8)}{(9br-4)^2}$, $\frac{(a-A)^2 r(9br-8)}{(9br-4)^2}$	$\frac{r(9br-8)(4a-4A+(-2a+A)br)^2}{4(8+br(9br-20))^2}$, $\frac{r(-4a+6A+3(a-2A)br)(2a(3br-4)(9br-14)-3A(32+br(9br-32)))}{18(8+br(9br-20))^2}$
$\alpha_i = \frac{3}{2}$			$\frac{(2a-3A)r(12A+a(9br-14))}{18(3br-2)^2}$, $\frac{(2a-3A)r(12A+a(9br-14))}{18(3br-2)^2}$

Table A.2. Owner's profits π_i^{DD} and π_j^{DD} for $\theta = \frac{1}{4}$

	$\alpha_j = \frac{1}{2}$	$\alpha_j = 1$	$\alpha_j = \frac{3}{2}$
$\alpha_i = \frac{1}{2}$	$\frac{8(2a-A)r(7(a+7A)+144br(a-2A))}{(35-144br)^2}$, $\frac{8(2a-A)r(7(a+7A)+144br(a-2A))}{(35-144br)^2}$	$-\frac{4r(15A+a(32br-35))(a(5+8br(15-16br))+6A(5+2br(-19+16br)))}{9(32br-25)^2(4br-1)^2}$, $\frac{8r(2a-3A)^2}{9(32br-25)}$	$\frac{8r(-506a+207A+144(2a+A)br)(a(-2875+576br(36br-55))-9A(575+16br(144br-353)))}{9(1725+64br(108br-151))^2}$, $\frac{8r(-10a+45A+48(2a-5A)br)(a(20815+192br(324br-539))-3A(7935+16br(1296br-2537)))}{9(1725+64br(108br-151))^2}$
$\alpha_i = 1$		$\frac{8(a-A)^2r(72br-49)}{(72br-35)^2}$, $\frac{8(a-A)^2r(72br-49)}{(72br-35)^2}$	$\frac{8r(288br-169)(110a-99A+36(-2a+A)br)^2}{9(2145+4br(864br-1475))^2}$, $\frac{4r(-65a+117A+96(a-2A)br)(a(35035+24br(1296br-2813))-6A(4719+2br(1296br-3737)))}{9(2145+4br(864br-1475))^2}$
$\alpha_i = \frac{3}{2}$			$\frac{8(2a-3A)r(147A+a(144br-203))}{9(48br-35)^2}$, $\frac{8(2a-3A)r(147A+a(144br-203))}{9(48br-35)^2}$

Table A.3. Owner's profits π_i^{DD} and π_j^{DD} for $\theta = \frac{1}{2}$

	$\alpha_j = \frac{1}{2}$	$\alpha_j = 1$	$\alpha_j = \frac{3}{2}$
$\alpha_i = \frac{1}{2}$	$\frac{2(2a-A)r(a+A+4abr-8Abr)}{9(4br-1)^2}$, $\frac{2(2a-A)r(a+A+4abr-8Abr)}{9(4br-1)^2}$	$\frac{r(7A+3a(8br-7))(A(-14+9br(25-36br))+3a(-7+2br(36br-17)))}{9(7+3br(24br-19))^2}$, $\frac{2r(72br-49)(A+6abr-9Abr)^2}{9(7+3br(24br-19))^2}$	$\frac{2r(-110a+33A+36(2a+A)br)(-33A+36Abr(53-36br)+a(-187+144br(9br-10)))}{9(33+16br(27br-31))^2}$, $\frac{2r(A(3-60br)+a(24br+2))(a(55+48br(81br-110))-3A(121+4br(324br-569)))}{9(33+16br(27br-31))^2}$
$\alpha_i = 1$		$\frac{2(a-A)^2r}{18br-9}$, $\frac{2(a-A)^2r}{18br-9}$	$\frac{2r(72br-25)(20a-15A+9(-2a+A)br)^2}{9(75+br(216br-275))^2}$, $\frac{r(-5a+15A+24(a-2A)br)(-3A(250+br(324br-755))+a(925+6br(324br-515)))}{9(75+br(216br-275))^2}$
$\alpha_i = \frac{3}{2}$			$\frac{2(2a-3A)r(3A+a(4br-5))}{9(4br-3)^2}$, $\frac{2(2a-3A)r(3A+a(4br-5))}{9(4br-3)^2}$

