Business Strategies Towards the Creation, Absorption and Dissemination of New Technologies

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Preface

This cumulative thesis comprises four theoretical papers related to business strategies towards the creation, absorption and dissemination of new technologies.

The first paper "Absorptive Capacity and Connectedness: Why Competing Firms also Adopt Identical R&D Approaches" is published in the *International Journal of Industrial Organization*, 23 (2005) 467-481. The Elsevier Science B.V. copyright is acknowledged. The paper was presented at the "European Summer School on Industrial Dynamics" (ESSID 2003), ZEW and University of Bocconi, in Corse.

The second paper "Cooperation or Competition in R&D When Innovation *and* Absorption Are Costly" is forthcoming in *Economics of Innovation and New Technology,* 2006. I acknowledge the Taylor and Francis copyright. This paper was presented at the conference 'Industrial Organization and Innovation', INRA and GEAL, in Grenoble and at the 'Jahrestagung 2005', Verein für Socialpolitik, in Bonn.

The third paper "Excess Absorptive Capacity and the Persistence of Monopoly" was presented at 'EARIE 2005', European Association of Research in Industrial Economics, in Porto, the '2nd ZEW Conference on Innovation and Patenting', ZEW, in Mannheim and the annual meeting of the German Association of Business Administration (GEABA), 'VI. Symposium zur ökonomischen Analyse der Unternehmung', in Freiburg.

The fourth paper "Knowledge Transfer in Buyer-Supplier Relationships – When It (Not) Occurs" is the result of joint research with Werner Bönte. The paper was presented at 'EARIE 2005', European Association of Research in Industrial Economics, in Porto and the annual meeting of the German Association of Business Administration (GEABA), 'VI. Symposium zur ökonomischen Analyse der Unternehmung', in Freiburg.

Hamburg, November 2005 Lars Wiethaus

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Contents

General Introduction

1 Creation, Absorption and Dissemination of New Technologies

In high-tech industries the creation of new technologies is the most important origin of competitive advantage. At the same time, new technologies, developed by one's competitor, constitute the most severe threat to a firm's established market position. Not surprisingly high-tech firms invest substantial amounts of money in research and development (R&D), i.e. up to 15.5 % of sales[1] in the pharmaceuticals & biotechnology sector as well as in the IT hardware sector. R&D expenditures in the five most R&D intensive sectors amount to a fivefold of companies' dividends[2]. The decision on the optimal R&D budget as well as its allocation to certain activities becomes, as Baumol (2002) puts it, "a matter of life and death" for many firms. These decisions are notably complex for at least two reasons. The first, rather general one, arises from strategic behavior in high tech industries. The second reason is due to the specific properties of new technologies. We shall briefly deal with each point.

With respect to strategic behavior, Leahy and Neary (1997) note that "since R&D is a component of fixed costs, industries where it is important tend to be concentrated". Indeed the bulk of R&D, in absolute terms, is undertaken by firms with high market shares (Scherer 1967, Blundell and Griffith 1998). By the same token most and major innovations are generated by dominant firms (e.g. Sorescu et al. 2003). In concentrated, oligopolistic industries one firm's *creation of a new technology*, say the introduction of a faster microprocessor, materially affects other firms' demand and profitability respectively. Being aware of this fact firms need to make their decisions in anticipation of a competitor's likely action as well as under consideration of competitors' responses. Between 2001 and 2003 the microprocessor manu-

[1] European Commission, "Monitoring industrial research: the 2004 EU industrial R&D investment scoreboard".

[2] DTI, "The 2004 R&D Scoreboard. The top 700 UK and 700 international companies by R&D Investment", www.innovation.gov.uk. Geroski et al. (1993), Bayus et al. (2003) and Sorescu et al. (2003) provide empirical studies on the relationship between innovation and firm profitability.

facturer AMD, for instance, devoted about 2.3 billion US $ to R&D (15% to 30% of sales) while having summed up losses of more than 1.5 billion[3]. Such aggressive R&D investments would be rather unlikely in absence of Intel's progress and the threat of falling behind the technological edge. In this respect, however, investments in new technology creation do not seem to differ from any other sort of fixed costs, like investments in capacity.

What distinguishes an investment in new technology creation, e.g. R&D investments, essentially from an investment in tangible assets is that new technologies comprise, to some extent, the properties of a public good[4]. A public good is both nonrival, i.e. its use by one person does not preclude its use by another person, and nonexcludable, i.e. the owner of a good cannot prevent others from using it. New technologies are nonrival in the sense that "once the cost of creating a new set of instructions has been incurred, the instructions can be used over and over again at no additional cost" (Romer 1990).

The extent to which new technologies are nonexcludable depends on the nature of the technology in question and the legal system. For instance new technologies as an outcome of basic research are less excludable as compared to those that arise from solving a firm specific problem. The legal system of patent and property rights protection, too, varies across countries and industries, being notably strong in the pharmaceutical and chemical industry and rather weak in the semiconductor or biotechnology industry (e.g. Cohen et al. 2000). Nonexcludabilities in new technology creation are commonly expressed as technology or knowledge spillovers which "include any original, valuable knowledge generated in the research process which becomes publicly accessible, whether it be knowledge fully characterizing an innovation, or knowledge of a more intermediate sort" (Cohen and Levinthal 1989). Important channels of spillovers are fluctuations of scientists or information that has to be made public in order to commercialize a new technology (Mansfield 1985).

As a consequence of technological spillovers firms cannot appropriate all

[3]See annual reports, www.amd.com.

[4]A second fundamental difference is that the outcome of R&D is uncertain which is, however, not the focus of this thesis.

of their R&D efforts exclusively (Nelson 1959, Arrow 1962, Spence 1984) which further complicates R&D related decisions. In particular it may be profitable to reduce investments in new technology creation as compared to a situation in which a firm's own efforts would not simultaneously enhance the competitiveness of its rival. Indeed, Jaffe (1998) stresses the implicit connection between spillovers and strategic R&D reduction: "proponents and/or reviewers will cite the diffuse and high-risk nature of the potential benefits as reasons why private capital is not forthcoming, or note that the project is not part of the proponent's core business". As an indicator of the importance of spillovers for R&D investments empirical literature as summarized by Griliches (1992) suggests a spillover level[5] between 50% and 100% relative to private R&D investments within the industrial sector. Having said this, spillovers are not exogenously given for a firm but determined by additional actions, namely efforts to absorb and the firm's willingness to disseminate new technologies.

Efforts to *absorb new technologies* are necessary because the latter do not rain "down upon its beneficiaries like manna from heaven, [in the sense that] no effort is needed of the recipients, not even purchase of a bucket" (Kamien and Zang 2000). Rather firms need the ability "to identify, assimilate and exploit existing information", i.e. absorptive capacity. In this context Cohen and Levinthal (1989) highlighted the 'second face' of R&D: learning. That is, besides the incentive to generate innovations, firms also seek to improve their absorptive capacity. Anecdotal[6] as well as empirical[7] evidence support the relevance of absorptive capacity as a second motivation for R&D investments.

However, the absorption of externally developed new technologies does not (necessarily) require R&D efforts in terms of an own innovation. Empirical studies[8] indicate that absorption requires specific R&D efforts to imitate

[5] Measured as the gap between the social rate of return and the private rate of return on R&D investments. The spillover rates of Table 1 in Griliches (1992, p. S43) are expressed as the excess of the social rate of return with respect to the private rate of return (relative to the social rate of return). Jaffe (1986) provides an early study on the importance of knowledge spillovers.

[6] See Cohen and Levinthal (1989, 1990) and the work cited.

[7] See Griffith et al. (2003).

[8] See "Cooperation or Competition in R&D When Innovation *and* Absorption Are

(rather than to innovate). As a consequence firms need to adjust their decisions towards new knowledge creation with respect to both their rivals' likely innovation and absorption efforts. The paper "Cooperation or Competition in R&D When Innovation *and* Absorption Are Costly" analyzes firms' simultaneous decisions with respect to innovation and absorption. The paper "Excess Absorptive Capacity and the Persistence of Monopoly" addresses the question how an incumbent firm may utilize its absorptive capacity as a means to discourage a potential entrant's innovation efforts and consequently entry.

Yet technological spillovers are not exclusively described through a firm's involuntary leakage of knowledge and another firm's efforts to absorb this knowledge. In addition firms may have an incentive to stimulate the *dissemination of new technologies*. In the case of vertically related firms, i.e. buyer-supplier relationships, the incentive for new technology dissemination occurs because this usually increases the efficiency of the buyer-supplier relationship. Moreover, at first glance, firms do not risk the loss of a competitive advantage in vertical relationships. Yet this paints only half the picture if a supplier, for instance, maintains relationships with additional buyers. Then each buyer needs to trade off efficiency gains from knowledge dissemination against the threat of technology transfer through a common supplier (see the paper "Knowledge Transfer in Buyer-Supplier Relationships - When It (Not) Occurs").

If firms are horizontally related, incentives for knowledge dissemination are less straightforward because competitive advantages, in general, are tied to technological advantage. However one may think of two reasons why also competing firms may foster knowledge flows. Provided these flows are sufficiently reciprocal (von Hippel 1987) firms are better off through the exchange of knowledge as compared to an individual creation of knowledge. Furthermore knowledge dissemination frees firms from the above sketched dilemma of aggressive R&D investments: if the dissemination of new technologies is guaranteed there hardly exists any pressure of creating them in the first place. The practice of horizontal knowledge dissemination is well documented through case evidence of von Hippel (1987), Schrader (1990) and

Costly" for an overview.

Baumol (2001) but has not been explained theoretically[9]. The paper "Absorptive Capacity and Connectedness: Why Competing Firms also Adopt Identical R&D Approaches" deals with that question.

2 Purpose and Contributions

This thesis aims to identify and to close some gaps in the literature dealing with business strategies towards the creation, absorption and dissemination of new technologies. In doing so it comprises four theoretical papers. The following abstracts and Figure 1 briefly link each paper to one ore more of the above mentioned topics (creation, absorption and dissemination) and report its main findings and contributions to the literature. For further details the reader is referred to the particular paper.

Absorptive Capacity and Connectedness: Why Competing Firms also Adopt Identical R&D Approaches[10] This paper explores firms' decisions regarding the dissemination and absorption of new technologies as well as their creation. In particular firms determine both the dissemination and absorption through their choices of R&D approaches. Whereas identical (broad) R&D approaches 'connect' firms with their R&D environment and maximize knowledge dissemination and absorptive capacities, the opposite holds for idiosyncratic R&D approaches. The model shows that competing firms choose identical R&D approaches in order to maximize knowledge flows between each other. In essence, this frees firms from the dilemma of aggressive investment in R&D. Our analysis contrasts with Kamien and Zang's (2000) finding that competing firms chose idiosyncratic R&D approaches. We demonstrate that their model also yields a Nash equilibrium for identical (broad) R&D approaches.

[9] Knowledge dissemination, of course, may take place in the form of technology licensing. See Baumol (2004) for an overview.

[10] This paper is published, see Wiethaus (2005). Molto et al. (2005) have independently developed a related model with similar results.

Cooperation or Competition in R&D When Innovation and Absorption Are Costly This paper analyses cost-reducing R&D investments by firms that behave non-cooperatively or cooperatively. Firms face a trade-off between allocating their R&D investments to innovate or to imitate, i.e. to create ot to absorb new technologies. We find that the non-cooperative behavior not only induces more imitation (absorption) but also, for the most part, more innovation investments. Only the cooperative behavior, however, ensures that R&D investments are allocated efficiently to innovation and to imitation (absorption) in the sense that any given amount of industry-wide cost-reduction is obtained for the minimum overall R&D costs.

Excess Absorptive Capacity and the Persistence of Monopoly This paper considers a monopolist's precommitment to absorb a potential entrant's innovation as a means of entry deterrence. This precommitment, i.e. excess absorptive capacity, always decreases the entrant's efforts to create new technologies whereas it increases (decreases) the monopolist's efforts if potential duopoly profits are low (high). If potential competition is à la Bertrand, a certain degree of excess absorptive capacity indeed suffices to render the monopolist more innovative than the entrant, such that even if the innovation is drastic, monopoly will tend to persist. More excess absorptive capacity increases the monopolist's equilibrium payoff whereas it decreases the entrant's.

Knowledge Transfer in Buyer-Supplier Relationships: When It (Not) Occurs A buyer's technical knowledge may increase the efficiency of its supplier. Suppliers, however, frequently maintain relationships with additional buyers. Knowledge dissemination then bears the risk of benefiting one's own competitor due to opportunistic knowledge transmission through the common supplier. We show that in one-shot relationships no knowledge dissemination takes place because the supplier has an incentive for knowledge transmission and, in anticipation of this outcome, buyers refuse to disseminate any of their knowledge. In repeated relationships knowledge dissemination is stabilized by larger technological proximity between buyers and suppliers and destabilized by the absolute value of the knowledge.

Paper	Topic	Setting	Important decision variables	Main finding and contribution to the literature
Absorptive Capacity and Connectedness: Why Competing Firms also Adopt Identical R&D Approaches	Creation, absorption and dissemination of new technologies	Horizontally related firms, non-cooperative	Innovation efforts, R&D approaches	Firms adopt identical R&D approaches to foster knowledge dissemination and reduce innovation efforts as a consequence
Cooperation or Competition in R&D When Innovation *and* Absorption Are Costly	Creation and absorption of new technologies, public welfare	Horizontally related firms, (non-) cooperative	Innovation efforts, imitation/ absorption efforts	Cooperative R&D tends to reduce technological progress (relative to competition) but induces the efficient allocation of R&D resources
Excess Absorptive Capacity and the Persistence of Monopoly	Creation and absorption of new technologies	Monopolist, potential entrant	Innovation efforts, (monopolist has absorptive capacity)	Absorptive capacity constitutes an entry barrier
Knowledge Transfer in Buyer-Supplier Relationships – When It (Not) Occurs	Dissemination of new technologies	Monopolistic supplier, downstream duopoly	Knowledge disclosure (to a common supplier), further knowledge transmission through the supplier	A common supplier disseminates knowledge to all of its buyers. Each buyer refuses knowledge disclosure to the supplier in one-shot games. Repeated games facilitate knowledge disclosure.

Figure 1: Overview on the papers' topics and contributions

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Absorptive Capacity and Connectedness: Why Competing Firms also Adopt Identical R&D Approaches

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Abstract

This paper explores the endogenous determination of R&D appropriability through the firms' choice of R&D approaches. Whereas identical broad R&D approaches 'connect' firms with their R&D environment and maximize absorptive capacities, the opposite holds for idiosyncratic R&D approaches. Our model shows that competing firms choose identical R&D approaches in order to maximize knowledge flows between each other. In essence, this frees firms from the dilemma of aggressive investment in R&D. Our analysis contrasts with Kamien and Zang's (2000) finding that competing firms chose idiosyncratic R&D approaches. We demonstrate that their model also yields a Nash equilibrium for broad identical R&D approaches.

JEL Classification: O31, O32, L13

Keywords: Absorptive Capacity; Spillovers; Appropriability; Innovation; R&D.

1 Introduction

Would competing firms follow the same research tracks (i.e. adopt identical R&D approaches) with the purpose of fostering flows of technical knowledge between each other?

Kamien and Zang (2000) argue that competing firms choose different research tracks, i.e. adopt purely idiosyncratic R&D approaches in order not to provide any valuable knowledge for their competitor: "The intuition [...] is that firms offset exogenous spillovers by choosing firm-specific R&D approaches. They only choose broad R&D approaches when there is no danger that they will confer a benefit on their rival". However, this theoretical prediction appears to be contradicted by some anecdotal evidence. For example, in the semiconductor industry, Lim (2000) has found that all major competitors, including IBM, Motorola, Intel, AMD and many others, adopted the same R&D approach in order to develop interconnects through which electricity could flow between various circuit elements, namely that of copper technology. Alternatives such as aluminium technology would have been feasible since each metal has its own advantages and disadvantages and "even had they chosen copper, they might have developed something other than the damascene process, and could certainly have deposited copper some other way (e.g., PVD, CDV, or electroless deposition)" (Lim 2000). This suggests that copper technology was not the 'obvious' solution and as such was independently developed by each firm. The decision whether or not to pursue the copper approach apparently involved a trade-off between high appropriability of each firm's own R&D on the one hand, and "connectedness to external sources of technical knowledge" (Lim 2000) on the other hand[1].

By investigating this trade-off in more detail we wish to shed some light on a so-far less acknowledged aspect of absorptive capacity, namely the firms' decisions with respect to R&D approaches or - more generally speaking - the firms' connectedness[2]. The concept of absorptive capacity itself was introduced by Cohen and Levinthal (1989) as a "second face of R&D" which

[1] Cockburn and Henderson (1998) empirically support the relevance of 'connectedness' between for-profit and publicly funded research in pharmaceuticals.

[2] The above-mentioned studies by Kamien and Zang (2000) and Lim (2000) have considered connectedness, although only Lim (2000) uses the term 'connectedness'.

builds up "the firm's ability to assimilate and exploit existing information". Subsequent studies have primarily focused on *internal R&D as a way to achieve absorptive capacity.* In this line of research Grünfeld (2003) pointed out that the absorptive capacity (or learning) effect of R&D not only creates an additional incentive for a firm's own investments but also, due to lower R&D appropriability, a strategic disincentive for the competitor. Our study complements Grünfeld's (2003) work in the sense that we re-examine Kamien and Zang's (2000) analysis by focusing on *absorptive capacity through firms' connectedness.*[3]

The firms' choice of their connectedness will determine industry-wide R&D appropriability: the more (less) connected firms are, the lower (higher) will be R&D appropriability. R&D appropriability has long been a matter of policy concern and is widely discussed in the context of cooperative and non-cooperative R&D[4] (D'Aspremont and Jacquemin, 1988 - DJ throughout)[5]. In general it is argued that in the case of low appropriability, cooperative R&D yields the highest R&D investments, whereas in the case of high appropriability, the competitive R&D mode induces the highest R&D incentives. Hence it is important to know which degree of appropriability is implied endogenously by the firms' decisions in a cooperative and a competitive R&D environment.

In the case of cooperative R&D, it has been shown that firms endogenously *maximize* knowledge flows between each other, whether, for example, in terms of full knowledge-sharing (Poyago-Theotoky, 1999) or through the adaptation of identical R&D approaches (Kamien and Zang, 2000). This outcome is also socially desirable in terms of R&D investments, output quantities

[3]Cassiman et al. (2002) present a model in which absorptive capacity is built up through basic R&D expenditures. Kamien and Zang (2000) use the terms 'broad R&D approach' and 'basic R&D' as synonyms. Martin (2002) analyzes absorptive capacity in the context of a tournamant model with uncertainty.

[4]For the remainder of the paper we refer to cooperative R&D in the case of joint profit maximization and to non-cooperative or competitive R&D in the case of independent profit maximization.

[5]Suzumura (1992) extends the DJ framework to a broader set of cost and demand assumptions. A review of models with exogenous spillover levels is provided by De Bondt (1996).

and the firms' profits (Kamien, Müller and Zang, 1992).

In the case of competitive R&D decisions on the other hand, previous studies predicted that firms endogenously *minimize* knowledge flows, i.e. they do not disclose any of their knowledge to a competitor (Poyago-Theotoky, 1999) or they select idiosyncratic R&D approaches (Kamien and Zang, 2000)[6]. Minimum knowledge flows clearly induce the highest R&D investment incentives in the competitive case; the welfare implications, nonetheless, are ambiguous: Anbarci et al. (2002) have found that even high knowledge flows and comparably low R&D investments may improve welfare, as long as competitors' R&D activities are sufficiently complementary to each other. Because they treat knowledge flows as an exogenous phenomenon a theoretical prediction of whether and how high knowledge flows among competitors actually occur is missing.

We shall offer one explanation by analyzing a simple three-stage competitive R&D model. In the first stage, firms adopt R&D approaches. In particular, the more (less) one firm's R&D is related to a rival's, the higher (lower) are knowledge flows. Subsequently, firms decide on their R&D investments and finally engage in Cournot competition[7]. We would, of course, expect cooperating firms to adopt identical R&D approaches because they can internalize the beneficial effects of knowledge flows. But we find that also competing firms adopt identical R&D approaches. Their purpose is not only to benefit from a rival's R&D. There also exists a strategic incentive to reduce appropriability: it frees firms from a prisoner's dilemma that would otherwise force them to invest aggressively in R&D. Hence our results seem to contradict the previous finding by Kamien and Zang who find that competing firms adopt idiosyncratic R&D approaches in order to secure perfect appropriability of their R&D investments.

Why do our results appear contrary to Kamien and Zang's? The answer is that there exists a second Nash equilibrium in the Kamien and Zang

[6] Though their result is restricted to a profit comparison in the case of full vs. no knowledge disclosure, Kultti and Takalo noted in 1998 that competitive firms have an incentive to foster knowledge flows as long as it is guaranteed that information flows are sufficiently symmetric.

[7] We adhere to Kamien and Zang's game-structure and strategic choice variables in order to ensure comparability.

model which also implies the adoption of broad identical R&D approaches in the competitive case. It might have been overlooked because in their model the first-order conditions of the competitive case are analytically intractable. This drawback is due to Kamien and Zang's rich framework which, in contrast to our model, also accounts for internal R&D as a determinant for absorptive capacity. We establish the second Nash equilibrium of their model via simulations. It is then easy to verify full consistency between the overall predictions of Kamien and Zang's model and the one in this paper. These are the same predictions as those provided by the seminal work of DJ; obtained here in a setting in which knowledge flows are endogenous through the firms' absorptive capacities.

The remainder of the paper is organized as follows: in section two we present the model, section three discusses our results in relation to Kamien and Zang's analysis, section four concludes.

2 A simple model

In this section we analyze a simple three-stage model. In the game's first stage, firms decide on their R&D approaches. In the second stage, R&D expenditures are chosen and finally output quantities. All decisions are made non-cooperatively as the cooperative case would simply replicate Kamien and Zang's solutions for their cooperative case, viz., firms select purely broad (identical) R&D approaches to maximize spillover-flows. We propose that a firm's effective R&D level is given as

$$X_i = x_i + \beta \ \delta_i \ \delta_j \ x_j, \quad i = 1, 2, \ \ i \neq j. \tag{1}$$

By (1) the i'th firm obtains an effective cost reduction X_i, which amounts to its own R&D efforts, x_i and a fraction of its rival's R&D efforts, x_j. In particular the variable δ_i, $0 \leqslant \delta_i \leqslant 1$, $i = 1, 2$ represent the firms' choices of R&D approaches: selection of a higher value of δ_i, $i = 1, 2$ refers to broader (more similar) R&D approaches. That is, a firm's absorptive capacity depends solely on its R&D approach: $AC_i = \delta_i$, $i = 1, 2$. Broader R&D approaches keep firms better connected with the R&D environment, which is equivalent to higher absorptive capacities, i.e. $\partial AC_i/\partial \delta_i > 0$ and

$\delta_i = 1 \Rightarrow AC_i = 1$. Connectedness, however, works if and only if the i'th firm's counterpart $j \neq i$ also connects itself by selecting a broad R&D approach. This means that although if firm i follows a purely broad R&D approach, $\delta_i = 1$ and thus maximizes *potential* knowledge flows firm j might still disconnect itself by adopting an idiosyncratic R&D approach, $\delta_j = 0$. The parameter β, $0 \leqslant \beta \leqslant 1$ refers to the exogenous spillover level commonly employed in the literature.

Each firm seeks to maximize its profit function

$$\pi_i = (a - q_i - q_j)q_i - (A - X_i)q_i - (\gamma/2)x_i^2, \quad i = 1, 2, \quad i \neq j, \tag{2}$$

where the demand function $P(Q) = (a - q_i - q_j)$ determines the market price as a function of the quantity $Q = q_i + q_j$ produced by firm i and j respectively. Firms have the option to lower their constant marginal production cost A by the magnitude of their effective R&D level X_i as given by (1). R&D costs, $(\gamma/2)x_i^2$, ensure decreasing returns to R&D expenditures, x_i.

Third-stage solution Applying backward induction, we first derive the firms' third stage choices. In particular, from equation (2) we obtain the Nash equilibrium in output quantities as:

$$q_i^* = \frac{a - A + 2X_i - X_j}{3}, \quad i = 1, 2, \ i \neq j. \tag{3}$$

Second-stage solution Given the solution to the third stage problem, the second-stage profit-functions can be rewritten as:

$$\pi_i = (q_i^*)^2 - (\gamma/2)x_i^2, \quad i = 1, 2. \tag{4}$$

The first-order condition with respect to R&D expenditures can be expressed by:

$$\frac{\partial \pi_i}{\partial x_i} = \frac{2}{3}q_i^* \left(2\frac{\partial X_i}{\partial x_i} - \frac{\partial X_j}{\partial x_i}\right) - \gamma x_i = 0, \quad i = 1, 2, \quad i \neq j. \tag{5}$$

Note that by (1),

$$\left(2\frac{\partial X_i}{\partial x_i} - \frac{\partial X_j}{\partial x_i}\right) = 2 - \beta\delta_i\delta_j, \quad i = 1, 2, \quad i \neq j. \tag{6}$$

We use (3) and (6) to solve (5) for the i'th firm's optimal expenditure level

$$x_i^* = \frac{2(a-A)(2-\beta\delta_i\delta_j)}{\Psi_i}, \quad i=1,2, \quad i \neq j, \tag{7}$$

where

$$\Psi_i = 9\gamma - 2(2-\beta\delta_i\delta_j)(1+\beta\delta_i\delta_j) \geqslant 0, \quad i=1,2, \quad i \neq j. \tag{8}$$

Note that we are guaranteed to satisfy second-order conditions if $\gamma > 8/9$ which will be assumed throughout.

First-stage solution Finally, we are interested in the game's first stage solution in which firms non-cooperatively decide about their R&D approaches. We state our findings in

Proposition 1 *The non-cooperative R&D game has two symmetric subgame-perfect Nash equilibria. One involves fairly broad (identical) R&D approaches,*

$$\delta_i^{**}, \quad \textit{with} \ \ 0.94 \leqslant \delta_i^{**} \leqslant 1, \quad i=1,2.$$

Furthermore, δ_i^{**} *satisfies*

$$\delta_i^{**} = 1 \quad \textit{for all } \beta < 0.884, \quad i=1,2.$$

The second one implies purely idiosyncratic R&D approaches,

$$\delta_i^* = 0, \quad i=1,2.$$

Proof. See Appendix.

Throughout we refer to the symmetric subgame perfect Nash equilibria (in pure strategies) simply as equilibria. The Proof of Proposition 1 is contained in the appendix; here we argue by the particular effects which lead to our result. As in the findings of Kamien and Zang (2000), the first-order condition can be described by a direct and a strategic effect. Note that strategic effects which are zero by the second stage solution (envelope theorem) are omitted:

$$\frac{\partial \pi_i}{\partial \delta_i} = \frac{\partial q_i^*}{\partial \delta_i} + \frac{\partial q_i^*}{\partial x_j}\frac{dx_j^*}{d\delta_i}, \quad i=1,2, \quad i \neq j. \tag{9}$$

The direct effect,

$$\frac{\partial q_i^*}{\partial \delta_i} = \frac{\beta \delta_j (2x_j^* - x_i^*)}{3} \underset{i=j}{\geqslant} 0 \tag{10}$$

is non-negative provided that $2x_j^* \geqslant x_i^*$. This means the i'th firm gains directly through the adoption of a broader R&D approach as long as its own expenditures, x_i^* are not too high in proportion to a rival's one, x_j^*. The intuition is that due to broader R&D approaches, firms obtain additional reductions of their marginal production costs without having to incur any additional R&D expenditures. Since δ_i determines not only incoming but also outgoing knowledge flows, however, connectedness for the i'th firm pays off if and only if the amount of knowledge to be received from a rival is sufficiently high. Von Hippel (1987) and Schrader (1990) have reported this pattern in the context of information trading between rivals' employees. Such trading does take place, but only if each engineer considers its counterpart's knowledge to be sufficiently reciprocal. Kultti and Takalo (1998) noted the desirability of symmetric knowledge exchange between competitors by comparing firms' profits in the case of knowledge exchange vs. no knowledge exchange.

Next, we have the familiar 'appropriability term'

$$\frac{\partial q_i^*}{\partial x_j} = \frac{2\beta\delta_i\delta_j - 1}{3} \leqslant 0 \Longleftrightarrow \beta\delta_i\delta_j \leqslant \frac{1}{2}, \quad i = 1,2, \quad i \neq j. \tag{11}$$

This effect is well-known from the research joint-venture literature: a rival's R&D efforts have a positive effect on a firm's profits provided that the overall level of appropriability is sufficiently low and vice versa (recall $\beta \gtrless 0.5$ in the DJ case).

Lastly, what are the effects of a change in δ_i on the rival's optimal R&D expenditures in the game's second stage, x_j^*? By $\gamma > 8/9$ it follows that $(9\gamma - 2(2 - \beta\delta_i\delta_j)^2) > 0$. This suffices to show that

$$\frac{dx_j^*}{d\delta_i} = \frac{2(-a + A)\beta\delta_j(9\gamma - 2(2 - \beta\delta_i\delta_j)^2)}{\Psi_i^2} \leqslant 0, \quad i = 1,2, \quad i \neq j. \tag{12}$$

A broader R&D approach results in lower appropriability and hence reduces the profitability of R&D investments from a rival's point of view.

In order to explore the overall effect of a change of δ_i on profits in (9) it helps to distinguish two cases. First suppose the appropriability term $\partial q_i^*/\partial x_j$ is negative. In this case the overall effect of adopting a broader R&D approach is clearly positive: not only do firms profit from the direct effect in (10), but, in addition, a broader R&D approach by (12) reduces the rival's R&D investments that, by (11), hurt the firm's own profits. From (11) it can be observed that appropriability term is certainly negative if $\beta < 0.5$ or $\delta_i\delta_j < 0.5$. Now suppose the appropriability term $\partial q_i^*/\partial x_j$ is positive which means that the rival's R&D does not hurt but increases a firm's own profits. In this case firms have to trade-off the positive direct effect in (10) against the disincentive a broader R&D approach causes to a rival's R&D investments in (12). Again, by (11) this trade-off can only occur if $\beta > 0.5$ where by Proposition 1 it is assured that within this trade-off the positive direct effect dominates the negative strategic one as long as $\beta < 0.884$ or $\delta_i < 0.94$. Only if the negative strategic effect eventually dominates the direct effect, if $\beta = 1$ say, do firms counteract by choosing a slightly more specific R&D approach than $\delta_i = 1$.

The derivation of the second equilibrium is as follows. Note that by (10) and (12) $\partial\pi_i/\partial\delta_i = 0$ for $\delta_j = 0$. Clearly, if only one of the firms chooses a purely firm-specific R&D approach by (1) any strategic interaction concerning R&D approaches is ruled out, and effective R&D reduces to x_i. That is, neither firm can profitably deviate from a given profile $\delta_i^* = \delta_j^* = 1$. This result is well known from Kamien and Zang (2000), notably for the same reasons (see below).

On the selection of one equilibrium As we have identified two Nash equilibria in pure strategies, we are now interested to ascertain which is more desirable from the firms' point of view and hence which is more likely to determine the industry outcome. Our arguments are based on Pareto and risk dominance. Throughout we make use of

Definition 1 *Let I denote the case in which firms adopt broad identical R&D approaches,* $\delta_i = 1, \;\; i = 1, 2$ *and let S denote the case in which firms select a purely specific R&D approach,* $\delta_i = 0, \;\; i = 1, 2.$

Furthermore, note the following comparative statics properties of symmetric profits:

Lemma 1 *Symmetric profits, $\pi_i^\ell = \pi_j^\ell = \pi^\ell$, $\ell = I, S$ satisfy*

$$\frac{\partial \pi^I}{\partial \beta} > 0 \quad \textit{for all } \beta < \hat{\beta}, \quad 0.884 \leqslant \hat{\beta} \leqslant 1, \quad i = 1,2, \tag{13}$$

and

$$\frac{\partial \pi^I}{\partial \beta} < 0, \quad \textit{for all } \beta > \hat{\beta}, \quad 0.884 \leqslant \hat{\beta} < 1, \quad i = 1,2. \tag{14}$$

Moreover,

$$\frac{\partial \pi^S}{\partial \beta} = 0, \quad \textit{for all } \beta, \quad i = 1,2, \tag{15}$$

and

$$\pi^I = \pi^S, \quad \textit{for } \beta = 0, \quad i = 1,2. \tag{16}$$

Proof. See Appendix.

Having these results at hand we can state

Proposition 2 *The equilibrium involving broad (identical) R&D approaches, δ_i^{**}, (weakly) Pareto dominates the equilibrium for idiosyncratic R&D approaches, δ_i^*.*

Proof. To show that $\pi(\delta^{**}) \geqslant \pi^S$ we first show that symmetric first stage profits satisfy $\pi^I > \pi^S$ for the special cases of $\beta = 1$ and thereafter derive $\pi^I > \pi^S$ for $0 < \beta < 1$. It follows then that $\pi(\delta^{**}) \geqslant \pi^I$ whereas $\pi(\delta^{**}) = \pi^I = \pi^S$ if $\beta = 0$. Symmetric first stage profits are given by

$$\pi^\ell = (q^{*\ell})^2 - \frac{1}{2}\gamma(x^{*\ell})^2, \quad \ell = I, S \tag{17}$$

where the star indicates the third stage and the second stage Nash equilibrium respectively. In particular, if $\beta = 1$ by (1) and (3) we have

$$q^{*I} = \frac{a - A + 2x^{*I}}{3}, \tag{18}$$

and

$$q^{*S} = \frac{a - A + x^{*S}}{3}, \tag{19}$$

where by (7),

$$x^{*I} = \frac{2(a-A)}{9\gamma - 4}, \tag{20}$$

and

$$x^{*S} = \frac{4(a-A)}{9\gamma - 4}. \tag{21}$$

It follows that $\pi^{*I} > \pi^{*S}$ since $x^{*I} < x^{*S}$, but upon substitution of (20) in (18) and (21) in (19), $q^{*I} = q^{*S}$. Given this, cases $\beta < 1$ follow by Lemma 1. In particular, $0 < \beta < \hat{\beta} \Longrightarrow \pi^I > \pi^S$ as $\pi^I = \pi^S$ if $\beta = 0$ and $\partial\pi^S/\partial\beta = 0$, whereas $\partial\pi^I/\partial\beta > 0 \Longleftrightarrow \beta < \hat{\beta}$. Next, $\beta > \hat{\beta} \Longrightarrow \pi^I > \pi^S$ because $\pi^I > \pi^S$ if $\beta = 1$ and $\partial\pi^S/\partial\beta = 0$, whereas $\partial\pi^I/\partial\beta < 0 \Longleftrightarrow \beta > \hat{\beta}$. Next, $\pi(\delta^{**}) \geqslant \pi^I$ follows by the Proof of Proposition 1: $\delta^{**} < \delta^I \Longleftrightarrow d\pi/d\delta < 0 \; \forall \; \delta > \delta^{**}$. Finally, if $\beta = 0 \Longrightarrow \pi(\delta^{**}) = \pi^I = \pi^S$ from Proposition 1 ($\pi(\delta^{**}) = \pi^I$) and Lemma 1 ($\pi^I = \pi^S$). ■

The intuition behind these results is that the selection of appropriability through R&D approaches allows firms to free themselves from dilemmas of over- and underinvestment in R&D respectively. This may be observed by considering the appropriability to be determined solely through R&D approaches (i.e. $\beta = 1$).

If firms selected purely specific R&D approaches and thereby allowed no spillovers to occur, they would be forced to invest aggressively: an exclusive R&D investment gives the innovator a competitive advantage at the commercialization stage, while the non-innovator's position in the product market would be worse than it otherwise would be. The result is well-known: both firms end up with high R&D investments that are less profitable as compared to the case in which neither of them had actually engaged in R&D. However, 'precommitment to weak appropriability' essentially frees firms from this dilemma as both the incentive to gain an exclusive competitive advantage and (as a result) the threat of a considerable disadvantage diminish. As a result, R&D investments are reduced when firms choose broader R&D approaches[8].

[8] Whether or not a simultaneous reduction of appropriability (i.e. more spillovers) and equilibrium R&D investments reduces technological progress and in turn lessens product-market-competiveness depends on the way in which spillovers enter the R&D production function. Amir (2000) provides a seminal discussion of this pattern and Hauenschild

The logic behind the underinvestment case follows by similar arguments. If R&D approaches were identical, firms would have to cut back on bilaterally profitable R&D investments because they would risk a one-sided reduction of their rival's investments. Free-riding pays off in this case because of the weak appropriability regime and (convex) R&D costs. 'Precommitment to higher appropriability' through more specific R&D approaches now protects investments and eliminates under-investment[9]. That is, the equilibrium choices of R&D approaches yield the profit-maximizing appropriability regime given uncoordinated equilibrium R&D investment decisions.

In contrast, if firms coordinate their decisions at the R&D stage, they are able to internalize the benefits from each other's R&D and *therefore* maximize spillover flows between each other[10]. The crucial difference between competitive and cooperative firms adopting broader (up to identical) R&D approaches is that competitive ones reduce their R&D investments as a result, whereas cooperative investments increase if appropriability decreases.

It remains to be validated that firms also prefer the equilibrium involving broad (identical) R&D approaches, δ_i^{**}, with respect to risk dominance. In doing so we restrict our attention to the 2×2 game which follows by considering solely the firms' equilibrium choices as reasonable strategies. Risk dominance of δ_i^{**} follows then straightforwardly if one keeps in mind that the defection outcome, at which i chooses δ_i^{**} whereas $j \neq i$ adopts δ_j^*, yields the same payoffs for i *and* j as the case in which both play δ_i^*. This payoff structure is displayed below. The proposed payoffs follow by (1), since, if only one of the firms adopts the purely idiosyncratic R&D approach, $\delta_i = \delta_i^* = 0$, each firm's effective R&D level collapses to x_i. Accordingly in this case both

(2004) an extension to R&D with uncertainty. Anberci et al. (2003) give an alternative interpretation by the explicit introduction of complementarity into firms' R&D activities.

[9] Again, following the model assumptions this happens only in a very limited parameter-range.

[10] It might be easily checked that Kamien and Zang's solution for the cooperative case (firms choose purely general R&D approaches) also applies for our set-up. Calculations are omitted for the sake of brevity.

firms earn $\pi^S \leqslant \pi(\delta^{**})$.

	δ_j^{**}	$\delta_j^* = 0$
δ_i^{**}	$\pi(\delta^{**})$, $\pi(\delta^{**})$	π^S, π^S
$\delta_i^* = 0$	π^S, π^S	π^S, π^S

Payoff structure if firms select one of the two Nash equilibria.

We summarize these considerations in

Proposition 3 *In the 2 × 2 game in which each player's strategies are given by the equilibrium choices, δ_i^* and δ_i^{**}, $i = 1, 2$, the equilibrium for broad (identical) R&D approaches, δ_i^{**}, risk dominates the equilibrium for idiosyncratic R&D approaches, δ_i^*.*

Proof. For any positive probability that j selects δ_j^{**}, i is strictly prefers selecting δ_i^{**} instead of δ_i^*, since $\pi_i(\delta_i^{**}, \delta_j^{**}) = \pi(\delta^{**}) \geqslant \pi^S = \pi_i(\delta_i^{**}, \delta_j^*) = \pi_i(\delta_i^*, \delta_j^*)$, $i = 1, 2$, $i \neq j$. ■

We may conclude that the introduction of R&D approaches provides a ready interpretation of how firms manage to share their knowledge without exposing themselves to the risk of receiving less information in return. Essentially, it is a firm's ability to influence both *incoming* and *outgoing* knowledge flows at the same time that leads to our results[11].

3 Relationship to Kamien and Zang's model

Kamien and Zang have found that competing firms chose purely idiosyncratic R&D approaches - just the opposite result from ours. Thus, the question arises whether this divergence simply stems from the fact that we have focused on absorptive capacity in terms of *R&D approaches* but have neglected the relationship between absorptive capacity and *internal investment levels.* In this section, we intend to demonstrate that this is not the case. However, it is not our purpose to re-examine the complete analysis of Kamien

[11] In contrast, Poyago-Theotoky (1999) derives reversed results. In her knowledge-sharing model, firms are assumed to provide *outgoing* knowledge flows only. Not surprisingly, competing firms make no use of this option.

and Zang's competitive case. Admittedly, we have not succeeded in providing an explicit solution due to intractable first-stage first-order conditions. Nonetheless, it is possible to derive simulation results from which we present two examples[12].

Recall the effective R&D level as presupposed by Kamien and Zang[13]

$$X_i^K = x_i + (1-\delta_i^K)(1-\delta_j^K)\beta x_i^{\delta_i^K} x_j^{1-\delta_i^K}, \quad i=1,2, \quad i \neq j. \tag{22}$$

As mentioned above in Kamien and Zang's representation of a firm's effective R&D level X_i^K, firm i's absorptive capacity $AC_i = (1-\delta_i^K)x_i^{\delta_i^K}$ depends on both firm i's internal R&D x_i and its R&D approach δ_i^K, where, for computational reasons, $\delta_i^K = 1-\delta_i$. Accordingly, in Kamien and Zang $\delta_i^K = 0$ refers to purely broad R&D approaches and $\delta_i^K = 1$ to purely idiosyncratic R&D approaches, precisely the opposite interpretation to that in our paper[14].

We are interested in the behavior of Kamien and Zang's first-order condition for the competitive case (see equation (21) in their paper, superscript K is omitted),

$$\frac{\partial \pi_i}{\partial \delta_i} = \frac{\partial q_i^*}{\partial \delta_i} + \frac{\partial q_i^*}{\partial x_j}\frac{dx_j^*}{d\delta_i} = 0, \quad i=1,2, \quad i \neq j. \tag{23}$$

In Kamien and Zang's model the second stage Nash equilibrium cannot be solved for $x_i \neq x_j$ explicitly but only for symmetric values, $x_i^* = x_j^* = x^*$ (see (14)K). In order to derive $dx_j^*/d\delta_i$ we thus totally differentiate both firm i's second-stage first-order condition $\partial \pi_i/\partial x_i = 0$ (equation (12)K) and the analogous first-order condition for firm j, $\partial \pi_j/\partial x_j = 0$ with respect to δ_i.

[12] An extended analysis is available from the author upon request.

[13] For the remainder, superscript K refers to Kamien and Zang (2000).

[14] For a detailed discussion of Kamien and Zang's model set-up the reader is referred to the original paper.

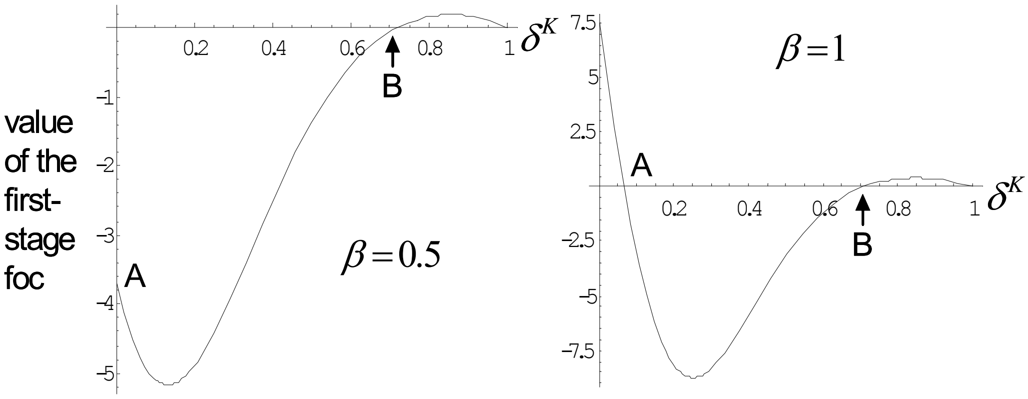

Figure 1: Symmetric (non-cooperative) first-stage first-order conditions in the Kamien and Zang model as a function of R&D approaches, $\delta_i^K = \delta_j^K = \delta^K, i = 1, 2$.

This yields two equations which can be solved for[15]

$$
\begin{aligned}
dx_j^*/d\delta_i \quad = \quad & [(2\frac{\partial q_i^{*2}}{\partial \delta_i \partial x_i} + 2q_i^* \frac{\partial^2 q_i^*}{\partial \delta_i \partial x_i})(2\frac{\partial q_j^{*2}}{\partial x_i \partial x_j} + 2q_j^* \frac{\partial^2 q_j^*}{\partial x_i \partial x_j}) \\
& -(2(\frac{\partial q_i^*}{\partial x_i})^2 + 2q_i^* \frac{\partial^2 q_i^*}{\partial x_i^2} - \gamma)(2\frac{\partial q_j^{*2}}{\partial \delta_i \partial x_j} + 2q_j^* \frac{\partial^2 q_j^*}{\partial \delta_i \partial x_j})] \\
& * 1 \ / \ [(2(\frac{\partial q_i^*}{\partial x_i})^2 + 2q_i^* \frac{\partial^2 q_i^*}{\partial x_i^2} - \gamma)(2(\frac{\partial q_j^*}{\partial x_j})^2 + 2q_j^* \frac{\partial^2 q_j^*}{\partial x_j^2} - \gamma) \\
& \quad -(2\frac{\partial q_i^{*2}}{\partial x_j \partial x_i} + 2q_i^* \frac{\partial^2 q_i^*}{\partial x_j \partial x_i})(2\frac{\partial q_j^{*2}}{\partial x_i \partial x_j} + 2q_j^* \frac{\partial^2 q_j^*}{\partial x_i \partial x_j})]
\end{aligned}
\quad (24)
$$

Now the derivatives of (24) and (23) can be computed and the first-order condition (23) can be plotted as a function of $\delta_i^K = \delta_j^K = \delta^K$. For the sake of brevity we depict only two examples each assuming parameter values $a = 200$, $A = 100$, and $\gamma = 2$ where the left graph of Figure 1 represents the case of $\beta = 0.5$ and the right one the case of $\beta = 1$[16].

There are three relevant points to discuss with respect to the first-order condition. First, the first-order condition goes from positive to negative at $\delta_i^K = 1$, this constituting the Nash equilibrium for purely idiosyncratic R&D

[15] This formulation differs from equation (22) in the Kamien and Zang paper. While (22) is correct in the special case of $\delta_i^K = 1$, the authors agreed that their calculation of $dx_j^*/d\delta_i$ and the subsequent discussion of the first-order condition are in general incorrect.

[16] Alternative parameter values do not change the patterns described below. Again, extensive simulations are available from the author upon request.

approaches. It is the solution discussed by Kamien and Zang and reflects the case in which strategic interaction concerning R&D approaches vanishes if only one of the firms adopts such a R&D approach:

$$X_i^K\big|_{\delta_j^K=1} = x_i, \quad i = 1, 2, \quad i \neq j. \tag{25}$$

Accordingly, the i'th firm cannot profitably deviate from a given equilibrium profile $\delta_i^* = \delta_j^* = 1$. Secondly, the first-order conditions are zero at point B which however constitutes a profit-minimum as first-order conditions run from negative to positive in B. Thirdly, we have point A. In the case of not too high exogenous spillovers (e.g. $\beta = 0.5$) the first-order condition remains negative left from point B. This means that every move closer to a rival's R&D approach ($\delta_i \rightarrow 0$) has a positive impact on profits and establishes $\delta_i^K = 0$ as a corner solution. Next to this corner solution, as displayed by the right graph of Figure 1, an interior solution may exist, though with the reservation that exogenous spillovers are already high (e.g. $\beta = 1$). It is worth noting that even in case of $\beta = 1$, firms still adopt fairly broad R&D approaches. Analogous to our results (see Proposition 1) we summarize the following:

Remark 1 *If absorptive capacity is determined by both internal R&D and R&D approaches (Kamien and Zang case), the non-cooperative R&D game has two symmetric Nash-equilibria: one for broad (identical) R&D approaches, and one for idiosyncratic ones.*

With respect to Pareto and risk dominance, Propositions 2 and 3 hold for the Kamien and Zang case respectively, i.e. the Nash equilibrium for broad identical R&D approaches constitutes the global profit maximum and risk dominates the one for idiosyncratic R&D approaches. This follows by a comparison of each model's effective R&D levels evaluated at the equilibrium profiles[17]:

$$X_i\big|_{\delta_i^S=\delta_j^S=0} = X_i^{K\ S}\big|_{\delta_i^{K\ S}=\delta_i^{K\ S}=1} = x_i, \quad i = 1, 2, \quad i \neq j, \tag{26}$$

[17] From the right-hand graph of Figure 1 it is also apparent that $\delta^{K\ **} > 0 \Longleftrightarrow d\pi^K/d\delta^K > 0$ for all $\delta^K < \delta^{K\ **}$. Thereby $\pi(\delta^{K\ **}) \geqslant \pi^I$.

$$X_i|_{\delta_i^I=\delta_j^I=1} = X_i^{K\ I}|_{\delta_i^{K\ I}=\delta_i^{K\ I}=0} = x_i + \beta x_j, \quad i = 1, 2, \quad i \neq j. \tag{27}$$

Recall that model set-ups only differ in the firms' effective R&D levels X_i and X_i^K respectively. But by Remark 1, (26) and (27) this difference vanishes endogenously through the firms' choices of R&D approaches. In fact, by (27) the DJ model set-up is obtained if we focus on the global profit maximum. We can thus conclude

Remark 2 *Based on Pareto and risk dominance both Kamien and Zang's and our model predict that firms select broad (identical) R&D approaches. In turn both models' predictions concerning equilibrium R&D efforts, output quantities and profits correspond to the predictions of the DJ model.*

4 Conclusions

We find that competing firms tend to adopt identical R&D approaches to achieve a high degree of connectedness which in turn reduces R&D appropriability. This pattern is in accordance with anecdotal evidence, but has been shown analytically only in the context of research joint ventures (i.e. joint profit maximization). Next to direct gains (i.e. costless cost reductions) the incentive to achieve low appropriability is due to a dilemma which otherwise forces firms to invest aggressively in R&D.