Table A.4. *Owner's profits π_i^{DD} and π_j^{DD} for $\theta = \frac{3}{4}$*

	$\alpha_j = \frac{1}{2}$	$\alpha_j = 1$	$\alpha_j = \frac{3}{2}$
$\alpha_i = \frac{1}{2}$	$\frac{8(2a-A)r(55a+25A+144br(a-2A))}{(35-144br)^2}$, $\frac{8(2a-A)r(55a+25A+144br(a-2A))}{(35-144br)^2}$	$-\frac{4r(13A+a(96br-65))(26A+36Abr(-43+144br)+a(143+24br(23-144br)))}{(91+36br(96br-59))^2}$, $\frac{8r(288br-169)(A-36Abr+a(2+24br))^2}{(91+36br(96br-59))^2}$	$\frac{(-28a+21A+32(a-A)br)(-42a+7A+16br(2a+A))}{4b(48br-49)^2}$, $\frac{4(2a-5A)r(-364a+496A+288br(a-A))}{9(48br-49)^2}$
$\alpha_i = 1$		$\frac{8(a-A)^2r(72br-25)}{(72br-35)^2}$, $\frac{8(a-A)^2r(72br-25)}{(72br-35)^2}$	$\frac{8r(-2a+A)^2}{288br-49}$, $\frac{4r(7(a+3A)+96(a-2A)br)(-42A+4Abr(91-48br)+a(35+8br(48br-55)))}{(288br--49)^2(4br-3)^2}$
$\alpha_i = \frac{3}{2}$			$\frac{8(2a-3A)r(75A+a(144br-155))}{9(48br-35)^2}$, $\frac{8(2a-3A)r(75A+a(144br-155))}{9(48br-35)^2}$

Note. The profits for $(\alpha_i = \frac{1}{2}, \alpha_j = \frac{3}{2})$ have been obtained by setting $x_i^{DD} = 0$, $x_j^{DD} = \frac{28(2a-5A)}{3(48br-49)}$.

Table A.5. *Owner's profits π_i^{DD} and π_j^{DD} for $\theta = 1$*

	$\alpha_j = \frac{1}{2}$	$\alpha_j = 1$	$\alpha_j = \frac{3}{2}$
$\alpha_i = \frac{1}{2}$	$\frac{(2a-A)r(A-18Abr+a(9br+4))}{2(9br-2)^2}$, $\frac{(2a-A)r(A-18Abr+a(9br+4))}{2(9br-2)^2}$	$\frac{ar(2a-3A)}{18br-9}$, $\frac{(2a-3A)^2 r}{36br-18}$	$\frac{(-5a+9(a-A)br)(-20a+9br(2a+A))}{2b(27br-25)^2}$, $\frac{(2a-5A)r(-95a+125A+81br(a-A))}{2(27br-25)^2}$
$\alpha_i = 1$		$\frac{(a-A)^2 r(9br-2)}{(9br-4)^2}$, $\frac{(a-A)^2 r(9br-2)}{(9br-4)^2}$	$\frac{(18br-1)(8a+9br(-2a+A))^2}{18b^2 r(54br-35)^2}$, $\frac{(a+6br(a-2A))(3Abr(128-81br)+a(-32+6br(81br-68)))}{9b^2 r(54br-35)^2}$
$\alpha_i = \frac{3}{2}$			$\frac{(2a-3A)r(3A+a(9br-8))}{18(3br-2)^2}$, $\frac{(2a-3A)r(3A+a(9br-8))}{18(3br-2)^2}$

Note. The profits for $(\alpha_i = \frac{1}{2}, \alpha_j = \frac{3}{2})$ have been obtained by setting $x_i^{DD} = 0$, $x_j^{DD} = \frac{5(2a-5A)}{27br-25}$.

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