The introduction of absorptive capacity in terms of *R&D approaches* is unlikely to change the predictions of the DJ model. In fact it turns out that both settings - the cooperative one (which was not the challenge here) and the competitive one - ultimately lead to those identical broad R&D approaches that imply the DJ formulation. Consequently, the DJ formulation of a firm's effective R&D level need not implicitly assume "that the firms have formed a research joint venture" as stated by Kamien and Zang (2000).

It is important to emphasize that our results are driven by the R&D approaches' property of simultaneously affecting incoming and outgoing knowledge flows. This explanation closes the gap between previous work that reported information exchange between competitors (e.g. Baumol, 2000, Kultti and Takalo, 1998) on the one hand, and those who found no such exchange as an equilibrium strategy (e.g. Poyago-Theotoky, 1999, Kamien and Zang,

2000) on the other. With Kultti and Takalo (1998), we conclude that whenever firms find a device to assure the simultaneous sending and receiving of information they will pursue this strategy, whereas they will not if they face any risk of receiving less information in return (Poyago-Theotoky, 1999). The application of absorptive capacity and R&D approaches is but the first step to explain how even competing firms implicitly share their knowledge. Apparently not only the *incentive* itself, but the *way* firms exchange information is a promising field for future research. For instance, a framework that incorporates trust in this context might be helpful to obtain new insights (e.g. Bönte 2003).

Our analysis supplements recent findings by Anbarci et al. (2002). In contrast to previous analyses (e.g. Kamien, Müller and Zang, 1992) they point out that (exogenous) knowledge flows among competitors may improve welfare as compared to perfectly appropriable R&D, provided that the degree of complementarity in R&D outputs is sufficiently high. Yet the question of if and how competing firms actually implement this mode of collaboration has been left unresolved.[18] Identical R&D approaches provide an interpretation of how competing firms manage to foster knowledge flows between each other.

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[18] Amir (2000) already explained the role of complementarity in R&D outputs by comparison of the DJ and the KMZ framework.

Appendix

Proof of Proposition 1 First, suppose that $\beta \wedge \delta_i \wedge \delta_j \neq 0$. Note that for $\delta_i^{**},\ \ i = 1, 2$ constituting a Nash equilibrium it suffices to show that δ_i^{**} is a best response to $\delta_j^{**},\ \ i \neq j$. As π_i is continuously differentiable with respect to δ_i,

$$\frac{d\pi_i}{d\delta_i} > 0 \quad \text{for all } \delta_i < \delta_i^{**}, \quad i = 1, 2, \quad i \neq j, \tag{28}$$

implies δ_i^{**} being a better response than any $\delta_i < \delta_i^{**}$. The sign of the derivative $d\pi_i/d\delta_i$ can by (9) be computed as

$$\operatorname{sgn} \frac{d\pi_i}{d\delta_i} = \operatorname{sgn} \frac{2(-a + A)\beta\delta_j\Omega_i}{3(\Psi_i)^2}, \tag{29}$$

and thus $d\pi_i/d\delta_i > 0 \Leftrightarrow \Omega_i < 0$, where

$$\Omega_i = 16 - 24\beta\delta_i\delta_j + 12(\beta\delta_i\delta_j)^2 - 2(\beta\delta_i\delta_j)^3 - 27\gamma + 27\beta\delta_i\delta_j\gamma. \tag{30}$$

Next, define $\Omega_i' := \Omega_i(\gamma = 8/9)$ and note that $\Omega_i' < 0 \Rightarrow \Omega_i < 0$ as by the second-order condition $\gamma > 8/9$ and $\partial\Omega_i/\partial\gamma \leqslant 0$ for all $\beta \vee \delta_i \vee \delta_j \leqslant 1$. Then we have

$$\Omega_i' = 2(-4 + 6(\beta\delta_i\delta_j)^2 - (\beta\delta_i\delta_j)^3). \tag{31}$$

Since $\partial\Omega_i'/\partial k > 0,\ k = \beta, \delta_i, \delta_j$ define $\Omega_i'' := \Omega_i'(\beta = 1, \delta_j = \delta_i = \delta)$ and we know that $\Omega_i'' < 0 \Rightarrow \Omega_i' < 0$ as long as we look for simultaneously given best responses. The sign of $d\pi_i/d\delta_i$ is thus determined by

$$\Omega_i'' = 2(-4 + 6\delta^4 - \delta^6). \tag{32}$$

Note that Ω_i'' has a unique root for $\delta \approx 0.94$. In particular, $\Omega_i'' < 0 \Leftrightarrow \delta < 0.94$ and thereby $\delta < 0.94 \Rightarrow d\pi_i/d\delta_i \geqslant 0$. This means that any symmetric Nash equilibrium in R&D approaches will satisfy $\delta^{**} \geqslant 0.94$. Moreover, existence and uniqueness follows from (28) in the case of $\delta^{**} = 1$ and from (32) in the case of $\delta^{**} < 1$ since $d\pi_i/d\delta_i < 0$ only if $\Omega_i'' > 0$. We conclude by remarking that given $d\pi_i/d\delta_i$ changes its sign in $\delta^{**} < 1$ then $d\pi_i/d\delta_i$ goes from positive to negative and hence π_i is maximized. This completes the proof of the first claim.

The second claim follows immediately by similar arguments. In particular, define $\Omega_i''' := \Omega_i'(\delta_j = \delta_i = 1)$. Thus,

$$\Omega_i''' = 2(-4 + 6\beta^2 - \beta^3). \tag{33}$$

The unique root of Ω_i''' is $\beta \approx 0.884$. Hence, $\beta < 0.884 \Rightarrow d\pi_i/d\delta_i > 0$ and thereby establishes $\delta^{**} = 1$ being a corner solution. ■

Proof of Lemma 1 By (2), (3) and (7) we can compute (subscripts are omitted as we are interested in symmetric solutions)

$$\text{sgn}\frac{\partial \pi^I}{\partial \beta} = \text{sgn}\frac{16 - 24\beta + 12\beta^2 - 2\beta^3 - 27\gamma + \beta 27\gamma}{(4 + 2\beta - 2\beta^2 - 9\gamma)^3}. \tag{34}$$

Since $\gamma > 8/9$ by the second stage second-order condition, the denominator of (34) is always negative. Note that the numerator of (34) is decreasing in γ (for all $\beta < 1$) and for $\gamma = 8/9$ its unique root is $\beta \approx 0.884$, (34) being negative for $\beta < 0.884$. Thereby, $\partial\pi^I/\partial\beta > 0$, for all $\beta < 0.884$. The term $(-27\gamma + \beta 27\gamma)$ indicates that the numerator tends to be negative for $\beta > 0.884$ due to higher values of γ ($\gamma > 8/9$) whereby the uniqueness of the root in $\beta > 0.884$ remains. Moreover, it is evident that the numerator of (34) is certainly positive for $\beta = 1$. By continuity, this establishes the first and the second claim of Lemma 1. The rest of the proof is straightforward following arguments similar to those constituting $\delta^* = 0$ as a Nash equilibrium. In particular, $\pi_i^S/\partial\beta = 0$ because π_i^S itself cancels out any effects from β and for $\beta = 0$, likewise any effects from differences in δ are cancelled out; hence $\pi_i^S\big|_{\beta=0} = \pi_i^S\big|_{\beta=0}$. ■

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Cooperation or Competition in R&D When Innovation *and* Absorption Are Costly

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Abstract

This paper analyses cost-reducing R&D investments by firms that behave non-cooperatively or cooperatively. Firms face a trade-off between allocating their R&D investments to innovate or to imitate (absorb). We find that the non-cooperative behavior not only induces more imitation (absorption) but also, for the most part, more innovation investments. Only the cooperative behavior, however, ensures that R&D investments are allocated efficiently to innovation and to imitation (absorption) in the sense that any given amount of industry-wide cost-reduction is obtained for the minimum overall R&D costs.

JEL Classification: O31, O32, L13

Keywords: Absorptive Capacity, Cooperation; Spillovers; Innovation; Imitation; R&D.

1 Introduction

"European industry is investing too little in research and development (R&D). Governments want to see Europe's R&D investment rise from its current 1.9% of GDP to 3% by 2010. And industry, they say, should provide most of that extra investment" (The Economist 2003, "Reinventing Europe"). Yet to achieve this ambitious goal, policy makers might at least want to provide appropriate investment incentives. Aimed at restoring firms' incentives to engage in an activity whose results are only imperfectly appropriable due to knowledge spillovers, the European Commission has not only relaxed competition law to allow cooperative R&D among competitors[1] but encourages the formation of research joint ventures (RJVs) explicitly. Selected RJVs are receiving up to 50% of their costs whereby the Commission estimated that more than 5000 RJVs were funded in the fourth Framework Programme (1994-1998)[2]. Not surprisingly Caloghirou and Vonortas (2004) report a considerable increase of RJVs in Europe since the mid 1980s. Hagedoorn (2002) and Vonortas (1997) find the same pattern for worldwide and for U.S. partnerships.

The increasing willingness to engage in cooperative R&D arguably reflects some net benefit to the participating firms, arising, for instance, from R&D cost and risk sharing, minimization of transaction costs and economies of scale and scope[3]. Whether or not cooperative R&D does indeed stimulate firms' incentives to *invest* in R&D is far less definite and, by the same token, increasing technological progress and consumers' surplus are less clear cut.

[1] Barker and Cameron (2004) discuss block exemptions from Articles 81 and 82 of the EC Treaty (formerly Articles 85 and 86). U.S. policy moved in the same direction with the 1984 enactment of the National Cooperative Research Act (NCRA) to allow cooperation in 'earlier' stages of R&D. In 1993 the National Research and Production Act (NCRPA) extended cooperation to product development, prototyping and production (Geroski 1993, Vonortas 1997).

[2] The sixth Framework Programme (2002-2006) has a budget of 17.5 billion Euro, the most of which is devoted to RJV promotion, see Barker and Cameron (2004).

[3] Based on three categories of literature (i.e. transaction costs, strategic management and industrial organization), Hagedoorn et al. (2000) provide an overview on theoretical arguments related to incentives to form research partnerships and expected results from research partnerships.

Seminal theoretical contributions[4] by D'Aspremont and Jacquemin (1989) and Kamien et. al. (1992) seem to confirm that cooperative R&D induces more investments if knowledge spillovers are substantial: firms agree on high R&D investments that maximize their joint profits instead of trying to free-ride on each others' efforts. Our analysis reveals that this R&D stimulating effect of RJVs is significantly reduced (and may even vanish completely) if one accounts for some *specific* costs of receiving spillovers.

Since the investment stimulating effect of cooperative R&D depends crucially on the spillover-rate, previous recent theoretical studies by Kamien and Zang (2000)[5], Kaiser (2002 b), Grünfeld (2003), Martin (2003) and Leahy and Neary (2004) have emphasized[6] that knowledge spillovers, in turn, depend on the firms' ability to "identify, assimilate, and exploit knowledge from the environment", i.e. on the firms' absorptive capacities as defined by Cohen and Levinthal (1989). These studies commonly incorporate the concept of absorptive capacity by tying the receipt of spillovers to a firm's own R&D. This way, however, a firm *receives* valuable and applicable knowledge (i.e. R&D or process-innovations) if and only if the firm itself *creates* valuable and applicable knowledge for other firms to absorb.

Empirical evidence points in a different direction. Mansfield et al. (1981) identify specific costs of imitation as "all costs of developing and introducing the imitative product, including applied research, product specification, pilot plant or prototype construction, investment in plant and equipment, and manufacturing and marketing start-up. (If there was a patent on the innovation, the cost of inventing around it is included)". On average these costs represent up to 65% of the respective innovation cost. Link and Neufeld (1986) find out that those who are in charge of R&D "employ different R&D strategies, generally choosing between innovation or imitation" and Rosenberg and Steinmueller (1988) note that Japanese firms are very successful in the absorption of American firms' innovations whereas the Americans, "very

[4] See De Bondt (1996) for a survey. Kaiser (2002 a) provides an empirical study on cooperative and non-cooperative R&D in the German service sector.

[5] In contrast to Kamien and Zang's prediction, Wiethaus (2005) demonstrates that non-cooperative firms tend to adopt identical R&D approaches, just like cooperative firms. He also extends this finding to Kamien and Zang's original model.

[6] Campisi et al. (2001) focus on the role of absorptive capacity in R&D competition.

good at innovation", are rather poor imitators. Moreover Henderson and Cockburn (1996) identify "costs of maintaining absorptive capacity, which take the form here of large numbers of small and apparently unproductive programs". These observations suggest that a firm will imitate/absorb contingent on specific costs rather than contingent on an own innovation.

The distinction between innovation and imitation/absorption alters previous results regarding the efficiency of non-cooperative and cooperative R&D investment behavior and thus sheds some new light on the still prevalent question: "to what extent R&D cooperation is preferred to R&D competition by both firms and societies [...]" (Sena 2004). With specific costs of imitation/absorption cooperation only induces higher technological progress and consumer surplus than the non-cooperative behavior if patent protection is extremely weak and, at the same time, imitation/absorption is rather easy from a technological point of view[7]. However, we also detect a new, welfare enhancing, attribute of cooperative R&D investment decisions: resources targeted to innovate on the one hand and those targeted to imitate/absorb on the other are allocated efficiently in the sense that any given amount of cost reduction is obtained for the minimum overall investment costs.

Kanniainen and Stenbacka (2000) also analyze the strategic interaction between innovating and imitating firms. The authors focus, however, on the implications of their results on subsidy and patent policy and do not address how investment incentives are altered in the case of cooperation. The same applies for Takalo's (1998) model of innovation and imitation. Cassiman et al. (2002) emphasize the role of investments in specific types of R&D such as applied R&D, basic R&D and investments in intellectual property protection. In contrast to our work their investigation is on non-cooperative investment incentives of an incumbent firm facing a competitive fringe. Imitative and

[7] Based on the assumption that absorption requires no efforts at all, D'Aspremont and Jaquemin (1989) found R&D cooperation to induce more efforts than R&D competition if 50% of a firm's R&D results spill over to its competitor in the product market. According to Grünfeld (2003) this critical spillover rate shifts from 0.5 to about 0.618 due to the introduction of imitation/absorption as a function of innovation. With imitation/absorption as a function of specific investments like in our model, cooperation might not at all induce higher technological progress than the non-cooperative behaviour even if spillovers are perfect.

innovative R&D has, moreover, been analyzed by Hammerschmidt (1999) for the non-cooperative case. If exogenous spillovers increase, imitative R&D will increase whereas innovative R&D will decrease. On the one hand, we confirm her results, though within a different model set-up (see below). On the other hand, we extend her findings by the comparison of the non-cooperative case with the cooperative one in terms of technological progress and allocative efficiency of R&D investments.

The remainder of the paper is organized as follows. In section 2 we introduce a two stage duopoly model. We describe how each firm's first stage investment in innovation and imitation/absorption translates into some reductions of production costs. Then, for given amounts of cost reductions, we derive the second stage Nash equilibrium in output quantities. Section 3 deals with the firms' non-cooperative first-stage decisions. We formally (and separately) analyze firms' incentives to innovate and to imitate/absorb. This yields intermediate results helping to explain intuitively the firms' investment behavior. The Nash equilibrium is described by numerical solutions. Section 4 proceeds in a similar fashion proposing, however, a cooperative solution in the firms' investment decisions. In section 5 we employ the results of 3 and 4 in order to establish the welfare implications of non-cooperative vs. cooperative investment behavior in terms of technological progress, consumer surplus and allocative efficiency of R&D investments. Section 6 concludes and suggests directions for future research.

2 The Model

We consider a two-period duopoly model. In period 1, two identical firms $i = 1, 2$ determine their investment decisions aimed at process innovation. These decisions are analyzed for both non-cooperative and cooperative behavior[8]. In the second period firms compete in output-quantities, q_i.

First period: investment in cost reductions Each firm can reduce its constant marginal production costs, C, by a certain amount, X_i (cost

[8] We refer to the cooperative case if firms coordinate their decisions in order to maximize their joint profits, ceteris paribus.

reduction), through its efforts[9] to generate a process-innovation, A_i, and its efforts, B_i, to absorb/imitate the rival's innovation, A_j.

We define innovation efforts, A_i, to include all activities that lower a firm's production costs through the *creation and exploitation of new knowledge*. In turn innovation efforts not only benefit the ith firm but also enhances the knowledge-pool potentially available for i's rival j. Most obviously innovation efforts contain some kind of applied R&D.

We define imitation/absorption efforts, B_i, to include all activities that lower a firm's production costs through the *assimilation and exploitation of externally created new knowledge* (innovations). These efforts include improvements of a firm's absorptive capacity in general (Cohen and Levinthal 1989) and all investments to implement the imitation in particular (Mansfield et al. 1981). In turn innovation/absorption efforts do not per se provide any new knowledge for another firm. Simply put the identification and assimilation of new knowledge in form of a patent, its subsequent exploitation in form of reverse-engineering and its application to commercial ends do certainly require R&D but do not require taking out a new patent or some other sort of new knowledge. Also, instead of pushing R&D for one specific application a firm may enhance its absorptive capacity by gaining a fuller understanding of the broader scope of the research field. In this sense Rosenberg (1990) highlights the role of basic research "for evaluating the outcome of much applied research and for perceiving its possible implications" and to "understand, interpret and to appraise knowledge that has been placed upon the shelf" (see Cassiman et al. 2003 for an application). A firm's absorptive capacity, moreover, "depends on the structure of communication between the external environment and the organization, as well as among the subunits of the organization [...]" (Cohen and Levinthal 1990). Obviously a firm can establish and maintain a well-functioning organization in that sense without benefiting its rival.

The ith firm's cost reduction, X_i, can for example be written as the sum of its own innovation efforts, A_i, and a Cobb-Douglas relationship[10] between

[9]The terms efforts and investments are used synonymously throughout.

[10]The Cobb-Douglas relationship is convenient for analytical tractability and because parameters are easy to interpretate. Employing a CES function would be a more general

its efforts to imitate/absorb, B_i, and another firm's innovation efforts, A_j,

$$X_i = A_i + \beta B_i^{\alpha} A_j^{1-\alpha}, \quad i = 1, 2, \quad i \neq j. \tag{1}$$

As we abstract from uncertainty, innovation *efforts*, A_i, correspond to innovation *results*. Imitation/absorption efforts, B_i, translate into imitation/absorption results, $\beta B_i^{\alpha} A_j^{1-\alpha}$, as a function of exogenous parameters β, $0 \leqslant \beta \leqslant 1$, and α, $0 \leqslant \alpha < 1$ and, of course, A_j.

Note that higher values for α decrease the amount of cost reduction, X_i, that the ith firm obtains for any given level of $B_i \leqslant A_j$ (see Lemma 1), whereas higher values for α (are likely to)[11] reflect an increase the marginal productivity of B_i. The economic interpretation of α is what Cohen and Levinthal (1989) introduced as the difficulty of learning[12]. It is determined by "the complexity of knowledge to be assimilated and the degree to which the outside knowledge is targeted to the needs and concerns of the firm". Difficulty of learning makes imitation efforts, B_i, more critical to the absorption/imitation of a certain amount of A_j. Consequently α is likely to increase the marginal productivity of B_i whereas it reduces i's cost reduction for given values of A_j and B_i, ceteris paribus. The counterpart expression, $(1 - \alpha)$, can be interpreted as the ease of learning, respectively.

A lower value of β, of course, reduces the amount of i's cost reduction for given values of A_j and B_i; in contrast to (a higher) α, however, a lower β decreases the marginal productivity of B_i as well. The parameter β can thus be interpreted as a measure of patent-protection. Stronger (weaker) patent-protection, i.e. a lower (higher) β, decreases (increases) both the

approach, in particular, because it does not imply a substitution elasticicity of unity between B_i and A_j (I am grateful to an anonymeous referee who made this point). However this does not significantly alter the main qualitative results presented in section 5 (see also footnote 20). A robustness check is available from the author upon request.

[11] If B_i is very small compared to A_j, an increase in α may, in fact, decrease the marginal impact of B_i on X_i This is due to the model calibration with $0 \leqslant \alpha < 1$.

[12] Note that Cohen and Levinthal proposed that if learning became more difficult this would always decrease the marginal impact of a firm's own R&D on its absorptive capacity. This is in partial conflict, however, to the equal scale of innovation and imitation in (1) and thus in our model α does, for some parameter constellations not increase the marginal impact of B_i on X_i.

level of another firm's original innovation, A_j, that can be absorbed and the marginal productivity of firm i's efforts to absorb, B_i.

To clarify the difference between the legal dimension, β, and the technological dimension, α, consider the example of biotech drugs which are, despite weak patent protection, difficult to copy as "the process is prone to contamination and is highly variable, making the task complex and costly" (The Economist 2003, "Carbon Copy"). Thus α is relatively high and β is relatively low. Just the opposite seems to be true for conventional drugs where patent protection is relatively strong but once patents expire, it becomes a straightforward task to introduce a generic drug.

In line with the literature we propose that costs of innovation and imitation/absorption are A_i^2 and B_i^2 respectively[13] which formalizes decreasing returns to R&D investments.

Second period: Quantity competition In the product-market firms compete in quantities with linear demand, $P = a - bQ$, where $Q = q_i + q_j$. Initially firms have the same constant marginal production costs, $C_i = C_j = C$. Thus, after innovation and imitation has occurred in the first period, firms produce with constant marginal production costs $C - X_i$ in the second period. The ith firm's profit-function can be expressed by

$$\pi_i = (a - bQ)q_i - (C - X_i)q_i - A_i^2 - B_i^2, \quad i = 1, 2, \quad i \neq j. \tag{2}$$

The second stage Nash equilibrium is

$$q_i^* = (a - C + 2X_i - X_j)/3b, \quad i = 1, 2, \quad i \neq j. \tag{3}$$

Because variations in the parameters a, C and b do not change any of our qualitative conclusions it is convenient to assume $a - C = 1$ and $b = 1$ throughout.

Focusing on the symmetric case the second-stage Nash equilibrium can simply be expressed by

[13] An additional cost-parameter γ, as common in the literature, does not provide further insights and since $\gamma = 1$ guarantees sufficiently concave profit-functions we can leave it out.

$$q^* = (1 + X)/3 = (1 + A + \beta B^\alpha A^{1-\alpha})/3. \tag{4}$$

Equation (4) reflects that in a symmetric equilibrium output quantities, q^*, and profits, $\pi(q^*)$, are ceteris paribus increasing in weaker patent protection, β, and decreasing in the difficulty of learning, α, provided $B < A$ (see Lemma 1). Of course, the higher β and the smaller α the stronger is knowledge diffusion, ceteris paribus, and accordingly the larger is industry wide cost reduction and market size. In the analyses to follow we will refer to q^* as the *market size incentive* to invest in R&D.

3 The non-cooperative investment case

Upon substitution of (3) into (2), the ith firm's first-stage profit function can be written as

$$\pi_i^* = q_i^{*2} - A_i^2 - B_i^2, \quad i = 1, 2, \quad i \neq j, \tag{5}$$

where the first-order conditions,

$$\frac{\partial \pi_i^*}{\partial A_i} = q_i^* \frac{\partial q_i^*}{\partial A_i} - A_i = 0, \quad i = 1, 2, \quad i \neq j, \tag{6}$$

and

$$\frac{\partial \pi_i^*}{\partial B_i} = q_i^* \frac{\partial q_i^*}{\partial B_i} - B_i = 0, \quad i = 1, 2, \quad i \neq j. \tag{7}$$

have to be fullfilled simultaneously. Before we turn to the simultaneous equilibrium we explore the incentives to innovate and the incentives to imitate/absorb separately. For the analyses to follow it is useful to have the following intermediate result at hand:

Lemma 1 *In the symmetric case any profit-maximizing simultaneous solution to the first-order conditions (6) and (7) will satisfy* $B \leqslant A$.

Proof. See appendix.

Incentives to innovate Equation (6) demonstrates that the incentive to innovate is driven by the market size incentive, q_i^*, and a *competitive incentive*, $\partial q_i^*/\partial A_i$, where

$$\frac{\partial q_i^*}{\partial A_i} = \frac{1}{3}(2 - \beta \underbrace{(1-\alpha)\left(\frac{B_j}{A_i}\right)^{\alpha}}_{\substack{\textit{difficulty of learning} \\ \textit{and imitation effect}}}). \tag{8}$$

As mentioned above, the market size incentive to innovate is increasing in weaker patent protection, β, and decreasing in the difficulty of learning, α. Obviously from (8) and well known from the literature the competitive incentive to innovate decreases if patent protection becomes weaker, i.e. β increases. This general pattern is, however, modified by the difficulty of learning and imitation effect in (8). The requirement to exert efforts, B_j, in order to benefit from another one's innovation, i.e. $\alpha > 0$, increases incentives to innovate: because we presume $B_j \leqslant A_i$ by Lemma 1, the difficulty of learning and imitation effect is never larger than 1 and hence the negative term in (8) is never larger as in the case of $\alpha = 0$.[14] Indeed the incentive to secure itself a competitive advantage by the means of original innovations increases with the difficulty of learning, $\partial^2 q_i^*/\partial A_i \partial\alpha \geqslant 0$, unless $\beta = 0$ or $B_j = 0$. Clearly, innovations are not only protected by patent legislation but also by their complexity and the respective costs at which they can be absorbed by others[15].

Based on symmetry, i.e. substitution of q^* for q_i^* in (6) and omitting subscripts in (8), we can state:

Proposition 1 *In the symmetric non-cooperative case, for any given $B < A$ there exists a unique profit-maximizing solution to the firms' first-order*

[14] Of course $\alpha = 0$ constitutes the D'Aspremont and Jaquemin (1988) case.

[15] For instance Cohen et al. (2000) find that patents tend to be the least important means of innovation appropriation in the U.S. manufacturing sector. Similarly Sattler (2003) finds for Germany "that on average patents as well as registered designs are the least effective means of appropriability. Instead, long-term relationships, lead time, complexity of design and secrecy are substantially more effective". Cassiman et al. (2002) explicitly model how a firm may enhance the protection of its innovations by increasing the complexity of product or process design.

conditions (6) in A. Denoting this solution A′ we have

$$sign \frac{\partial A'}{\partial \beta} = sign \left[\left(\left. \frac{\partial q_i^*}{\partial A_i} \right|_{i=j} \right)^2 - (1 - \alpha) \right], \tag{9}$$

and

$$sign \frac{\partial A'}{\partial \alpha} = sign \left[\left(\left(\left. \frac{\partial q_i^*}{\partial A_i} \right|_{i=j} \right)^2 - (1 - \alpha) \right) \ln \left(\frac{B}{A} \right) + 1 \right]. \tag{10}$$

Proof. See appendix.

Proposition 1 states how, for a given level of B, optimal innovation efforts change if both the competitive incentive and the market size incentive are taken into account. Equation (9) reveals that the sign of A' in β depends on the strengths of the (squared) competitive incentive relative to $(1 - \alpha)$, the ease of learning. From (8) we can deduce that the squared competitive incentive ranges between 1/9 and 4/9. Therefore if learning is easy, $(1 - \alpha) > 4/9$, (9) is certainly negative. This is the commonly known case: the decrease in the competitive incentive dominates the increase in the market size incentive. However if learning is rather difficult, say $(1 - \alpha) < 4/9$, then efforts to innovate originally may increase in β which in turn implies that the increase in the market size incentive dominates the decrease in the competitive incentive[16].

The sign of the derivative of A' in α depends by (10) likewise on the interplay between the squared competitive incentive and the ease of learning $(1-\alpha)$. For the case that learning is rather easy, $(1-\alpha) > 4/9$, we have just established that the squared competitive incentive is certainly dominated. Taking into account that $\ln(B/A) \leqslant 0$ we then have that (10) is positive. Accordingly efforts to innovate increase if learning becomes more difficult. This is due to the protection effect which increases the competitive incentives. However if learning is already rather difficult and absorption/imitation efforts B are low relative to A (that is $\ln(B/A)$ gets large), (10) is negative

[16] A more profound analysis of the causes and consequences of this result is beyond the scope of the present paper which aims to compare non-cooperative and cooperative R&D investment incentives with each other. It shall be the subject to future research.

and if learning becomes more difficult this discourages innovation efforts. Now the decrease in the market size incentive dominates the increase in the competitive incentive.

Incentives to imitate/absorb By the first-order condition (7) the firms' imitation efforts, B_i, are, analogous to the previous section, caused by the market size incentive, q_i^*, and the competitive incentive, $\partial q_i^*/\partial B_i$,

$$\frac{\partial q_i^*}{\partial B_i} = \frac{2}{3}\beta\alpha\left(\frac{A_j}{B_i}\right)^{1-\alpha}. \tag{11}$$

The market size incentive to imitate/absorb is, once again by (4), increasing in weaker patent protection, β, and decreasing in the difficulty of learning, α. Alos taking the competitive incentive (11) into account reveals, not too surprisingly, that efforts to imitate/absorb are unambiguously increasing if patent protection becomes weaker. Moreover (11) confirms that the incentive to imitate is increasing in the amount of "knowledge that has been placed upon the shelf" (Rosenberg, 1990), A_j.

Proposition 2 *In the symmetric non-cooperative case, for any given $A > B$ there exists a unique profit-maximizing solution to the firms' first-order conditions (7) in B. Denoting this solution B' we have*

$$\frac{\partial B'}{\partial \beta} > 0, \tag{12}$$

and

$$sign\frac{\partial B'}{\partial \alpha} = sign\left[\left(\frac{1}{2}\left(\left.\frac{\partial q_i^*}{\partial B_i}\right|_{i=j}\right)^2 + \alpha\right)\ln\left(\frac{B}{A}\right) + 1\right]. \tag{13}$$

Proof. See appendix.

Proposition 2 states the comparative statics of B, for a given level of A, if both the market size and the competitive incentives are considered. By (11) it is obvious that (13) is certainly positive if α is sufficiently small whereas (13) is more likely to be negative the larger α and the larger the gap between B and A. Of course, $\alpha > 0$, initiates imitation/absorption incentives in the first place. But also, if it gets too difficult to learn, high returns of imitation/absorption investments in form of cheap external knowledge diminish. By the same token (13) is more likely to be negative (positive) the larger (smaller) A_j is relative to B_i.

Equilibrium characterization Since firms $i = 1, 2$ are identical we consider a symmetric Nash equilibrium in $A_i = A_j = A^*$ and $B_i = B_j = B^*$ where A^* and B^* need to satisfy the first-order conditions (6) and (7) for the symmetric case,

$$\left.\frac{\partial \pi_i^*}{\partial A_i}\right|_{i=j} = q^* \left.\frac{\partial q_i^*}{\partial A_i}\right|_{i=j} - A = 0 \tag{14}$$

and

$$\left.\frac{\partial \pi_i^*}{\partial B_i}\right|_{i=j} = q^* \left.\frac{\partial q_i^*}{\partial B_i}\right|_{i=j} - B = 0, \tag{15}$$

in A and B simultaneously. Note that q^* is given by (4) and derivatives $(\partial q_i^*/\partial A_i)|_{i=j}$ and $(\partial q_i^*/\partial B_i)|_{i=j}$ represent expressions (8) and (11) respectively omitting subscripts.

Unfortunately we cannot solve the first-order conditions (14) and (15) for A^* and B^* explicitly. The parameter space, however, is limited by $0 \leqslant \beta \leqslant 1$ and $0 \leqslant \alpha < 1$. Table 1 displays values for A^* and B^* as derived with Mathematica for alternative parameter constellations[17].

With one exception the results displayed in Table 1 suggest the following regularities:

- Efforts to innovate, A^*, are decreasing (increasing) in β if α is small (large). Moreover A^* is increasing in the difficulty of learning, α.
- Efforts to imitate/absorb, B^*, are increasing in both β and α.
- The ratio of imitation/absorption efforts to innovation efforts, B^*/A^*, is increasing both in β and in α, whereby $0 \leqslant B^*/A^* \leqslant 1$.

The economic logic behind these results can be deduced from the effects as discussed in the previous sections. Intuitively appealing imitation/absorption

[17] The results displayed in Table 1 remain robust with respect to alternative starting values for the numerical solution procedure.

α		β				
		0	0.2	0.5	0.8	1.0
	B^*/A^*	0	0	0	0	0
0	B^*	0	0	0	0	0
	A^*	2.857	2.631	2.222	1.754	1.429
	B^*/A^*	0	0.173	0.306	0.430	0.520
0.2	B^*	0	0.476	0.775	0.958	1.028
	A^*	2.857	2.757	2.532	2.223	1.978
	B^*/A^*	0	0.219	0.420	0.608	0.740
0.5	B^*	0	0.622	1.118	1.639	1.912
	A^*	2.857	2.846	2.799	2.700	2.582
	B^*/A^*	0	0.218	0.477	0.727	0.9
0.8	B^*	0	0.629	1.423	2.228	2.963
	A^*	2.857	2.884	2.984	3.147	3.293
	B^*/A^*	0	0.201	0.499	0.796	0.995
0.99	B^*	0	0.582	1.534	2.770	3.937
	A^*	2.857	2.890	3.073	3.477	3.957

B^* : equilibrium imitation/absorption efforts (times 10)

A^* : equilibrium innovation efforts (times 10)

Table 1: Innovation and imitation/absorption efforts in the non-cooperative equilibrium

efforts are increasing if patent protection decreases. By the same token efforts to innovate decrease in β because the potential competitive advantage diminishes if one's rival gets in possession of the innovation as well. This is true, however, if and only if learning is rather easy (small α). Otherwise, if learning is sufficiently difficult and imitation/absorption costly respectively, competitive advantages from innovation tend to persist. Along with increasing market size incentives, then, even efforts to innovate increase in β.

Generally an increase in the difficulty of learning, α, increases both innovation efforts and imitation/absorption efforts. The former is due to the technical protection of innovations whereas the latter stems from the fact that difficulty of learning renders imitation/absorption efforts more productive. Even though larger α reduce the ceteris paribus diffusion of knowledge just like smaller β, the potential reward of imitation/absorption efforts remains; in contrast to the case of smaller β. This causes the difference in the behavior of B^* in β and α respectively.

The exception to the just described patterns is for small β (e.g. $\beta = 0.2$). Then, beyond a certain degree of α (close to 0.99), B^* is in fact decreasing in α. We know by Proposition 2 that next to the decreasing market size incentive also the competitive incentive may decrease in α if an imitator has to incur much imitation/absorption efforts (i.e. high α) to obtain a small amount of valuable knowledge (small β). Intuitively appealing, firms will not engage in an exhausting activity with low returns.

4 The cooperative investment case

In the cooperative case each firm takes into account the effects of its own efforts to innovate and imitate/absorb respectively on the counterpart's profits, that is the ith firm now maximizes joint-profits

$$\pi_i^* + \pi_j^* = q_i^{*2} + q_j^{*2} - A_i^2 - B_i^2 - A_j^2 - B_j^2, \quad i = 1, 2, \quad i \neq j \tag{16}$$

with respect to A_i and B_i. To interpret the case of cooperative imitation/absorption keep in mind that (1) implies a multipath R&D process in which firms are likely to pursue different activities, each being more or less promising (Kamien, Muller and Zang 1992). That is β represents essentially the fraction of a firm's knowledge that is different from what the partner already knows. Of course, one may argue that β increases in cooperative ventures as knowledge might by voluntarily shared[18] but that does not replace the need to induce some efforts in order to imitate/absorb the partner's knowledge: "participating firms also must be prepared to invest internally in the absorptive capacity that will permit effective exploitation of the venture's knowledge output" (Cohen and Levinthal 1990).

[18] For instance Bönte and Keilbach (2003) and Lhuillery (2003) find empirical evidence for voluntary knowledge disclosure in R&D partnerships. Atallah (2003) shows that RJV members indeed disclose their knowledge among each other as long as the leakage of knowledge to non-members does not exceed a certain treshhold level.

The cooperative first-order conditions for each firm are given by

$$\frac{\partial(\pi_i^* + \pi_j^*)}{\partial A_i} = q_i^* \frac{\partial q_i^*}{\partial A_i} + q_j^* \frac{\partial q_j^*}{\partial A_i} - A_i = 0, \quad i = 1, 2, \quad i \neq j \tag{17}$$

and

$$\frac{\partial(\pi_i^* + \pi_j^*)}{\partial B_i} = q_i^* \frac{\partial q_i^*}{\partial B_i} + q_j^* \frac{\partial q_j^*}{\partial B_i} - B_i = 0, \quad i = 1, 2, \quad i \neq j. \tag{18}$$

In the following two sections we analyze the effects of cooperation on the incentives to innovate and on the incentives to imitate/absorb separately. Then we turn to the comparison of the simultaneous cooperative and non-cooperative equilibrium. Similar to the non-cooperative case we can state:

Lemma 2 *In the symmetric cooperative case any profit-maximizing simultaneous solution to the first-order conditions (17) and (18) will satisfy $B \leqslant A$.*

Proof. See appendix.

Effects of cooperation on incentives to innovate Comparing the non-cooperative first-order condition (6) with the cooperative one (17), reveals that the sign of

$$\frac{\partial q_j^*}{\partial A_i} = \frac{1}{3}(2\beta \underbrace{(1-\alpha)\left(\frac{B_j}{A_i}\right)^{\alpha}}_{\substack{\textit{difficulty of learning} \\ \textit{and imitation effect}}} - 1), \tag{19}$$

determines whether the non-cooperative or the cooperative mode induces stronger efforts to innovate. As long as a firm's innovation efforts increase a rival's equilibrium output quantity and (19) is positive, the cooperative mode encourages by (17) innovation efforts as compared to the non-cooperative mode, (6), and vice versa.

How is the sign of (19) shaped in the light of the difficulty of learning and imitation effect? If there is no need to learn at all (i.e. $\alpha = 0$) the labeled part of (19) vanishes and the treshhold level $\beta \lesseqgtr 0.5$ of the D'Aspremont and Jacquemin (1989) model alone determines which of the two cases induces stronger incentives to innovate. However, if efforts to imitate/absorb become more important the derivative $(\partial q_j^*/\partial A_i)$ decreases, i.e.

$$\frac{\partial^2 q_j^*}{\partial A_i \partial \alpha} = -\frac{2}{3}\beta\left(\frac{B_j}{A_i}\right)^{\alpha}\left(1 - (1-\alpha)\ln\left(\frac{B_j}{A_i}\right)\right) \leqslant 0. \tag{20}$$

The sign follows because $B_j \leqslant A_i$ and hence the second bracketed term in (20) is non-negative. Thereby the higher α the more likely (19) is negative and the more likely does the non-cooperative mode induce stronger incentives to innovate as compared to the cooperative one.

On the other hand (19) is increasing in both weaker patent protection, β, and another firm's efforts to absorb, B_j. Either effect fosters knowledge flows and thereby reduces the possibility to gain a competitive advantage in the quantity competition (second-stage).

Effects of cooperation on incentives to imitate/absorb The effect of imitation efforts, B_i, on a rival's equilibrium output-quantity, q_j^*,

$$\frac{\partial q_j^*}{\partial B_i} = -\frac{1}{3}\beta\alpha\left(\frac{A_j}{B_i}\right)^{1-\alpha}, \tag{21}$$

is non-positive which means by (18) and (7) that firms reduce efforts to imitate/absorb in the cooperative case relative to the non-cooperative case. Imitation/absorption reduces the imitator's costs but, unlike innovation, does not provide a direct positive externality that might create additional investment incentives if firms cooperate. In contrast, upon intensified product-market competition, imitation/absorption indirectly hurts the counterpart's profits. Cooperation allows firms to internalize this negative externality and accordingly softens the intensity of product-market competition .

Equilibrium characterization The first-order conditions for a joint profit maximum in the symmetric cooperative case is obtained upon substitution of (8) and (19) into (17) and respectively of (11) and (21) into (18):

$$\left.\frac{\partial(\pi_i^* + \pi_j^*)}{\partial A_i}\right|_{i=j} = q^* \left.\frac{\partial q_i^*}{\partial A_i}\right|_{i=j} + q^* \left.\frac{\partial q_j^*}{\partial A_i}\right|_{i=j} - A = 0, \tag{22}$$

and

$$\left.\frac{\partial(\pi_i^* + \pi_j^*)}{\partial B_i}\right|_{i=j} = q^* \left.\frac{\partial q_i^*}{\partial B_i}\right|_{i=j} + q^* \left.\frac{\partial q_j^*}{\partial B_i}\right|_{i=j} - B = 0. \tag{23}$$

Proceeding in a similar fashion as in the non-cooperative case we obtain numerical solutions to (22) and (23) in A and B for alternative parameter values of β and α. Denoting these solutions $\hat{A}$ and $\hat{B}$, Table 2 provides some examples of the cooperative equilibrium values in relation to the results of the non-cooperative case A^* and B^*. Note that the displayed numbers in Table 2 represent the ratios of cooperative investments to the respective non-cooperative investments from Table 1.

α		β				
		0	0.2	0.5	0.8	1.0
0	$\frac{\hat{B}/\hat{A}}{B^*/A^*}$	-	-	-	-	-
	$\hat{B}/B^*$	-	-	-	-	-
	$\hat{A}/A^*$	0.438	0.603	1.0	1.781	2.8
0.2	$\frac{\hat{B}/\hat{A}}{B^*/A^*}$	-	0.914	0.785	0.670	0.599
	$\hat{B}/B^*$	-	0.476	0.560	0.687	0.814
	$\hat{A}/A^*$	0.438	0.521	0.712	1.026	1.360
0.5	$\frac{\hat{B}/\hat{A}}{B^*/A^*}$	-	0.955	0.861	0.761	0.694
	$\hat{B}/B^*$	-	0.447	0.472	0.510	0.547
	$\hat{A}/A^*$	0.438	0.468	0.548	0.670	0.789
0.8	$\frac{\hat{B}/\hat{A}}{B^*/A^*}$	-	0.985	0.936	0.868	0.818
	$\hat{B}/B^*$	-	0.436	0.430	0.421	0.414
	$\hat{A}/A^*$	0.438	0.442	0.460	0.485	0.506
0.99	$\frac{\hat{B}/\hat{A}}{B^*/A^*}$	-	1.0	1.0	0.996	0.991
	$\hat{B}/B^*$	-	0.435	0.420	0.391	0.360
	$\hat{A}/A^*$	0.438	0.435	0.421	0.393	0.365

$\hat{B}/B^*$: cooperative / non-cooperative absorption efforts in equilibrium

$\hat{A}/A^*$: cooperative / non-cooperative innovation efforts in equilibrium

Table 2: Innovation and imitation/absorption efforts in the simultaneous cooperative Nash equilibrium

For the comparison of non-cooperative and cooperative equilibrium investments, Table 2 demonstrates the following patterns:
Relative the non-cooperative case we have:

- Cooperative innovation efforts, $\hat{A}$, are increasing (decreasing) in β if α is small (large). Cooperative innovation efforts are decreasing in the difficulty of learning, α. The 'critical β' for which the cooperative mode induces higher investments than the non-cooperative one, $\hat{A} > A^*$, is increasing in the difficulty of learning, α.

- Cooperative efforts to imitate/absorb, $\hat{B}$, are, similar to $\hat{A}$, increasing (decreasing) in β if α is small (large). Cooperative efforts to imitate/absorb, $\hat{B}$, are decreasing in α. Within the complete parameter range, cooperative efforts to imitate/absorb are lower than non-cooperative ones.

- In the cooperative mode firms allocate less recourses to imitate/absorb. This divergence is increasing both in β and in α.

The results of Table 2 reveal that the R&D stimulating feature of cooperation hinges rather critically on the presumption that no specific imitation/absorption efforts are needed on the beneficiary's side. For instance $\alpha = 0.2$ is sufficient to shift the well known $\beta = 0.5$ treshhold[19] roughly up to $\beta = 0.8$ and if $\alpha = 0.5$ the non-cooperative mode unambiguously creates stronger incentives to innovate than the cooperative one (e.g. $\hat{A}/A^* = 0.630$ for $\beta = 1$). With regard to industry-wide cost reductions (i.e. technological progress) and consumer surplus, however, the combined effect of innovation and imitation/absorption efforts in equilibrium have to be considered. The next section deals with this question and determines the critical values for β and α at which the cooperative mode yields higher technological progress.

5 Welfare

Technological progress and consumer surplus Consumer surplus is measured by the output quantities produced in (the symmetric) equilibrium (4), where X has to be substituted by the technological progress (i.e. effective cost reduction) which is attained in the non-cooperative equilibrium

$$X^* = A^* + \beta {B^*}^{\alpha} {A^*}^{1-\alpha},$$

[19] This is the critical spillover-level in the D'Aspremont and Jacquemin (1989) model, up to which cooperative efforts are higher than non-cooperative ones (see first line of Table 2). Halmenschlager (2004) finds a critical spillover-level of 1/3 if two lagging firms conduct R&D in order to catch up with one leader.

and the cooperative equilibrium respectively,

$$\hat{X} = \hat{A} + \beta \hat{B}^{\alpha} \hat{A}^{1-\alpha}.$$

It is obvious that

$$X^* - \hat{X} \lesseqgtr 0 \Longleftrightarrow q^*(X^*) \lesseqgtr q^*(\hat{X}).$$

As we cannot provide an explicit analytical solution for A^*, B^* and $\hat{A}$, $\hat{B}$ we can neither do so for X^* and $\hat{X}$.

Nonetheless we offer a numerical approximation. In particular we substitute all the equilibrium solutions for (A^*, B^*) and ($\hat{A}$, $\hat{B}$), which from a few were presented in Tables 1 and 2, into X^* and $\hat{X}$ respectively. We then obtain a list of numerical values for $X^* - \hat{X}$ as a function of α and β. The line in Figure 1 depicts all combinations of α and β at which $X^* - \hat{X} = 0$. Figure 1 is a contour plot[20] of the values we obtained for $X^* - \hat{X}$, that is a geographic map of $X^* - \hat{X}$ at which each contour joins values of the same height. We modified the plot such that only the null contour was actually plotted. To the north-west of the line $X^* - \hat{X} > 0$ and to the south-east we have that $X^* - \hat{X} < 0$. Thus for a broad range of parameter constellations, technological progress and consumer surplus is indeed lower in the cooperative case as compared to the non-cooperative one[21].

What restores non-cooperative incentives and respectively destroys cooperative incentives so fundamentally? One can think of two major effects that increase non-cooperative investment incentives rather than cooperative ones. First the requirement to exert specific costs in order to imitate/absorb protects innovations. Thereby firms profit more effectively from innovating in the non-cooperative case because they can achieve a competitive advantage rather exclusively (see (8)) whereas the positive externalities to be shared for

[20] In fact Figure 1 is a *List*ContourPlot of $X^* - \widehat{X}$. The Mathematica file is available from the author upon request.

[21] A robustness-check of these results, employing a CES function instead of the Cobb-Douglas form in (1), is available from the author upon request. For reasonable parameter-extensions our results become more pronounced in the sense that the region of $X^* < \widehat{X}$ decreases. In addition, the mathematica file underlying Figure 1 (and intermediate results of the paper) is available upon request.

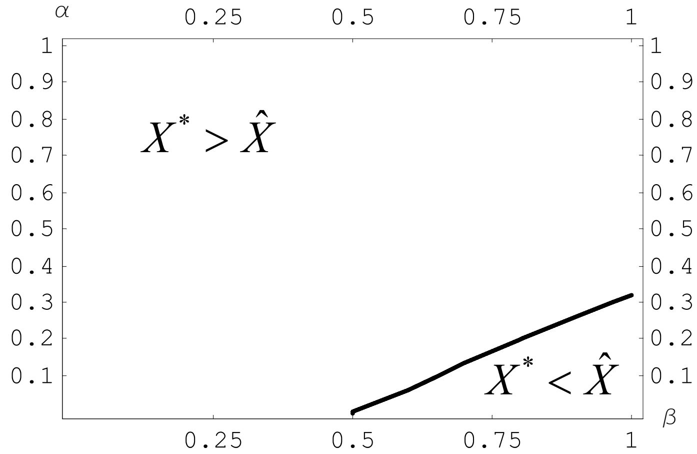

Figure 1: Parameter constellations of α and β that determine whether the non-cooperative case, or the cooperative case yields larger technological progress, X^*, $\widehat{X}$, and consumer surplus, $q^*(X^*), q^*(\widehat{X})$.

free in the cooperative case diminish by (19). The second reason stems from the fact that the alternative way to obtain a cost reduction, namely through imitation/absorption, does from another firm's point of view not at all provide any positive externality but only intensifies competition in the product market (see (11) vs. (21)). Hence, in this case cooperation only serves as a device to cut back on aggressive investments to imitate/absorb which hurts technological progress and consumers relative to the non-cooperative case.

Allocative efficiency of R&D investments In the non-cooperative case firms always allocate a larger fraction of their overall investments to imitate/absorb as compared to the cooperative case. This raises the question which case induces the more efficient allocation in the sense that a given level of cost reduction, X_i, is attained for minimum overall investments. We derive the non-cooperative and the cooperative equilibrium allocation of efforts, B^*/A^* and $\hat{B}/\hat{A}$, and then compare these with the efficient allocation.

As for the non-cooperative and the cooperative case we have by (14) and (15) and respectively (22) and (23):

Proposition 3 *In equilibrium firms allocate their efforts in the ratio that equals the ratio of the competitive incentives, i.e.*
in the non-cooperative case

$$\frac{B^*}{A^*} = \frac{\left.\frac{\partial q_i^*}{\partial B_i}\right|_{A^*,\ B^*}}{\left.\frac{\partial q_i^*}{\partial A_i}\right|_{A^*,\ B^*}} = \frac{2\beta\alpha\left(\frac{A^*}{B^*}\right)^{1-\alpha}}{2-\beta(1-\alpha)\left(\frac{B^*}{A^*}\right)^{\alpha}}, \tag{24}$$

and in the cooperative case

$$\frac{\hat{B}}{\hat{A}} = \frac{\left.\left(\frac{\partial q_i^*}{\partial B_i}+\frac{\partial q_j^*}{\partial B_i}\right)\right|_{\hat{A},\hat{B}}}{\left.\left(\frac{\partial q_i^*}{\partial A_i}+\frac{\partial q_j^*}{\partial A_i}\right)\right|_{\hat{A},\hat{B}}} = \frac{\beta\alpha\left(\frac{\hat{A}}{\hat{B}}\right)^{1-\alpha}}{1+\beta(1-\alpha)\left(\frac{\hat{B}}{\hat{A}}\right)^{\alpha}}. \tag{25}$$

Proof. Substitution of (15) into (14) via q^* implies (24) and substitution of (23) into (22) via q^* implies (25). ■

Next, if firms allocate their R&D resources efficiently, each investment-type, A_i and B_i, is employed such that the marginal overall cost reduction due to the investment, $\partial(X_iq_i + X_jq_j)/\partial A_i$ and $\partial(X_iq_i + X_jq_j)/\partial B_i$, equals the marginal cost of the respective investment-type, $2A_i$ and $2B_i$:

$$\left.\frac{\partial(X_iq_i^* + X_jq_j^*)}{\partial A_i}\right|_{i=j} = (q^* + \frac{X}{3})\left(1+\beta(1-\alpha)\left(\frac{B}{A}\right)^{\alpha}\right) = 2A \tag{26}$$

and

$$\left.\frac{\partial(X_iq_i^* + X_jq_j^*)}{\partial B_i}\right|_{i=j} = (q^* + \frac{X}{3})\left(\beta\alpha\left(\frac{A}{B}\right)^{1-\alpha}\right) = 2B \tag{27}$$

In any case where (26) and (27) are not satisfied simultaneously it is possible to achieve a higher cost reduction (or technological progress) for given R&D costs through re-allocation of A_i and B_i. This brings us to

Proposition 4 *In the efficient case firms allocate their resources in the same ratio as in the cooperative case, i.e.*

$$\frac{B}{A} = \frac{\beta\alpha\left(\frac{A}{B}\right)^{1-\alpha}}{1+\beta(1-\alpha)\left(\frac{B}{A}\right)^{\alpha}}. \tag{28}$$

Proof. We substitute (27) into (26) via $(q^* + X/3)$ and solve for B/A to get (28). Comparison of (28) and (25) completes the proof. ■

To understand the logic behind Proposition 4 one may view cooperation as to comprise two independent optimization procedures: first on the overall investment level and, secondly, on the allocation of this investment level either to innovate or to imitate/absorb. Obviously, once the investment level is fixed, it is certainly Pareto optimal from the firms' point of view to allocate efforts such that overall cost reductions, $X_i q_i^* + X_j q_j^*$, are maximized. The divergence between the non-cooperative allocation to the optimal (cooperative) allocation is displayed by the ratio $(\hat{B}/\hat{A})/(B^*/A^*)$ in Table 2: the misallocation of R&D resources gets more pronounced the weaker patent protection, β, and the larger the ease of learning, $(1-\alpha)$.

6 Conclusions

This paper has analyzed how the introduction of specific imitation and absorption efforts affects non-cooperative and cooperative incentives to invest in cost reductions. Two main findings are contributed. First, non-cooperative incentives to invest in cost-reducing R&D (whether for imitative/absorptive or for innovative purposes) are, for the most part, larger than cooperative ones. Second, only in the cooperative case, however, firms will allocate their resources efficiently in the sense that the maximum industry-wide cost reduction is obtained for any given level of overall investments. The non-cooperative case, in contrast, induces too much imitation/absorption relative to innovation. Simply put, cooperation (RJVs) might be rather ineffective in creating incentives whereas it guarantees that resources are not wasted. We conclude that cooperation is hardly beneficial from the consumers' point of view, inducing, for the most part, less technological progress and consumer surplus than the non-cooperative case whereas from the firms' perspective cooperation appears even more attractive than previously assumed.

European governments have clearly stated their primary goal of R&D policy, namely to rise R&D investments up to 3% of GDP by 2010. Our results suggest that the relaxation of competition law combined with substantial funding of cooperative R&D might not always be the appropriate tool to induce increasing R&D investments when it comes to horizontally related firms. While there may exist other good reasons to encourage cooperative R&D among product-market competitors, weak R&D appropriability is hardly a sufficient condition if one agrees that receipt of spillovers requires some, if moderate, specific investments.

A profound theoretical welfare analysis, of course, has to trade-off the negative consumers' perspective and the positive firms' perspective against each other. Future theoretical work should investigate under which circumstances the loss of technological progress might be outweighed by the increase in the firms' profits and an efficient allocation of R&D resources. Moreover it would be interesting to know empirically whether there exist industry patterns regarding the difficulty of learning.

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Appendix

Proof of Lemma 1 and Propositions 1 and 2. For notational convenience let

$$F_A = q^* f_{qA} - A = 0, \tag{29}$$

and

$$F_B = q^* f_{qB} - B = 0 \tag{30}$$

denote the first-order conditions (14) and (15) respectively where

$$f_{qA} = \left.\frac{\partial q_i^*}{\partial A_i}\right|_{i=j} = \frac{1}{3}\left(2 - \beta(1-\alpha)\left(\frac{B}{A}\right)^{\alpha}\right), \tag{31}$$

and

$$f_{qB} = \left.\frac{\partial q_i^*}{\partial B_i}\right|_{i=j} = \frac{2}{3}\beta\alpha\left(\frac{A}{B}\right)^{1-\alpha}. \tag{32}$$

Lemma 1. We proceed by showing that the left hand side of (30) is non-positive if (29) is satisfied and $B = A$. Then the fact that $\partial F_B/\partial B < 0$ if $B > A$ completes the proof.

Upon substitution of A for B in (30) we have

$$F_B|_{B=A} = \frac{2}{9}\beta\alpha(1 + A(\beta+1)) - A, \tag{33}$$

whereas upon substitution of A for B, (29) can be solved for

$$A = \frac{2 - \beta(1-\alpha)}{1 - (\beta+1)(2 - \beta(1-\alpha))}. \tag{34}$$

Then we substitute (34) into (33) to obtain

$$F_B|_{\ B=A}|_{F_A=0} = -\frac{2 - \beta - \beta\alpha}{7 - \beta(1-\alpha) + \beta^2(1-\alpha)} \leqslant 0. \tag{35}$$

Next

$$\left.\frac{\partial F_B}{\partial B}\right|_{B>A} = \frac{\partial q^*}{\partial B} f_{qB} + q^* \frac{\partial f_{qB}}{\partial B} - 1 < 0, \tag{36}$$

follows because

$$\left.\frac{\partial q^*}{\partial B} f_{qB}\right|_{B>A} = \frac{2}{9}\left(\beta\alpha\left(\frac{A}{B}\right)^{1-\alpha}\right)^2 \leqslant \frac{2}{9} \tag{37}$$

and $\partial f_{qB}/\partial B \leqslant 0$ by (32). Thus the first-order condition (30) is non-positive if $B = A$ and if $B > A$ it must be smaller. But then F_B cannot go from positive to negative in B if both $B > A$ and (29) is satisfied. ■

Proposition 1. By the implicit function rule, if

$$\frac{\partial F_A}{\partial A} = \frac{\partial q^*}{\partial A} f_{qA} + q^* \frac{\partial f_{qA}}{\partial A} - 1 \neq 0 \tag{38}$$

there exists a function $A' = f(B, \beta, \alpha)$ that satisfies (29) in A and has partial derivatives

$$\frac{\partial A'}{\partial \beta} = -\frac{\partial F_A/\partial \beta}{\partial F_A/\partial A} \tag{39}$$

and

$$\frac{\partial A'}{\partial \alpha} = -\frac{\partial F_A/\partial \alpha}{\partial F_A/\partial A}. \tag{40}$$

In order to evaluate (38) note that for the first term we have

$$\frac{\partial q^*}{\partial A} f_{qA} \leqslant \frac{4}{9} \tag{41}$$

because

$$\frac{\partial q^*}{\partial A} = \frac{1}{3}\left(1 + \beta(1-\alpha)\left(\frac{B}{A}\right)^{\alpha}\right) \leqslant \frac{2}{3} \tag{42}$$

and $f_{qA} \leqslant 2/3$ by (31). In order to evaluate the second term we substitute the solution to (29) via $q^* = A/f_{qA}$ into (38) and re-write the second term as

$$\frac{A}{f_{qA}} \frac{\partial f_{qA}}{\partial A} = \frac{\beta\alpha(1-\alpha)B^{\alpha}}{2A^{\alpha} - \beta(1-\alpha)B^{\alpha}} \leqslant 3 - 2\sqrt{2}. \tag{43}$$

Then by (41) and (43), (38) is strictly negative and A' exists.
Moreover, since

$$F_A|_{A=0} = 2/9 > 0 \tag{44}$$

the function A' establishes the values for A in which (29) goes from positive to negative and thus establishes a profit-maximum. (First claim).

Next, since $\partial F_A/\partial A < 0$ we have by (39) that

$$sign \frac{\partial A'}{\partial \beta} = sign \frac{\partial F_A}{\partial \beta} \tag{45}$$

where

$$\frac{\partial F_A}{\partial \beta} = \frac{\partial q^*}{\partial \beta} f_{qA} + q^* \frac{\partial f_{qA}}{\partial \beta} \tag{46}$$

Substituting the solution to (29) into (46) via $q^* = A/f_{qA}$ yields

$$\left.\frac{\partial F_A}{\partial \beta}\right|_{F_A=0} = B^\alpha A^{1-\alpha} \frac{(f_{qA})^2 - (1-\alpha)}{f_{qA}}. \tag{47}$$

Since the denominator of (47) is strictly positive we have

$$sign \frac{\partial A'}{\partial \beta} = sign \left[(f_{qA})^2 - (1-\alpha) \right]. \tag{48}$$

This establishes the second claim.

Finally, be similar arguments we have

$$sign \frac{\partial A'}{\partial \alpha} = sign \frac{\partial F_A}{\partial \alpha} \tag{49}$$

where

$$\frac{\partial F_A}{\partial \alpha} = \frac{\partial q^*}{\partial \alpha} f_{qA} + q^* \frac{\partial f_{qA}}{\partial \alpha}. \tag{50}$$

Again we substitute the solution to (29) into (50) via $q^* = A/f_{qA}$ and obtain

$$\left.\frac{\partial F_A}{\partial \alpha}\right|_{F_A=0} = \beta B^\alpha A^{1-\alpha} \frac{\left((f_{qA})^2 - (1-\alpha)\right) \ln\left(\frac{B}{A}\right) + 1}{f_{qA}}. \tag{51}$$

Hence

$$sign \frac{\partial A'}{\partial \alpha} = sign \left[\left((f_{qA})^2 - (1-\alpha)\right) \ln\left(\frac{B}{A}\right) + 1 \right] \tag{52}$$

This establishes the third claim.■

Proposition 2. By the implicit function rule, if

$$\frac{\partial F_B}{\partial B} = \frac{\partial q^*}{\partial B} f_{qB} + q^* \frac{\partial f_{qB}}{\partial B} - 1 \neq 0 \tag{53}$$

the function $B' = f(A, \beta, \alpha)$ that satisfies (30) in B exists and has partial derivatives

$$\frac{\partial B'}{\partial \beta} = -\frac{\partial F_B / \partial \beta}{\partial F_B / \partial B} \tag{54}$$

and

$$\frac{\partial B'}{\partial \alpha} = -\frac{\partial F_B / \partial \alpha}{\partial F_B / \partial B}. \tag{55}$$

Upon substitution of (30) via $f_{qB} = B/q^*$ into (53) we know that

$$\left.\frac{\partial q^*}{\partial B} f_{qB}\right|_{F_B=0} = \frac{\partial q^*}{\partial B}\frac{B}{q^*} = \frac{\beta\alpha B^{\alpha} A^{1-\alpha}}{1 + A + \beta B^{\alpha} A^{1-\alpha}} < 1 \tag{56}$$

whereas $\partial f_{qB}/\partial B \leqslant 0$ and thus (53) is strictly negative.
Moreover,

$$F_B|_{B=0} = \infty \tag{57}$$

and thereby the function B' establishes the values for B in which (30) goes from positive to negative and thus constitutes a profit-maximum. (First claim).
Obviously $\partial B'/\partial\beta > 0$ as both $\partial q^*/\partial\beta > 0$ and $\partial f_{qB}/\partial\beta > 0$. (Second claim).
Finally, applying the implicit-function-rule again, since $\partial F_B/\partial B < 0$ we have

$$sign\frac{\partial B'}{\partial\alpha} = sign\frac{\partial F_B}{\partial\alpha} \tag{58}$$

where

$$\frac{\partial F_B}{\partial\alpha} = \frac{\partial q^*}{\partial\alpha} f_{qB} + q^* \frac{\partial f_{qB}}{\partial\alpha}. \tag{59}$$

Substitution of $q^* = B/f_{qB}$ as implied by (30) yields

$$\frac{\partial F_B}{\partial\alpha} = \frac{1}{3}\ln\frac{B}{A}\beta B^{\alpha} A^{1-\alpha} f_{qB} + \frac{B}{\alpha}\left(1 - \alpha\ln\frac{A}{B}\right), \tag{60}$$

which, after some re-arrangements, implies

$$sign\frac{\partial B'}{\partial\alpha} = sign\left[1 + \ln\frac{B}{A}\left(\frac{1}{2}\left(f_{qB}\right)^2 + \alpha\right)\right]. \tag{61}$$

■

Proof of Lemma 2. For notational convenience let

$$C_A = q^* c_{qA} - A = 0 \tag{62}$$

and

$$C_B = q^* c_{qB} - B = 0 \tag{63}$$

denote the cooperative first-order conditions (22) and (23) respectively where

$$c_{qA} = \left.\frac{\partial q_i^*}{\partial A_i}\right|_{i=j} + \left.\frac{\partial q_j^*}{\partial A_i}\right|_{i=j} = \frac{1}{3}\left(1 + \beta(1-\alpha)\left(\frac{B}{A}\right)^{\alpha}\right), \tag{64}$$

and

$$c_{qB} = \left.\frac{\partial q_i^*}{\partial B_i}\right|_{i=j} + \left.\frac{\partial q_j^*}{\partial B_i}\right|_{i=j} = \frac{1}{3}\beta\alpha\left(\frac{A}{B}\right)^{1-\alpha}. \tag{65}$$

The proof of Lemma 2 follows by similar arguments as the proof of Lemma 1. We have

$$C_B|_{\ B=A}|_{C_A=0} = -\frac{1-\beta(2\alpha-1)}{8-\beta(2-\alpha)-\beta^2(1-\alpha)} \leqslant 0. \tag{66}$$

Moreover

$$\left.\frac{\partial C_B}{\partial B}\right|_{B>A} = \frac{\partial q^*}{\partial B}c_{qB} + q^*\frac{\partial c_{qB}}{\partial B} - 1 < 0, \tag{67}$$

follows because

$$\left.\frac{\partial q^*}{\partial B}c_{qB}\right|_{B>A} = \left(\frac{1}{3}\beta\alpha\left(\frac{A}{B}\right)^{1-\alpha}\right)^2 \leqslant \frac{1}{9} \tag{68}$$

and $\partial c_{qB}/\partial B \leqslant 0$ by (65). ■

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Excess Absorptive Capacity and the Persistence of Monopoly

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Abstract

We consider a monopolist's precommitment to imitate a potential entrant's innovation as a means of entry deterrence. This precommitment, i.e. excess absorptive capacity, always decreases the entrant's efforts to innovate whereas it increases (decreases) the monopolist's efforts if potential duopoly profits are low (high). If potential competition is à la Bertrand, a certain degree of excess absorptive capacity indeed suffices to render the monopolist more innovative than the entrant, such that even if the innovation is drastic, monopoly will tend to persist. More excess absorptive capacity increases the monopolist's equilibrium payoff whereas it decreases the entrant's.

JEL Classification: O31, O32, L13

Keywords: Absorptive Capacity; Persistence of Monopoly; Entry deterrence; Innovation; Imitation

1 Introduction

In high-tech industries the persistence of dominant, monopolistic firms can be explained by superior innovative performance of the monopolist relative to a potential entrant. Superior performance, in turn, follows greater incentives to invest in new products or processes. Accordingly, market structure in high-tech industries is tied to the question whether it is the incumbent or the entrant who has greater incentives to innovate. Arrow (1962), Gilbert and Newberry (1982) and Reinganum (1983) provide seminal answers based on asymmetries in the monopolist's and the potential entrant's returns from a successful innovation (see below). Numerous refinements[1] of these early works argue that an incumbent's initial technological lead or some kind of precommitment to innovate (Etro 2004) reduces an entrant's incentives to innovate and induces the persistence of monopoly respectively.

As an alternative explanation we consider how an incumbent's precommitment to *imitate* preserves its dominant position. The idea is based on the fact that innovations, in general, are subject to knowledge spillovers[2] for which the recipient needs to have absorptive capacity, i.e. the "ability to identify, assimilate, and exploit knowledge from the environment and to apply it to commercial ends" (Cohen and Leventhal 1989 and 1990). Our central assumption is that an incumbent rather than an entrant has built up and maintains such a capacity, either simply as a by-product of previous R&D or, somewhat more purposely, by means of basic research (Rosenberg 1990) and "large numbers of small and apparently unproductive [research] programs" (Henderson and Cockburn 1996). In either case some costs of imitation are sunk. This precommitment to imitate constitutes a credible (counter-)threat to the entrant's innovative threat.

Apparently a monopolist only needs absorptive capacity to affect potential competition. We highlight the strategic dimension with the notion of absorptive capacity in *excess* to the amount needed if there were no potential competition (i.e. zero absorptive capacity[3]).

[1] See Tirole (1988), chapter 10, for an overview.

[2] See Griliches (1992) for an overview.

[3] Needless to say, this picture is highly stylized in the sense that a monopolist which is not threatened by entry may still benefit from an absorptive capacity due to knowledge

To illustrate the idea of excess absorptive capacity, consider Microsoft's reaction to Netscape's competitive threat. Case evidence provided by Klein (2001) suggests that Microsoft's browser, Internet Explorer, was clearly inferior to Netscape's Navigator during 1995-96[4]. But "during 1995-97, Microsoft devoted more than $ 100 million per year to browser software development", and in September 1997 Microsoft achieved superiority in internet browser technology with the release of Internet Explorer 4.0. Apparently Microsoft not only possessed the absorptive capacity to catch up with the progress in browser technology but also had stronger investment incentives to develop the superior and hence eventually successful browser[5].

In light of the initially cited theories on incentives to innovate, Microsoft's massive investments are indeed surprising. According to Gilbert and Katz (2001) the battle between Microsoft and Netscape was essentially about establishing a programming platform; in particular Navigator was a distribution vehicle for Java and server based applications whereas Internet Explorer was linked to Windows. Due to network effects the dominant programming platform would in turn promote the persistence of Microsoft's monopoly or the creation of new monopoly, respectively. Hence, in the terminology of Reinganum (1983), the innovation at stake was drastic (no efficiency effect) such that the entrant, Netscape, should have invested more than the incumbent[6]. At the same time Arrow's (1962) replacement effect might have arguably been strong due to Microsoft's comfortable returns from Windows whereas Netscape possessed the initial technological advantage, which, again, supports less investments by the incumbent Microsoft.

How does excess absorptive capacity help to explain this investment be-

spillovers from research institutes or universities. We abstract from such linkages for the sake of simplicity.

[4]The quality evaluation of Internet Explorer and Navigator was based on the share of "wins" in three independent computer magazines.

[5]Microsoft's success in the battle with Netscape has been primarily related to its aggressive (zero) pricing of Internet Explorer and its tying of Internet Explorer to Windows. Klein (2001), however, reports that it was not before Microsoft had a comparable product available until Internet Explorer's usage began to increase.

[6]Even if one argued that the development of the internet browser technology was deterministic rather than uncertain the Gilbert and Newberry (1982) model would predict at least innovation efforts of equal size.

havior? And to which degree does it benefit (hurt) the incumbent (entrant)? These are the questions we seek to answer in this paper. In particular we set up a model in which the incumbent maintains excess absorptive capacity. It is measured by the probability of an immediate imitation of an entrant's innovation. Knowing this probability firms choose their investments to innovate under uncertainty.

With respect to the first question, we show that excess absorptive capacity reduces the entrant's innovation investments and has two effects on the incumbent's investments. On the one hand it induces an *aggressive innovation effect*: deterring the entrant's innovation efforts increases the profitability of the incumbent's investments. On the other hand excess absorptive capacity creates a *copycat effect*, countervailing the former: an incumbent reduces its own innovation efforts to free ride on a successful innovation by the entrant. The copycat effect vanishes if profits in post-innovation competition approach zero (i.e. Bertrand competition). Then the aggressive innovation effect might indeed be sufficiently strong to guarantee more innovation efforts by the incumbent; even, as illustrated above, if the innovation is drastic (as defined by Reinganum 1983) and the incumbent replaces, for the most part, itself (Arrow 1962). These findings are consistent with the (scarce) empirical evidence on innovation behavior by incumbents and entrants[7].

The second question, i.e. to what extent excess absorptive capacity benefits (hurts) the incumbent (entrant), is closely related to Cohen and Levinthal's (1994) analysis of a monopolist's incentives to invest in absorptive capacity. Their model, however, regards absorptive capacity as a public good to be shared with potential entrants, namely the identification of promising new technologies. As criticized by Joglekar et al. (1997), their model omits "one critical element of absorptive capacity, namely a firm's ability to defend itself against the threat of external technology". Whereas Joglekar et al. (1997) "never indicate how their alternative specifications

[7] Blundell and Griffith (1999) find a positive relationship between innovation and market share (to reflect incumbency) as well as between innovation and a firm's knowledge stock. In contrast, Czarnitzki and Kraft (2004) find entrants more likely to innovate which might be due to the fact that they employ a *relative* measure for innovativeness: the R&D-to-sales ratio. Our model, however, aims to explain *absolute* incentives to innovate.

change [Cohen and Levinthal's] results"[8], our model addresses this question. Excess absorptive capacity clearly mimics such a defense capability, and we find it increases (decreases) the incumbent's (entrant's) equilibrium payoff.

The paper is organized as follows. Section two presents a description of the model. In section three we analyze how (a given) excess absorptive capacity affects the incumbent's and the entrant's incentives to innovate. In particular we start with the simple case of post-innovation Bertrand competition and then extend our findings to the general case in which a post-innovation duopoly is profitable. Building on the results of three, section four analyzes an incumbent's incentives to accumulate excess absorptive capacity. We first investigate the change of the firms' equilibrium payoffs due to excess absorptive capacity and then establish its absolute (maximum) value. Section five concludes.

2 The model

We consider a two stage setting. In the first stage only the incumbent, I, exists and builds up an absorptive capacity. Subsequently, in stage two, I and the (potential) entrant, E, decide simultaneously on their efforts/investments to obtain an innovation under uncertainty. A successful innovation benefits the innovator in terms of lower production costs (process-innovation) or enhanced product quality (product-innovation); either interpretation is suitable. We propose that innovations cannot be fully protected by patents which means that both firms can innovate successfully and that innovations can be imitated. Imitation, however, does not occur automatically, like 'manna from heaven', but requires absorptive capacity, the "ability to identify, assimilate, and exploit knowledge from the environment and to apply it to commercial ends" (Cohen and Levinthal 1989, 1990).

For simplicity we normalize the entrant's absorptive capacity to zero, whereas the incumbent's absorptive capacity is measured by the probability, β_I, of an immediate imitation of a potential entrant's innovation, where $0 \leqslant \beta_I \leqslant 1$. In the innovation stage the level of β_I is given and common

[8] Cohen and Levinthal's (1997) reply to Joglekar's et al. "Comments on 'Fortune Favors the Prepared Firm'".

			gross payoffs	
			entrant	incumbent
(non-)	α_E	α_I	π^D	π^D
success	α_E	$(1-\alpha_I)\beta_I$	π^D	π^D
cases	α_E	$(1-\alpha_I)(1-\beta_I)$	π^L	π^F
	$(1-\alpha_E)$	α_I	0	$\pi^M(\underline{c})$
	$(1-\alpha_E)$	$(1-\alpha_I)$	0	$\pi^M(\overline{c})$

Table 1: Firms' gross payoffs depending on innovation and imitation successes

knowledge. Furthermore we follow Rosen (1991) and Kanniainen and Stenbacka (2000) in modelling innovation efforts directly through the probability of a successful innovation by the incumbent and entrant respectively[9], α_I and α_E, where $0 \leqslant \alpha_I, \alpha_E \leqslant 1$. The firms thus determine α_I and α_E and bear innovation costs of the form $(a/2)\alpha_I^2$ and $(a/2)\alpha_E^2$, where $a > 0$.

As displayed by Table 1, the firms' payoffs depend on which one of them gets the innovation. If both firms innovate successfully (first row), either firm earns symmetric duopoly profits π^D. The same applies if only the entrant innovates whereas the incumbent succeeds in imitating (second row). If the entrant is successful and the incumbent does neither manage to innovate nor to imitate (third row), the entrant receives (cost- or quality-) leader profits, π^L, and the incumbent gets follower profits respectively. Consider now the cases in which the entrant fails to innovate. Then, of course, the entrant earns nothing and the incumbent gets monopoly profits given by the new technology, $\pi^M(\underline{c})$, or monopoly profits for the old technology, $\pi^M(\overline{c})$, depending on whether or not the incumbent innovates successfully (fourth and fifth row).

We assume $\pi^M(\underline{c}) > \pi^M(\overline{c})$ and $\pi^L > \pi^D \geqslant \pi^F \geqslant 0$ with equality only if competition is à la Bertrand. Moreover, $\pi^M(\underline{c}) \geqslant \pi^L$ with equality only if the innovation is drastic. Finally, we make the standard assumption $\pi^M(\underline{c}) > 2\pi^D$, i.e. intensified competition reduces industry profits.

The incumbent's and the entrant's innovation stage payoff functions can

[9]The terms innovation efforts, investments and success probability are used synonymously throughout the paper.

be written as

$$V_I = \alpha_I(1-\alpha_E)\pi^M(\underline{c}) + \alpha_I\alpha_E\pi^D + (1-\alpha_I)(1-\alpha_E)\pi^M(\overline{c}) + (1-\alpha_I)\alpha_E\beta_I\pi^D + (1-\alpha_I)\alpha_E(1-\beta_I)\pi^F - (a/2)\alpha_I^2, \quad (1)$$

and, respectively,

$$V_E = \alpha_E(1-\alpha_I)(1-\beta_I)\pi^L + \alpha_E\alpha_I\pi^D + \alpha_E(1-\alpha_I)\beta_I\pi^D - (a/2)\alpha_E^2. \quad (2)$$

3 Incentives to innovate (2nd stage)

In section three we seek answers to the following questions. First, how does excess absorptive capacity change the incumbent's and the entrant's equilibrium innovation efforts? Secondly we investigate which of the firms exerts more innovation efforts in absolute terms and, as a consequence, is more likely to dominate the post-innovation market. In doing so we start with the case of potential Bertrand competition in section 3.1. In this case there exists only one effect of excess absorptive capacity, the aggressive innovation effect. In the more general and complicated case of non-Bertrand competition (section 3.2) an additional (copycat) effect occurs.

In the second stage the incumbent maximizes (1) with respect to α_I and the entrant (2) with respect to α_E, given the incumbent's excess absorptive capacity, β_I. The first-order conditions are

$$\frac{\partial V_I}{\partial \alpha_I} = (1-\alpha_E)(\pi^M(\underline{c}) - \pi^M(\overline{c})) + \alpha_E(1-\beta_I)(\pi^D - \pi^F) - a\alpha_I = 0 \quad (3)$$

and

$$\frac{\partial V_E}{\partial \alpha_E} = (1-\alpha_I)(1-\beta_I)\pi^L + (\beta_I(1-\alpha_I) + \alpha_I)\pi^D - a\alpha_E = 0. \quad (4)$$

To assure concavity of the profit functions (1) and (2) in α_I and α_E we assume $a > \pi^M(\underline{c})$, i.e. second-order conditions are always satisfied. By (3) and (4) this assumption also guarantees an interior solution to the firms' maximization problem with $\alpha_I, \alpha_E < 1$. The interpretation of this technically motivated assumption is that innovation projects are so complex that firms never find it optimal to set $\alpha_I, \alpha_E = 1$.

3.1 Bertrand competition and the aggressive innovation effect

In the case of potential Bertrand competition we have $\pi^D = \pi^F = 0$. Let α_I^r and α_E^r denote the incumbent's and the entrant's reaction-function as implied by (3) and (4), then

$$\alpha_I^r = (1 - \alpha_E)(\pi^M(\underline{c}) - \pi^M(\overline{c}))/a \tag{5}$$

and

$$\alpha_E^r = (1 - \alpha_I)(1 - \beta_I)\pi^L/a. \tag{6}$$

By (5), α_I^r is independent of β_I and thus excess absorptive capacity has no direct effect on the incumbent's optimal innovation efforts. Since competition is à la Bertrand the incumbent would actually not benefit from imitating an entrant's innovation (i.e. $\pi^D = 0$) and hence β_I does not affect its optimization procedure directly. Due to (6), however, the entrant's optimal innovation efforts are decreasing in β_I. Since (5) and (6) imply that the firms' decision variables are strategic substitutes as defined by Bulow et al. (1984), i.e. $\partial\alpha_I^r(\alpha_E)/\partial\alpha_E < 0$ and $\partial\alpha_E^r(\alpha_I)/\partial\alpha_I < 0$, the decrease of the entrant's efforts causes an increase of the incumbent's equilibrium innovation efforts (see Figure 1). Upon substitution of (6) into (5) and solving for α_I, we obtain the incumbent's equilibrium innovation efforts[10],

$$\alpha_I^* = \frac{(\pi^M(\underline{c}) - \pi^M(\overline{c}))(a - (1 - \beta_I)\pi^L)}{a^2 - (1 - \beta_I)(\pi^M(\underline{c}) - \pi^M(\overline{c}))\pi^L}, \tag{7}$$

and upon substitution of (5) into (6) we solve for the entrant's equilibrium efforts respectively,

$$\alpha_E^* = \frac{(1 - \beta_I)(a - (\pi^M(\underline{c}) - \pi^M(\overline{c}))\pi^L}{a^2 - (1 - \beta_I)(\pi^M(\underline{c}) - \pi^M(\overline{c})\pi^L}. \tag{8}$$

[10] Comparative statics of α_I^* and α_E^* are discussed for the more general case in section 3.2, see Lemma 1.

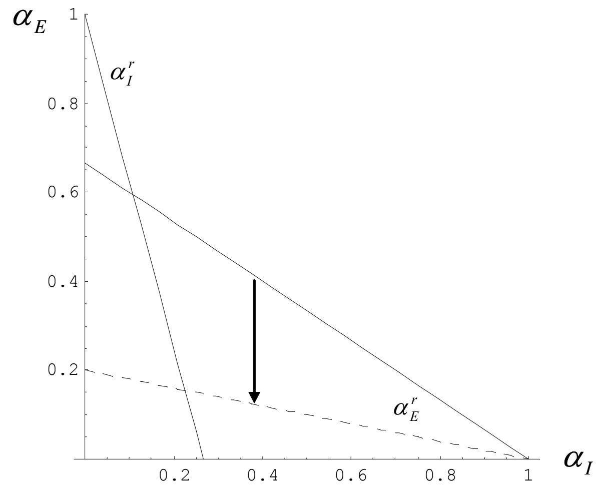

Figure 1: Bertrand competition and the aggressive innovation effect ($\partial\alpha_I^*/\partial\beta_I > 0$): the entrant's reaction curve, α_E^r, turns inward due to an increase in the incumbent's absorptive capacity. Example: $\beta_I = 0$ (solid lines), $\beta_I = 0.7$ (dashed line); $a = 15$, $\pi^M(\underline{c}) = \pi^L = 10$, $\pi^M(\overline{c}) = 6$.

The change of equilibrium innovation efforts in excess absorptive capacity. Differentiating (7) and (8) with respect to β_I yields

$$\frac{\partial\alpha_I^*}{\partial\beta_I} = \frac{a(a-(\pi^M(\underline{c})-\pi^M(\overline{c})))(\pi^M(\underline{c})-\pi^M(\overline{c}))\pi^L}{(a^2-(1-\beta_I)(\pi^M(\underline{c})-\pi^M(\overline{c}))\pi^L)^2} > 0, \tag{9}$$

and

$$\frac{\partial\alpha_E^*}{\partial\beta_I} = -\frac{a^2(a-(\pi^M(\underline{c})-\pi^M(\overline{c}))\pi^L}{(a^2-(1-\beta_I)(\pi^M(\underline{c})-\pi^M(\overline{c}))\pi^L)^2} < 0, \tag{10}$$

We can state

Proposition 1 *(a) Aggressive innovation effect: if $\pi^D = 0$, excess absorptive capacity increases the incumbent's efforts to innovate, $\partial\alpha_I^*/\partial\beta_I > 0$.*
(b) Excess absorptive capacity decreases the entrant's efforts to innovate, $\partial\alpha_E^*/\partial\beta_I < 0$.

Proof. Straightforward by (9) and (10).

Excess absorptive capacity acts as a *complement* to an incumbent's innovation efforts. The incumbent's absorptive capacity reduces the probability that the entrant captures, after a successful innovation, the profits of a cost- or quality-leader, π^L, which decreases the marginal profitability of the entrant's innovation efforts. The reduction of the entrant's innovation efforts in turn increases the probability of a unique innovation by the incumbent which secures monopoly profits, $\pi^M(\underline{c})$. It is worth emphasizing that here excess absorptive capacity has the purely strategic value of deterring an entrant's innovation (and entry, respectively). The incumbent itself gains nothing from its absorptive capacity, i.e. $\pi^D = 0$, once the entrant has in fact innovated.

Which firm will innovate with a higher probability? Note that (7) and (8) have identical denominators and hence, by the numerators, $\alpha_I^* - \alpha_E^* < 0$ if and only if

$$\pi^M(\underline{c}) - \pi^M(\overline{c}) - (1 - \beta_I)\pi^L < 0, \tag{11}$$

which implies the following

Proposition 2 *If $\pi^D = 0$, the entrant innovates with a higher probability than the incumbent, $\alpha_E^* > \alpha_I^*$, if and only if*

$$\beta_I < \frac{\pi^L - (\pi^M(\underline{c}) - \pi^M(\overline{c}))}{\pi^L}.$$

There exists a 'limit absorptive capacity' in the sense that $\alpha_E^* = 0$ if and only if $\beta_I = 1$.

Proof. Straightforward by (11) (first claim) and (8) (second claim).

To understand the intuition behind Proposition 2 it is useful to begin with a special case:

Corollary 1 *In the case of a drastic innovation, $\pi^L = \pi^M(\underline{c})$, the entrant innovates with a higher probability than the incumbent, $\alpha_E^* > \alpha_I^*$, if and only if*

$$\beta_I < \frac{\pi^M(\overline{c})}{\pi^M(\underline{c})}.$$

Due to Reinganum (1983) it has been well established that an entrant has greater incentives to innovate than an incumbent, provided the innovation is drastic (or if the entrant, at least, captures a sufficiently high share of the post-innovation market) and there is uncertainty in the innovation process. Corollary 1 meets these conditions and, indeed, confirms Reinganum's result in case there exists no excess absorptive capacity, $\beta_I = 0$. However, since $\pi^M(\bar{c})/\pi^M(\underline{c}) < 1$, Corollary 1 also establishes that a certain degree of excess absorptive capacity, $\beta_I \leqslant 1$, suffices to make the incumbent more innovative than the entrant. How does this happen?

Recall that the assumption of a drastic innovation eliminates Gilbert and Newberry's (1982) efficiency effect according to which the entrant lacks some incentives to innovate because, unlike the incumbent, it does not monopolize the post-innovation market if it innovates successfully. Excess absorptive capacity essentially revitalizes Gilbert and Newberry's argument because the threat of an immediate imitation reduces the expected value of the entrant's innovation. This way the entrant expects lower values from a successful innovation than the incumbent, even if the innovation itself would be sufficiently drastic to force the (non-successful) incumbent out of the market.

According to Arrow (1962) the incumbent monopolist also lacks some incentives to innovate because it only replaces its old profit stream with a new one. Therefore the smaller its incremental profits from an innovation $(\pi^M(\underline{c}) - \pi^M(\bar{c}))$, i.e. the *stronger* the replacement effect, the more excess absorptive capacity a monopolist needs to commit itself to higher innovation efforts than the entrant. Indeed if the ratio $\pi^M(\underline{c})/\pi^M(\bar{c})$ approaches 1 so must β_I. At this limit, in fact, the entrant will not try to innovate at all and neither would the incumbent, as can easily be checked by (7).

Proposition 2 relaxes the assumption of a drastic innovation and explicitly accounts for Gilbert and Newberry's argument that an entrant profits less from an innovation of a given size than an incumbent, i.e. $\pi^L < \pi^M(\underline{c})$. Due to this effect, of course, the incumbent needs less absorptive capacity to commit itself to a higher innovation level.

3.2 Non-Bertrand competition and the copycat-effect

Consider now the more general case of $\pi^D > 0$ and $\pi^F > 0$, a setting that would reflect, for instance, Cournot competition or Bertrand competition with differentiated products. The first-order conditions (3) and (4) then imply reaction functions of the form

$$\alpha_I^r = \left[(1-\alpha_E)(\pi^M(\underline{c}) - \pi^M(\overline{c})) + \alpha_E(1-\beta_I)(\pi^D - \pi^F)\right]/a, \qquad (12)$$

and

$$\alpha_E^r = \left[(1-\alpha_I)(1-\beta_I)\pi^L + (\beta_I(1-\alpha_I) + \alpha_I)\pi^D\right]/a. \qquad (13)$$

By (12) and in contrast to (5), an increase in excess absorptive capacity reduces the incumbent's innovation efforts. As illustrated by Figure 2, the incumbent's reaction curve turns inward if its absorptive capacity increases. Since the post-innovation duopoly is profitable, substituting own innovation efforts with an imitation of the entrant's innovation becomes attractive and creates a *copycat-effect* of excess absorptive capacity, counteracting the aggressive innovation effect. The aggressive innovation effect is indeed still apparent since α_E^r is also decreasing in β_I, i.e. $\partial\alpha_E^r/\partial\beta_I = -(1-\alpha_I)(\pi^L - \pi^D)/a < 0$, and the firms' innovation efforts remain strategic substitutes to each other, i.e. $\partial\alpha_I^r/\partial\alpha_E < 0$ as long as $(\pi^M(\underline{c}) - \pi^M(\overline{c})) > (1-\beta_I)(\pi^D - \pi^F)$. Throughout the paper we focus on cases in which the latter inequality indeed holds by assuming that[11]

$$(\pi^M(\underline{c}) - \pi^M(\overline{c})) > (\pi^D - \pi^F). \qquad (14)$$

The occurrence of the copycat-effect raises two questions. First, under which conditions does it dominate the aggressive innovation effect, such that, as displayed by Figure 2, excess absorptive capacity decreases the incumbent's efforts to innovate instead of increasing them. Secondly, how does the copycat-effect change our predictions about whether it is the incumbent or the entrant who has greater incentives to innovate.

To deal with these questions we derive the incumbent's and the entrant's equilibrium innovation efforts by solving the firms' first-order conditions (3)

[11] It is true that $(\pi^M(\underline{c}) - \pi^M(\overline{c})) > (\pi^D - \pi^F)$ if potential competition is à la Cournot with linear demand (see example below). An obvious application of $\pi^M(\underline{c}) - \pi^M(\overline{c}) < \pi^D - \pi^F$, would be a strong replacement-effect and limit pricing by the entrant, $\pi^F = 0$. The assumption $(\pi^M(\underline{c}) - \pi^M(\overline{c})) > (\pi^D - \pi^F)$ could be potentially critical for the proof of the derivative of α_I^* with respect to π^D and π^L in Lemma 1 and the proof of the first claim of Proposition 5

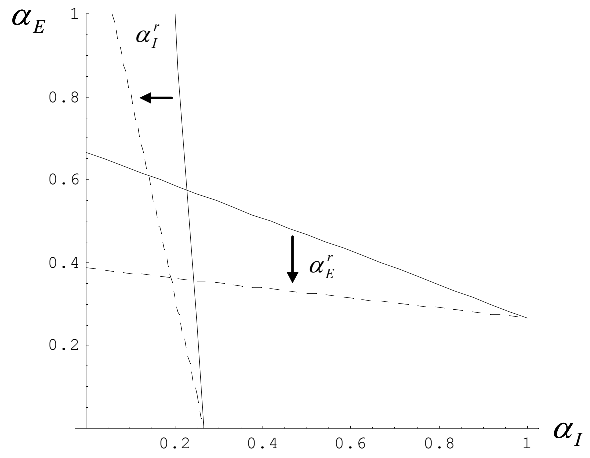

Figure 2: Non-Bertrand competition and dominance of the copycat effect $(\partial\alpha_I^*/\partial\beta_I < 0)$: the entrant's and the incumbent's reaction curves, α_E^r and α_I^r, turn inward due to an increase in the incumbent's absorptive capacity. Example: $\beta_I = 0$ (solid lines), $\beta_I = 0.7$ (dashed lines); $a = 15$, $\pi^M(\underline{c}) = \pi^L = 10$, $\pi^M(\overline{c}) = 6$, $\pi^D = 4$, $\pi^F = 1$.

and (4) simultaneously for

$$\alpha_I^* = \frac{a(\pi^M(\underline{c}) - \pi^M(\overline{c})) - \Omega(\pi^L - \beta_I(\pi^L - \pi^D))}{a^2 - \Omega(1-\beta_I)(\pi^L - \pi^D)} \tag{15}$$

and

$$\alpha_E^* = \frac{a(\pi^L - \beta_I(\pi^L - \pi^D)) - (1-\beta_I)(\pi^M(\underline{c}) - \pi^M(\overline{c}))(\pi^L - \pi^D)}{a^2 - \Omega(1-\beta_I)(\pi^L - \pi^D)}, \tag{16}$$

where

$$\Omega = (\pi^M(\underline{c}) - \pi^M(\overline{c})) - (1-\beta_I)(\pi^D - \pi^F), \tag{17}$$

and $0 < \Omega < a$ by (14). The fact that $\Omega < a$ also implies that the denominators of (15) and (16) are strictly positive.

For the analysis to follow it is convenient to have the following intermediate results at hand:

Lemma 1 *(a) The incumbent's equilibrium innovation efforts, α_I^*, are increasing in $\pi^M(\underline{c})$ and decreasing in $\pi^M(\overline{c})$, π^L, π^D and π^F,* *(b) the entrant's equilibrium innovation efforts, α_E^*, are decreasing in $\pi^M(\underline{c})$ and increasing in $\pi^M(\overline{c})$, π^L, π^D and π^F.*

Proof. See Appendix.

The logic behind Lemma 1 can be deduced from a firm's individual incentive to innovate and the fact that innovation efforts are strategic substitutes. In particular an increase in $\pi^M(\underline{c})$ increases the profit stream the incumbent gets on top of its current monopoly profits, $\pi^M(\overline{c})$. Hence the incumbent invests more and, as a consequence of the strategic substitutability, the entrant less. This logic applies to an increase in π_L and $\pi^M(\overline{c})$ respectively. The entrant increases its innovation efforts if π^D gets larger because in the case of a profitable post-innovation duopoly it profits from its innovation even if the incumbent also innovates or imitates. The increase of α_E^* in π^D again causes α_I^* to decrease in π^D. In order to understand the change of α_I^* in π^F note the incumbent's incentives to innovate are not only driven by the profit it gains from an innovation if the entrant does not innovate, $\pi^M(\underline{c}) - \pi^M(\overline{c})$, but also by the probability to obtain π^D rather than π^F if the entrant innovates successfully. Hence the larger the incumbent's profits as a follower the smaller its incentives to innovate with the purpose to get π^D instead of π^F. The change of the entrant's probability to innovate, α_E^*, with respect to an increase in the follower's profits is, once again, caused by the fact that α_I and α_E are strategic substitutes.

The change of equilibrium innovation efforts in excess absorptive capacity. With respect to the incumbent it is helpful to assume $\beta_I = 0$ for a second and to think of two sources that create its incentives to innovate. First the incumbent seeks to earn incremental monopoly profits $\pi^M(\underline{c}) - \pi^M(\overline{c}) > 0$ in case the entrant does not innovate successfully. Secondly, in case the entrant is successful, the incumbent's own innovation still secures incremental profits $\pi^D - \pi^F > 0$ as compared to profits from the old technology/product, π^F. Now, excess absorptive capacity, $\beta_I > 0$, works as a substitute to the incumbent's own innovation in achieving the latter benefit, $\pi^D - \pi^F$, which is attainable, just as well, through an imitation. In contrast excess absorptive capacity complements the incumbent's own innovation to accomplish $\pi^M(\underline{c}) - \pi^M(\overline{c})$ by discouraging the entrant from innovating. In essence, the incumbent adopts a copycat (aggressive innovation) strategy if the substitutional (complementary) effects dominate. We state this more precisely in

Proposition 3 *(a) Dominance of the copycat effect: excess absorptive capacity decreases the incumbent's efforts to innovate,* $\partial\alpha_I^*/\partial\beta_I < 0$*, if*

$$\frac{\pi^M(\underline{c}) - \pi^M(\overline{c})}{\pi^D - \pi^F} + 2\beta_I \leqslant \frac{\pi^L}{\pi^L - \pi^D} + 1.$$

(b) Excess absorptive capacity decreases the entrant's efforts to innovate, $\partial\alpha_E^*/\partial\beta_I < 0$.

Proof. See Appendix.

As long as the weak inequality in Proposition 3 is satisfied we are guaranteed that, in contrast to Proposition 1, excess absorptive capacity is a *substitute* to an incumbent's efforts to innovate. Even though the reverse statement to Proposition 3 does not follow immediately if the inequality does not hold we focus on this restricted case as it still captures the main economic logic.

The left- (LHS) and the right-hand-side (RHS) of the inequality in Proposition 3 balances the strengths of the complementary or substitutional effects as caused by exogenous (market and technological) conditions. In particular the LHS accounts for the conditions that directly affect the incumbent's innovation incentives as sketched above. Accordingly the larger $\pi^D - \pi^F$ relative to $\pi^M(\underline{c}) - \pi^M(\overline{c})$ the more likely the incumbent will adopt a copycat strategy and cut back on own innovation efforts as a consequence of its absorptive capacity.

The RHS takes into account the entrant's incentives to innovate and, as a consequence, the relative effectiveness of a copycat or aggressive innovation strategy by the incumbent. Note first that large leader profits π^L increase an entrant's incentives to innovate. This makes outspending the entrant on R&D rather expensive but free-riding on the entrant's (likely) success attractive: the incumbent rather adopts a copycat strategy. On the other hand $\pi^L - \pi^D$ measures the effectiveness of excess absorptive capacity in order to induce an aggressive innovation strategy: the larger the gap between π^L and π^D, the more will the incumbent's absorptive capacity discourage an entrant's innovation, which in turn increases the likelihood that the incumbent gets $\pi^M(\underline{c})$ rather than π^D after an own successful innovation. This again renders the incumbent's innovation efforts more profitable. The lower $\pi^L - \pi^D$ the more likely will the incumbent adopt a copycat strategy.

The effect of β_I in the inequality can be explained as follows. The larger the incumbent's absorptive capacity the lower are by part *(b)* of Lemma 1 the entrant's incentives to innovate. Then it is in fact unlikely that the entrant will be successful at all, hence a copycat strategy becomes less attractive.

Given the fact that a potential entrant's efforts to innovate always decrease in excess absorptive capacity whereas the incumbent's efforts may either increase or decrease the question on the net effect of these changes is apparent. We provide the answer in

Proposition 4 *Excess absorptive capacity decreases the firms' overall innovation efforts, $\partial(\alpha_I^* + \alpha_E^*)/\partial\beta_I < 0$.*

Proof. See Appendix.

Which firm will innovate with a higher probability? In the general case of $\pi^D > 0$ and $\pi^F > 0$ the corresponding result to Proposition 2 is

Proposition 5 *The entrant innovates with a higher probability than the incumbent, $\alpha_E^* > \alpha_I^*$, if*

$$\beta_I < \frac{\pi^L - (\pi^M(\underline{c}) - \pi^M(\overline{c}))}{\pi^L - \pi^D}.$$

The higher β_I the more likely we have $\alpha_I^* > \alpha_E^*$ and $\beta_I = 1 \Longrightarrow \alpha_E^* = (\pi^D/a)$, i.e. there exists no 'limit absorptive capacity'.

Proof. See Appendix.

Proposition 5 confirms the main qualitative result of Proposition 2: the higher the excess absorptive capacity of the incumbent the less likely can we guarantee that $\alpha_E^* > \alpha_I^*$. The difference to Proposition 2 is that the condition in Proposition 5 depends also on post-innovation duopoly profits, π^D. The denominator reflects, again, how effective an incumbent's absorptive capacity works as a barrier to innovation and to entry respectively. If and only if the gap between the entrant's profit as a cost-leader, π^L, and the duopoly profit, π^D, gets sufficiently large, excess absorptive capacity can threaten the entrant such that it incurs less efforts to innovate than the incumbent.

An example: Potential Cournot Competition with linear demand and constant marginal costs As yet the results stated in Propositions 4 and 5 are not linked to a particular type of product market competition. This raises the question in which relation the particular profit differences may stand to each other for a given type of competition and innovation size. As an example we consider the case of Cournot competition with linear demand, $a - bQ$, where $Q = q_I + q_E$ in the case we calculate π^L, π^D, π^F, and $Q = q_I$ if we calculate $\pi^M(\underline{c})$, $\pi^M(\overline{c})$. We suppose, moreover, constant marginal costs of production, $c - x_i$, $i = I, E$, where $x_i \leqslant a - c$ measures the size of the i'th firm's process-innovation. Note that for π^F, $\pi^M(\overline{c})$ we have $x = 0$. Straightforward algebra, which is omitted for brevity, reveals that the following relations hold depending on the size of the innovation, x:

$$\begin{aligned} \text{minor innovation} &: \pi^L - \pi^D < \pi^D - \pi^F < \pi^M(\underline{c}) - \pi^M(\overline{c}) < \pi^L \\ \text{major innovation} &: \pi^D - \pi^F < \pi^L - \pi^D < \pi^M(\underline{c}) - \pi^M(\overline{c}) < \pi^L \\ \text{radical innovation} &: \pi^D - \pi^F < \pi^M(\underline{c}) - \pi^M(\overline{c}) < \pi^L - \pi^D < \pi^L. \end{aligned}$$

The example suggests that it is in particular $(\pi^L - \pi^D)$ which increases in the size of the innovation. If the innovation is minor then $(\pi^L - \pi^D) < (\pi^D - \pi^F)$ and the incumbent will rather adopt the copycat strategy. However if the innovation, x, exceeds a certain degree we have $(\pi^L - \pi^D) > (\pi^D - \pi^F)$ and eventually even $(\pi^L - \pi^D) > (\pi^M(\underline{c}) - \pi^M(\overline{c}))$. By Proposition 3 drastic innovations induce an aggressive innovation strategy by the incumbent and, as confirmed by Proposition 5, monopoly tends to persist in these cases.

4 Direct and strategic effects of excess absorptive capacity (1st stage)

Thus far we have left open the question of how much absorptive capacity will be built up by an incumbent. In seeking an answer, the difficulty of determining an appropriate cost measure for absorptive capacity arises. As aforementioned a firm may build up absorptive capacity partly as a by-product of previous research and partly through specific, extra investments. In our basic model, therefore, we abstract from such specific costs and restrict our attention to the direct and strategic effects, which excess absorptive capacity has on the incumbent's and the entrant's equilibrium payoffs[12]. Needless to say, the incumbent would have to trade off its benefits from absorptive capacity against the respective costs of building it up.

Effects on the incumbent's equilibrium payoff The derivative of the incumbent's equilibrium payoff V_I with respect to β_I can be written as

$$\frac{dV_I}{d\beta_I} = \frac{\partial V_I}{\partial \beta_I} + \frac{\partial V_I}{\partial \alpha_I}\frac{d\alpha_I^*}{d\beta_I} + \frac{\partial V_I}{\partial \alpha_E}\frac{d\alpha_E^*}{d\beta_I}, \tag{18}$$

where $\partial V_I/\partial \alpha_I = 0$ by the second stage maximization problem (envelope theorem) and $d\alpha_E^*/d\beta_I = \partial \alpha_E^*/\partial \beta_I$ as given by Proposition 3. We are thus left with the direct effect $\partial V_I/\partial \beta_I$ and the strategic effect $(\partial V_I/\partial \alpha_E)(d\alpha_E^*/d\beta_I)$. Calculating the respective derivatives from (1) and substituting these into (18) yields

$$\begin{aligned}\frac{dV_I}{d\beta_I} &= \underbrace{\alpha_E^*(1-\alpha_I^*)(\pi^D - \pi^F)}_{\textit{direct copycat effect, } >0} \qquad (19)\\ &\quad \underbrace{- \left[\alpha_I^* \underbrace{(\pi^M(\underline{c}) - \pi^D)}_{\textit{success benefit}} + (1-\alpha_I^*)\underbrace{(\pi^M(\overline{c}) - \beta_I \pi^D - (1-\beta_I)\pi^F)}_{\textit{failure benefit}}\right] \underbrace{\frac{d\alpha_E^*}{d\beta_I}}_{<0}}_{\textit{strategic deterrence effect, } >0}.\end{aligned}$$

According to (19) the incumbent benefits from more absorptive capacity for two reasons. As indicated by the first effect, the incumbent firm profits di-

[12] In the terminology of Fudenberg and Tirole (1984) we are analyzing the effects of excess absorptive capacity in the case of entry accommodation and entry deterrence respectively.

rectly because it receives incremental profits $(\pi^D - \pi^F)$ if only the entrant innovates successfully. On the other hand more absorptive capacity also benefits the incumbent for strategic reasons: decreasing the entrant's incentives to innovate, $\partial\alpha_E^*/\partial\beta_I < 0$, pays off because the incumbent firm then receives $\pi^M(\underline{c}) > \pi^D$ if it innovates successfully and $\pi^M(\overline{c}) > \beta_I\pi^D + (1-\beta_I)\pi^F$ if it fails to innovate. This positive strategic effect indicates that an incumbent over-invests in its absorptive capacity[13]. Without costs of absorptive capacity V_I is indeed maximized at $\beta_I = 1$.

Effects on the entrant's equilibrium payoff Proceeding in a similar way as above, we obtain

$$\frac{dV_E}{d\beta_I} = \frac{\partial V_E}{\partial \beta_I} + \frac{\partial V_E}{\partial \alpha_E}\frac{d\alpha_E^*}{d\beta_I} + \frac{\partial V_E}{\partial \alpha_I}\frac{d\alpha_I^*}{d\beta_I}, \tag{20}$$

where, again, $\partial V_E/\partial\alpha_E = 0$ and $d\alpha_I^*/d\beta_I = \partial\alpha_I^*/\partial\beta_I$ as given by Proposition 3. Calculating the respective derivatives from (2) and rearranging terms slightly gives

$$\frac{dV_E}{d\beta_I} = -\alpha_E^*(\pi^L - \pi^D)\left[(1-\alpha_I^*) + (1-\beta_I)\frac{d\alpha_I^*}{d\beta_I}\right] < 0. \tag{21}$$

Of course, excess absorptive capacity only affects the entrant's equilibrium payoff in case it succeeds in innovating, that is with probability α_E^*. Then excess absorptive capacity reduces the entrant's payoff by $(\pi^L - \pi^D)$, i.e. the incremental profit of being a cost- or quality-leader instead of a symmetric duopoly competitor. By the square bracketed expression in (21) this effect is contingent on two cases. First, if the incumbent does not innovate successfully, i.e. with probability $(1-\alpha_I^*)$, an additional unit of excess absorptive reduces the potential entrant's payoff simply because it increases the probability of an immediate imitation (by one unit). However, even if the incumbent does not imitate successfully, $(1-\beta_I)$, excess absorptive capacity still

[13] Benoit and Krishna (1991) show that preemptive capacity may facilitate entry in dynamic competition by increasing competitive intensity and, as a consequence, making a collusive outcome more sustainable. Hence if post-innovation competition is dynamic and preemptive absorptive capacity increases competitive intensity one might derive different conclusions regarding the incumbent's incentives to over-invest.

affects the entrant's payoff as it changes the incumbent's innovation behavior, $d\alpha_I^*/d\beta_I$. If the aggressive innovation effect dominates, $d\alpha_I^*/d\beta_I > 0$, the former is substantiated, whereas, if the copycat effect dominates, $d\alpha_I^*/d\beta_I < 0$, it is weakened. In any case the square bracketed expression remains positive such that the overall effect of excess absorptive capacity on the entrant's equilibrium payoff is certainly negative (see appendix). Thus excess absorptive capacity constitutes a barrier to entry. We summarize these considerations in

Proposition 6 *Excess absorptive capacity increases (decreases) the incumbent's (entrant's) second stage equilibrium payoff.*

Proof. See appendix.

5 Conclusion

As an alternative to studies that focus on how an incumbent's superior ability to innovate preserves its dominant position, this paper analyzes an incumbent's superior ability to imitate, i.e. its excess absorptive capacity, as a means of deterring an external innovation and entry respectively. The concept of excess absorptive capacity allows to relax assumptions of initial technological leads by the incumbent as well as first-mover-advantages in innovation. Yet even without these assumptions our results indicate that monopoly tends to persist. First we show that excess absorptive capacity always decreases the entrant's incentives to innovate whereas it increases (decreases) the incumbent's incentives if potential duopoly profits are low (high). In any case a larger excess absorptive capacity ensures that the incumbent tends to innovate with a higher probability than the entrant. Secondly we find excess absorptive capacity to increase (decrease) the incumbent's (entrant's) equilibrium payoffs.

Our paper suggests a number of extensions. First some of our (main) conclusions hinge on the fact that innovation efforts are strategic substitutes. If one defines innovation efforts as a flow of investments rather than an up-front expenditure, however, the firms' strategic variables are (often) complements[14] and it has to be validated in how far our results remain true in these cases[15]. Closely related, secondly, we applied a static set-up for something dynamic in nature. For a dynamic R&D race with knowledge accumulation Doraszelski (2003) derives simulation results that suggest firms invest more aggressively if they have a large knowledge stock. This bears resemblance to our aggressive innovation finding but seems to jar with the outcome of the copycat strategy. It appears worthwhile to integrate the advantages of both set-ups, an explicit formulation of absorptive capacity and the multistage nature of the Doraszelski (2003) model. Thirdly Hoppe et al. (2005) identify free-riding effects among several incumbents who bid for a license in order to prevent entrants from obtaining the license. Similar to their context in which each incumbent is willing to avoid entry but would rather prefer the other incumbent to pay the price of preemption, in our model several incumbents might rely on each other to bear the costs of maintaining an excess absorptive capacity.

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[14] See Martin (1999) for an overview of R&D games with strategic substitutes and complements.

[15] Chen (2000) shows that an incumbent's and an entrant's innovation investments depend crucially on whether the new product is a strategic substitute or complement to the monopolists old product.

Appendix

Proof of Lemma 1. For notational convenience let $f_I = 0$ and $f_E = 0$ denote the incumbent's and the entrant's first-order conditions as given by (3) and (4) which are satisfied in α_I^* and α_E^* as given by (15) and (16). Then we have by the implicit function rule and Cramer's rule that

$$\frac{\partial \alpha_i^*}{\partial \Pi} = \frac{\left|J_i^{\Pi}\right|}{|J|}, \quad i = I, E, \quad \Pi = \pi^M(\underline{c}), \pi^M(\overline{c}), \pi^L, \pi^D, \pi^F,$$

where $|J|$ is the Jacobian determinant of the equation system $f_I = 0$ and $f_E = 0$,

$$\begin{aligned} |J| &= \begin{vmatrix} \partial f_I/\partial \alpha_I & \partial f_I/\partial \alpha_E \\ \partial f_E/\partial \alpha_I & \partial f_E/\partial \alpha_E \end{vmatrix} \\ &= (\partial f_I/\partial \alpha_I)(\partial f_E/\partial \alpha_E) - (\partial f_I/\partial \alpha_E)(\partial f_E/\partial \alpha_I) \\ &= a^2 - \Omega(1-\beta_I)(\pi^L - \pi^D) > 0, \end{aligned} \tag{22}$$

where Ω is given by (17), $0 < \Omega < a$ by (14), and $\left|J_i^{\Pi}\right|$ is the determinant of the Jacobian with the i'th column replaced with partial derivatives, $-\partial f_i/\partial \Pi$. In particular

$$\left|J_I^{\pi^M(\underline{c})}\right| = \begin{vmatrix} -\partial f_I/\partial \pi^M(\underline{c}) & \partial f_I/\partial \alpha_E \\ -\partial f_E/\partial \pi^M(\underline{c}) & \partial f_E/\partial \alpha_E \end{vmatrix} = a(1-\alpha_E^*) > 0,$$

which implies, as $|J| > 0$ by (22), that $\partial \alpha_i^*/\partial \pi^M(\underline{c}) > 0$. Respectively we obtain

$$\begin{aligned} \left|J_I^{\pi^M(\overline{c})}\right| &= -a(1-\alpha_E^*) \Rightarrow \partial \alpha_I^*/\partial \pi^M(\overline{c}) < 0 \\ \left|J_I^{\pi^L}\right| &= -(1-\alpha_I^*)(1-\beta_I)\Omega \Rightarrow \partial \alpha_I^*/\partial \pi^L < 0 \\ \left|J_I^{\pi^D}\right| &= -a\alpha_E^*(\pi^D - \pi^F) - (\alpha_I^*(1-\beta_I) + \beta_I)\Omega \Rightarrow \partial \alpha_I^*/\partial \pi^D < 0 \\ \left|J_I^{\pi^F}\right| &= -a(1-\beta_I)\alpha_E^* \Rightarrow \partial \alpha_I^*/\partial \pi^F < 0. \end{aligned}$$

This establishes part *(a)*.

Next we calculate

$$\begin{aligned} \left|J_E^{\pi^M(\underline{c})}\right| &= \begin{vmatrix} \partial f_I/\partial \alpha_I & -\partial f_I/\partial \pi^M(\underline{c}) \\ \partial f_E/\partial \alpha_I & -\partial f_E/\partial \pi^M(\underline{c}) \end{vmatrix} \\ &= -(1-a_E^*)(1-\beta_I)(\pi^L - \pi^D) \Rightarrow \partial \alpha_E^*/\partial \pi^M(\underline{c}) < 0. \end{aligned}$$

Proceeding in a similar fashion yields

$$\begin{aligned}
\left|J_E^{\pi^M(\overline{c})}\right| &= (1-a_E^*)(1-\beta_I)(\pi^L-\pi^D) \Rightarrow \partial\alpha_E^*/\partial\pi^M(\overline{c}) > 0, \\
\left|J_E^{\pi^L}\right| &= a(1-\alpha_I^*)(1-\beta_I) \Rightarrow \partial\alpha_E^*/\partial\pi^L > 0, \\
\left|J_E^{\pi^D}\right| &= a(\alpha_I^*(1-\beta_I)+\beta_I) + \alpha_E^*(1-\beta_I)(\pi^D-\pi^F)(\pi^L-\pi^D) \\
&\Rightarrow \partial\alpha_E^*/\partial\pi^D > 0, \\
\left|J_E^{\pi^F}\right| &= (-1+\beta_I)^2\alpha_E^*(\pi^L-\pi^D) \Rightarrow \partial\alpha_E^*/\partial\pi^F > 0
\end{aligned}$$

This establishes part *(b)*.■

Proof of Proposition 3. Unfortunately implicit differentiation as in the proof of Lemma 1 does not reveal the sign of $\partial\alpha_I^*/\partial\beta_I$ and $\partial\alpha_E^*/\partial\beta_I$ respectively. Therefore we need to consider equilibrium innovation efforts, α_I^* and α_E^*, as given by (15) and (16) explicitly. In doing so let N_I and D denote the numerator and the denominator of (15). Then

$$\frac{\partial\alpha_I^*}{\partial\beta_I} = \frac{(\partial N_I/\partial\beta_I)D - (\partial D/\partial\beta_I)N_I}{D^2}, \tag{23}$$

where

$$\frac{\partial N_I}{\partial\beta_I} = (\pi^M(\underline{c})-\pi^M(\overline{c}))(\pi^L-\pi^D)-(\pi^D-\pi^F)\left[2\pi^L(1-\beta_I)-\pi^D(1-2\beta_I)\right],$$

and

$$\frac{\partial D}{\partial\beta_I} = \left[(\pi^M(\underline{c})-\pi^M(\overline{c}))-2(1-\beta_I)(\pi^D-\pi^F)\right](\pi^L-\pi^D).$$

Note that

$$\begin{aligned}
& \partial N_I/\partial\beta_I - \partial D/\partial\beta_I \\
=\; & (\pi^D-\pi^F)\left\{2(1-\beta_I)(\pi^L-\pi^D) - [2\pi_L(1-\beta_I)-\pi_D(1-2\beta_I)]\right\} \\
=\; & -(\pi^D-\pi^F)\pi^D
\end{aligned}$$

and hence $\partial N_I/\partial\beta_I < \partial D/\partial\beta_I$. Now suppose that $\partial N_I/\partial\beta_I \leqslant 0$. On the one hand, if $\partial D/\partial\beta_I > 0$ then $\partial\alpha_I^*/\partial\beta_I$ is unambiguously negative, because $D > 0 \wedge N > 0$. On the other hand, if $\partial D/\partial\beta_I < 0$ then $\partial\alpha_I^*/\partial\beta_I < 0$

because $\partial D/\partial \beta_I < 0 \Longrightarrow |\partial N_I/\partial \beta_I| > |\partial D/\partial \beta_I|$ and $D \geqslant N$. It is the case that $\partial N_I/\partial \beta_I \leqslant 0$ if and only if

$$\frac{\pi^M(\underline{c}) - \pi^M(\overline{c})}{\pi^D - \pi^F} \leqslant \frac{\left[2\pi^L(1-\beta_I) - \pi^D(1-2\beta_I)\right]}{\pi^L - \pi^D}$$

which can be re-written as

$$\begin{aligned} \frac{\pi^M(\underline{c}) - \pi^M(\overline{c})}{\pi^D - \pi^F} &\leqslant \frac{\pi^L + (\pi^L - \pi^D)(1-2\beta_I)}{\pi^L - \pi^D} \\ \Longleftrightarrow \frac{\pi^M(\underline{c}) - \pi^M(\overline{c})}{\pi^D - \pi^F} + 2\beta_I &\leqslant \frac{\pi^L}{\pi^L - \pi^D} + 1. \end{aligned}$$

This establishes the first claim.

Second claim.

$$\frac{\partial \alpha_E^*}{\partial \beta_I} = -\frac{1}{D^2}(\pi^L - \pi^D)\Phi,$$

where

$$\begin{aligned} &\Phi = a^3 - a^2(\pi^M(\underline{c}) - \pi^M(\overline{c})) \\ &+(-1+\beta_I)^2(\pi^M(\underline{c}) - \pi^M(\overline{c}))(\pi^L - \pi^D)(\pi^D - \pi^F) \\ &+a((\pi^M(\underline{c}) - \pi^M(\overline{c}))\pi^D - (1-\beta_I)(\pi^D - \pi^F)(\pi^D(1+\beta_I) + \pi^L(1-\beta_I)). \end{aligned} \tag{24}$$

Note that $\partial \alpha_E^*/\partial \beta_I$ is negative as long as Φ is positive. We have that

$$\frac{\partial \Phi}{\partial \pi^M(\underline{c})} = -a(a - \pi^D) + (-1+\beta_I)^2(\pi^L - \pi^D)(\pi^D - \pi^F) < 0$$

because $a > (\pi^D - \pi^F) \wedge (a - \pi^D) > (\pi^L - \pi^D)$ and respectively

$$\frac{\partial \Phi}{\partial \pi^M(\overline{c})} = a(a - \pi^D) - (-1+\beta_I)^2(\pi^L - \pi^D)(\pi^D - \pi^F) > 0.$$

We set $\pi^M(\underline{c}) = a$ and $\partial \pi^M(\overline{c}) = 0$ in order to evaluate Φ below its minimum level:

$$\Phi \,\Big|_{\pi^M(\underline{c})=a,\ \pi^M(\overline{c})=0} = a\pi^D(a - 2(1-\beta_I)(\pi^D - \pi^F)) > 0,$$

because $a > \pi^M(\underline{c}) > 2\pi^D$. (Second claim).■

Proof of Proposition 4. By similar arguments as in the proof of Lemma 1 we derive

$$\begin{aligned}\left|J_I^{\beta_I}\right| &= (1-\alpha_I^*)(\pi^L-\pi^D)\Omega - a\alpha_E^*(\pi^D-\pi^F)\\ \left|J_E^{\beta_I}\right| &= (\alpha_E^*(1-\beta_I)(\pi^D-\pi^F) - a(1-\alpha_I^*)(\pi^L-\pi^D),\end{aligned}$$

to establish, after some re-arrangements, that

$$\begin{aligned}\left|J_I^{\beta_I}\right| + \left|J_E^{\beta_I}\right| &= -\alpha_E^*(\pi^D-\pi^F)(a-(1-\beta_I)(\pi^L-\pi^D)\\ &\quad -(1-\alpha_I^*)(\pi^L-\pi^D)(a-\Omega)\\ &\Rightarrow \partial\alpha_I^*/\partial\beta_I + \partial\alpha_E^*/\partial\beta_I < 0.\end{aligned}$$

■

Proof of Proposition 5. First claim. Letting N_I and N_E still denote the numerators of (15) and (16) we have that $sign(\alpha_I^*-\alpha_E^*) \Longleftrightarrow sign(N_I-N_E)$. After some re-arrangements we can write

$$\begin{aligned}&N_I-N_E = a\left\{(\pi^M(\underline{c})-\pi^M(\overline{c}))-(\pi^L-\beta_I(\pi^L-\pi^D))\right\}\\ &-\left\{(1-\beta_I)(\pi^L-\pi^D)(\pi^M(\underline{c})-\pi^M(\overline{c}))+\Omega(\pi^L-\beta_I(\pi^L-\pi^D))\right\},\end{aligned}$$

where the first curly bracketed term is negative if and only if

$$\beta_I < \frac{\pi^L-(\pi^M(\underline{c})-\pi^M(\overline{c}))}{\pi^L-\pi^D},$$

and the second curly bracketed term is strictly positive. This establishes the first claim.

The second claim follows by

$$\frac{\partial(N_I-N_E)}{\partial\beta_I} = -a(\pi^L-\pi^D)-(\pi^D-\pi^F)(2\pi^L(1-\beta_I)-\pi^D(1-2\beta_I)) < 0,$$

and the third claim follows straightforwardly upon setting $\beta_I = 1$ in (16).■

Proof of Proposition 6. First claim (the incumbent's equilibrium pay-off). Straightforward by (19).

Second claim (the entrant's equilibrium pay-off). By (21), $dV_E/d\beta_I < 0$ if $\Psi = (1-\alpha_I^*)+(1-\beta_I)(d\alpha_I^*/d\beta_I) > 0$. By (15) and (23) we can compute $\Psi = a\Phi/D^2 > 0$, where D still denotes the denominator of (15) and $\Phi > 0$ is given by (24) in the proof of Proposition 4, second claim.■

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Knowledge Transfer in Buyer-Supplier Relationships - When It (Not) Occurs

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Abstract

A buyer's technical knowledge may increase the efficiency of its supplier. Suppliers, however, frequently maintain relationships with additional buyers. Knowledge disclosure then bears the risk of benefiting one's own competitor due to opportunistic knowledge transmission through the common supplier. We show that in one-shot relationships no knowledge disclosure takes place because the supplier has an incentive for knowledge transmission and, in anticipation of this outcome, buyers refuse to disclose any of their knowledge. In repeated relationships knowledge disclosure is stabilized by larger technological proximity between buyers and suppliers and destabilized by the absolute value of the knowledge.

JEL Classification: O31, O32, L13, L20

Keywords: Knowledge Transfer; Knowledge Spillovers; Cooperation; Innovation; Repeated Games.

1 Introduction

Knowledge sharing among vertically related firms is commonly regarded as a key ingredient to efficient buyer-supplier relationships. In particular, the disclosure of technical knowledge[1] by a customer may increase the supplier's production efficiency. Kotabe et al. (2003) document this positive effect empirically for suppliers in the U.S. and Japanese automotive industry. Moreover, increasing supplier performance usually translates into lower input prices or enhanced input quality respectively.[2] Thus, buyers indeed have an incentive to disclose their technical knowledge to their suppliers.[3]

Frequently, however, firms purchase inputs from the *same* suppliers as their rivals. If a common supplier is either not able or not willing to treat obtained knowledge confidentially, the leakage of knowledge to rivals may dampen or even outweigh the gains from an increased supplier performance. According to empirical evidence such concerns are ubiquitous. Grindley, Mowery and Silverman (1994) report that manufacturers of semiconductor materials and equipment (SME) were concerned over sharing information with members of SEMATECH (the Semiconductor Manufacturing Technology Consortium) because they feared the disclosure of proprietary information to their competitors. Cassiman and Veugelers (2002) and Bönte and Keilbach (2005) find that firms which cannot protect their proprietary innovations by strategic protection mechanisms, such as complex or idiosyncratic production processes, have a lower propensity to engage in knowledge sharing R&D cooperations with their suppliers.[4]

[1] Alternative types of valuable knowledge in vertical relationships are demand and cost information, see Lee and Whang (2000) for a survey of supply chain information sharing.

[2] For instance, Dyer and Hatch (2004 a, b) relate Toyota's superior quality- and profit performance to its more intense knowledge sharing with suppliers as compared to General Motors, Ford and Daimler-Chrysler.

[3] Of course, a supplier may also have an incentive to disclose its knowledge to customers. Harhoff (1996), for instance, shows that a monopolist supplier may voluntarily disclose knowledge to customers in order to induce process and product innovations by customers, which in turn may enhance the demand for the supplier's intermediate good.

[4] Firms may also engage in horizontal knowledge sharing with firms from the same industry. Empirical evidence suggests that such direct transfer occurs (Appleyard 1996, Sattler et al. 2003, Schrader, 1991). Jost (2005) investigates theoretically the limits of

Of course, suppliers will try to meet such objections. Consider, for example, the electronic manufacturer Flextronics who builds products for a bunch of high-tech firms, including direct competitors such as Motorola and Ericsson. According to Flextronics' management the company "had been able to erect 'fire walls' to prevent proprietary information from leaking between competitors".[5] The credibility of such promises, however, is questionable if the supplier benefits from knowledge transmission. Then the disclosed knowledge may be opportunistically misappropriated by the supplier, which immediately raises the question of how much knowledge the buyer should disclose in the first place.

We seek answers to these questions by employing a four stage model. In the first stage two downstream firms, i.e. buyers, decide how much of their proprietary technical knowledge they disclose to an upstream monopolist, i.e. their common supplier. Any disclosed knowledge increases the supplier's production efficiency. In the second stage the common supplier decides how much of one buyer's knowledge it transfers to the other one. In the third stage the supplier sets its price, i.e. the buyers' input price. In the fourth stage the downstream firms compete in output-quantities. This scenario is analyzed both for a one-shot buyer-supplier-relationship and for repeated relationships.

The combination of potential supplier opportunism and downstream competition is the key ingredient to our knowledge sharing model. Only few previous studies consider these issues. Baiman and Rajan (2002) address the role of opportunism in buyer-supplier relationships. In contrast to our work they focus on a bilateral buyer-supplier relationship in which the supplier misappropriates the information by using it for himself; for instance, the supplier may emerge as a competitor to the knowledge sharing buyer. Their setting thus reflects an arguably stronger and more costly kind of misappropriation than our knowledge-transfer scenario.

Similar to our setting Li (2002) and Zhang (2002) consider information sharing of competing downstream firms to a common supplier. In their model, however, information is about demand or cost uncertainty. As

such horizontal knowledge sharing networks.

[5] The New York Times 2001, "Ignore the Label, It's Flextronics Inside".

the supplier takes advantage of these informations to seek more rents from its buyers, the latter suffer from disclosing their knowledge in any bilateral buyer-supplier relationship. The leakage effect of information from one downstream firm to another is negative if demand information is at stake but positive when it comes to cost information. In contrast, the disclosure of technical knowledge in our model induces a positive effect within the bilateral buyer-supplier relationship (i.e. increased production efficiency and a lower input price) whereas the leakage of technical knowledge always hurts (benefits) the revealing (receiving) downstream firm.

Harhoff et al. (2003) propose that two downstream firms may reveal their innovations because their common supplier may refine them. Yet refinements are only profitable in the case that both downstream firms adopt the improved innovation. This in turn causes a downstream firm to reveal its innovation if and only if it expects the other downstream firm to adopt it too. Our study is in contrast motivated by the above mentioned empirical studies that suggest firms to disclose their innovation specifically if these cannot be adopted too easily by their competitor or if the innovation is treated confidentially by the supplier respectively.

Our study extends the scope of previous works as we analyze explicitly the supplier's incentive to behave opportunistically. Moreover, to behave opportunistically either in a one-shot buyer-supplier relationship or in repeated relationships. Our results suggest that this distinction is crucial to understand knowledge disclosure in buyer-supplier relationships. In particular we find that a buyer discloses its technical knowledge completely as long as the common supplier does not further transfer 'too much' of that knowledge to the other downstream firm. The supplier, however, has an incentive to give away all of its knowledge to downstream firms. The announcement to treat the obtained knowledge confidentially (e.g. to install 'firewalls') is thus not credible[6] (not a subgame perfect equilibrium) and, anticipating that, a downstream firm will not disclose any of its knowledge in the first place.[7]

[6] Miliou (2004) investigates the welfare effects of firewalls in a setting with exogenous spillovers from a buyer to a vertically integrated supplier. However, he leaves open the question of whether the supplier has an incentive to install a firewall.

[7] Thereby our results also indicate that the case of full knowledge sharing as analyzed

These predictions change if the buyer can threaten not to disclose its knowledge in subsequent periods. We identify two types of knowledge sharing equilibria in the repeated game. In the first one each buyer discloses its knowledge completely whereby the supplier does not further transfer 'too much' of it. In the second, more subtle one, each buyer, again, discloses its knowledge completely but the supplier further transfers all of it. This equilibrium occurs because revealing *and* receiving knowledge implies a net benefit for the downstream firms. Here, in fact, one buyer threatens the other one by not disclosing its knowledge in future periods if it did not receive an adequate amount of knowledge in return. Both types of equilibria are stabilized by a larger technological proximity between the buyers and the supplier and destabilized by the absolute value of knowledge.

The paper is arranged as follows. In section 2 we set up the model. In particular we derive the downstream firms' optimal output quantities in the fourth stage and the supplier's input price in the third stage of the model. In section 3 we analyze the downstream firms' incentives for knowledge disclosure in a one-shot relationships. In section 4 we investigate the case in which firms interact repeatedly. Section 5 concludes.

2 The Basic Model

We consider two vertically related industries where two firms in the downstream industry, $i = 1, 2$ transform the intermediate input produced by the upstream industry into a final output. The upstream industry is characterized by a monopolist supplier, u, as we are essentially interested in the case in which downstream competitors are related to a common supplier.

Our model consists of four stages. In the first stage each downstream firm (buyer) decides how much of its proprietary knowledge it discloses to the upstream monopolist (supplier). This knowledge transfer lowers the supplier's production costs. Once the upstream firm possesses the new knowledge, from i say, it decides in the second stage, whether it further transfers this knowledge to j. In the third stage the upstream firm sets the intermediate

by Ishii (2004) will not be an equilibrium.

input price and in the fourth stage the downstream firms compete in the final output market a la Cournot.

The upstream firm produces with marginal costs of production, $c - Y$, where c is an exogenous parameter, $c > Y$, and

$$Y = t(\alpha_i x_i + \alpha_j x_j), \quad i = 1, 2, \quad i \neq j \tag{1}$$

represents the amount of cost-reduction the upstream firm realizes due to the knowledge transfer of the downstream firms. In particular x_i (x_j) measures the size of i's (j's) proprietary knowledge. The endogenous variables $\alpha_i \in (0, 1)$, $i = 1, 2$, represent the fraction of knowledge the downstream firms actually disclose to u. The upstream firm's benefit from any amount of the downstream industry's knowledge, however, might be technologically limited. The parameter $t \in (0, 1)$ captures the degree of technological proximity between the upstream firm and the downstream firms.

The downstream firms' marginal costs of production are $A+w-X_i$, where A is an exogenous parameter, $A > X_i$, w is the intermediate input price and

$$X_i = x_i + \beta_i \alpha_j x_j, \quad i = 1, 2, \quad i \neq j \tag{2}$$

is the amount of cost-reduction each downstream firm realizes due to the sum of its own proprietary knowledge, x_i, and the fraction of its rival's knowledge, x_j, that gets into its domain. The ith firm receives its rival's knowledge according to the fraction α_j, the rival has previously revealed to the upstream monopolist and the fraction $\beta_i \in (0, 1)$, $i = 1, 2$, that is transferred from firm j's knowledge to firm i via the common supplier. According to equation (2) the ith downstream firm will utilize all of its rival's knowledge if $\alpha_j = \beta_i = 1$. This implies that these firms have chosen to follow the same technological trajectories in the first place. This presumption is in line with a recent finding of Wiethaus (2005) who shows that competing firms indeed tend to adopt identical R&D approaches[8]. Since we are interested in firms' incentives to disclose their proprietary knowledge but not in their incentives to create that knowledge we will assume throughout the rest of the paper that both firms

[8] He also extends this finding to Kamien and Zang's (2000) model according which the authors had previously predicted that competing firms adopted different R&D approaches.

possess an innovation of given and identical size: $x = x_i = x_j$ [9].

We summarize these considerations in the firms' profit functions. The ith downstream firm's profit-function can be written as

$$\pi_i = (P(Q) - (A + w - X_i))q_i, \quad i = 1, 2 \tag{3}$$

where $P(Q) = a - bQ$ determines the price of the final product as a function of the firms' joint output quantity, $Q = q_i + q_j$. We assume that both downstream firms pay the same input price w, i.e. the monopolist supplier does not differentiate the input price. Without loss of generality we assume $b = 1$. Supposing that the final product is produced with a 1:1 technology (one unit of final product requiring exactly one unit of input) the upstream firm's profit-function is

$$\pi_u = (w - (c - Y))Q. \tag{4}$$

Using the standard backwards induction procedure we first derive the firms' decisions starting in the fourth stage. Differentiation of (3) with respect to q_i and q_j respectively and then solving both first-order-conditions simultaneously for q_i and q_j yield the firms' equilibrium output quantities,

$$q_i^* = \frac{a - A - w + 2X_i - X_j}{3} \quad i = 1, 2 \ \ i \neq j. \tag{5}$$

where X_i, and X_j respectively, are given by (2). We assume that the downstream firms take the price of the intermediate input w as given.

In the third stage the upstream firm sets the intermediate input price. Anticipating the downstream firms' behavior in the final product market the upstream firm maximizes its profits upon substitution of

$$Q^* = q_i^* + q_j^* = \frac{2(a - A - w) + X_i + X_j}{3} \quad i = 1, 2 \ \ i \neq j \tag{6}$$

for Q in (4). Solving the first-order-condition, $\partial\pi_u/\partial w|_{Q=Q^*} = 0$, for w yields the intermediate input price

$$w^* = \frac{2(a - A + c - Y) + X_i + X_j}{4}. \tag{7}$$

[9] Firms' R&D investments have been anaylized extensively by, among others, D'Aspremont and Jacquemin (1988) and Kamien et al. (1992) for the case of horizontally related firms and by Atallah (2002) and Ishii (2004) for the case of vertically related firms.

By (6) and (7) it is apparent that a decrease of marginal costs in the downstream industry due to an increase in knowledge (X_i, X_j) creates an *additional demand effect* for the intermediate input which in turn increases the monopolist's profit-maximizing price[10], $\partial w^*/\partial X_i > 0$, and its profits respectively. If the downstream firms, however, disclose their knowledge to the upstream firm this lowers also upstream production costs by $Y = t(\alpha_i x + \alpha_j x)$ and, as a consequence, w^*. We will refer to this latter mechanism as the *cost efficiency effect.*

3 Knowledge disclosure in a one-shot relationship

We will investigate four scenarios when analyzing the remaining stages of the game: In the first one the parameter β is assumed to be exogenous because the upstream firm does not deliberately transfer knowledge disclosed by one downstream firm to the other downstream firm. Therefore, in this scenario the game reduces to a three-stage game. In the second case the upstream monopolist decides opportunistically whether or not to transfer the disclosed knowledge at the second stage. In both scenarios the downstream firm is supposed to maximize solely its own profits when deciding about disclosure of knowledge at the first stage. In the third scenario we propose a cooperative solution between the downstream firm and the upstream monopolist.

Absence of supplier opportunism In this section we analyze a downstream firm's incentive to disclose its knowledge to the upstream monopolist assuming that the latter does not behave opportunistically.[11] In other words the supplier treats disclosed knowledge confidentially and does therefore not take any action to pass on the disclosed knowledge to the other downstream firm.

[10] Banerjee and Lin (2003) point out that this effect raises a rival's costs and may hence stimulate downstream firms' R&D.

[11] A customer's expectation that a common supplier will not exploit the vulnerabilities created by knowledge disclosure may be viewed as the customer's trust in the supplier. See e.g. Bönte (2005).

In order to obtain the ith firm's output quantity we substitute w^* for w in (5) which yields

$$q_i^{**} = \frac{2(a - A - c + Y) + x(2 + 7\alpha_j\beta_i - 5\alpha_i\beta_j)}{12} \quad i = 1,2 \;\; i \neq j, \qquad (8)$$

given the monopolist's optimal price w^* and prior to i's knowledge disclosure to its supplier. The parameters β_i and β_j take the value zero if the upstream firm is able to keep the shared knowledge fully secret whereas positive values reflect the leakage of knowledge to downstream firms that is (here) not intended by the upstream firm. Making use of (8) and (7) we can write (3) as

$$\pi_i^* = (a - (q_i^{**} + q_j^{**}) - (A + w^* - X_i))q_i^{**} \quad i = 1,2 \;\; i \neq j. \qquad (9)$$

Differentiating (9) with respect to α_i yields

$$\frac{\partial \pi_i}{\partial \alpha_i} = x(2t - 5\beta_j)\frac{2(a - A - c + Y) + x(2 + 7\alpha_j\beta_i - 5\alpha_i\beta_j)}{72}. \qquad (10)$$

Note that the fraction in (10) is strictly positive which means that the sign of $(2t - 5\beta_j)$ alone determines whether knowledge transfer to the upstream monopolist is profitable from a downstream firm's point of view. We state this more precisely in

Lemma 1 *There exists a critical level of knowledge leakage from the upstream firm, u, to the ith firm's rival j, which determines whether the ith firm discloses all or nothing of its knowledge to the upstream firm. Denoting this critical level β_j^c, we have*

$$\beta_j^c \geqslant \frac{2}{5}t \Longrightarrow \alpha_i^* = 0,$$

and

$$\beta_j^c < \frac{2}{5}t \Longrightarrow \alpha_i^* = 1, \quad i = 1,2 \;\; i \neq j.$$

Proof. By (10), $\partial\pi/\partial\alpha_i > 0 \Longleftrightarrow 2t - 5\beta_j > 0$, for all $\alpha_i \in (0,1)$. ■

The intuition for this result is rather straightforward if we look at the marginal effects of knowledge disclosure by firm i on its own profit and on the rival's profit in a more general way:

$$\frac{\partial \pi_i}{\partial \alpha_i} = \underbrace{\underset{>0}{\frac{\partial \pi_i}{\partial X_i}} \underset{=0}{\frac{\partial X_i}{\partial \alpha_i}}}_{\substack{direct\ effect \\ =0}} + \underbrace{\underset{<0}{\frac{\partial \pi_i}{\partial w}} \underset{(<0)}{\frac{\partial w^*}{\partial \alpha_i}}}_{\substack{price\ effect \\ (>0)}} + \underbrace{\underset{<0}{\frac{\partial \pi_i}{\partial q_j}} \underset{\geqslant 0}{\frac{\partial q_j^{**}}{\partial \alpha_i}}}_{\substack{strategic\ effect \\ \leqslant 0}}, \tag{11}$$

$$\frac{\partial \pi_j}{\partial \alpha_i} = \underbrace{\underset{>0}{\frac{\partial \pi_j}{\partial X_j}} \underset{\geqslant 0}{\frac{\partial X_j}{\partial \alpha_i}}}_{\substack{direct\ effect \\ \geqslant 0}} + \underbrace{\underset{<0}{\frac{\partial \pi_j}{\partial w}} \underset{(<0)}{\frac{\partial w^*}{\partial \alpha_i}}}_{\substack{price\ effect \\ (>0)}} \tag{12}$$

The direct marginal effect of knowledge disclosure on ith firm's own profit in equation (11) is zero. Consequently, the decision of the ith firm about the disclosure of knowledge to the upstream monopolist is driven by a *price effect* and a *strategic effect.* The sign of the price effect in equation (11) depends on the sign of the change of the intermediate input price: $\partial w^*/\partial \alpha_i = -\frac{1}{4}x(2t - \beta_j)$. This sign will be positive if the *cost efficiency effect*, $2t$, is stronger than the *additional demand effect,* $-\beta_j$. The strategic effect is always negative because the ith firm's knowledge reduces j's production costs and increases its output quantity respectively: $\partial q_j^{**}/\partial \alpha_i = \frac{1}{12}x(2t + 7\beta_j)$. Obviously knowledge disclosure by downstream firms will not occur unless the price effect is positive.[12]

Thus, the sign of the marginal effect of knowledge disclosure on firm i's own profit is determined by the counteracting (positive) price effect and (negative) strategic effect. In contrast, the marginal impact of knowledge disclosure by firm i on the rival's profit is always positive provided $\beta_j \neq 0$. The price effect in (12) is positive because the price effect is the same for both firms and firm i will not have an incentive to disclose knowledge if this effect is negative or zero. The direct effect is positive because $\partial X_j/\partial \alpha_i = \beta_j x$.

Rather counter-intuitively, equations (11) and (12) imply that the ith firm will disclose its technical knowledge to the upstream monopolist being aware that this benefits its rival more than itself. However, according to Lemma 1 the rival must not benefit too much. For example, given the parameter t

[12] The brackets indicate that we suppose a positive price effect.

takes the value 1, firm i will only be willing to disclose its knowledge if less than 40% of this knowledge ($\beta_j < 2/5$) leak out to the competitor.

Taken together, for any additional unit of knowledge a buyer i transfers to its supplier it hinges critically on β_j whether the additional demand of firm j does not increase w^* too much and, furthermore, the loss of firm i's competitiveness in the final product market is not too strong. Thus, downstream firms will disclose their knowledge if the upstream firm is able and willing to keep the disclosed knowledge secret ($\beta = 0$) or if the level of involuntary knowledge leakage is, at least, not to high, i.e. $\beta/t < 2/5$.[13]

Presence of supplier opportunism So far, we have assumed that the upstream firm tries to treat shared knowledge confidentially. We will now endogenize β and allow for opportunistic behavior of the supplier. To derive the upstream firm's second stage profit-function we first substitute w^* for w in (6) to get

$$Q^{**} = \frac{2(a - A - c + Y) + X_i + X_j}{6} \quad i = 1, 2 \;\; i \neq j, \tag{13}$$

the final product production quantity, given w^*. Then, keeping in mind that w^* and Q^{**} are functions of $X_i = x + \alpha_j \beta_i x, \quad i = 1, 2, \quad i \neq j$, the upstream firm maximizes

$$\pi_u^* = (w^* - (A - Y))Q^{**} \tag{14}$$

with respect to β_i. The first-order-condition,

$$\frac{\partial \pi_u}{\partial \beta_i} = \frac{1}{12}\alpha_j x(2(a - A - c + Y) + X_i + X_j) \geqslant 0 \tag{15}$$

is non-negative, which brings us to

Proposition 1 *The upstream firm will always transfer all of the knowledge it obtains from a downstream firm, i, to i's rival, j, i.e.* $\beta_i^* = 1, \quad i = 1, 2.$

[13] A critical leakage level does also exist for knowledge disclosure in *horizontal* research joint ventures (RJVs) between competitors. Atallah (2003) shows that firms will not disclose their knowledge to their RJV partners (insiders) if leakage of knowledge to rivals which are not RJV partners (outsiders) exceeds a critical level. The latter is increasing (decreasing) in the number of insiders (outsiders).

Proof. Straightforward by (15).

The reason for this result is the additional demand effect. By comparison of (13) and (15) it is obvious that for any unit of knowledge the upstream firm transfers from one downstream firm to another, it increases the demand for its own intermediate input proportionally. However, if the ith firm expects that the upstream firm has an incentive to transfer all of the knowledge it receives from i to firm j, i.e. $\beta_j^* = 1$, we can conclude with the following

Proposition 2 *In the non-cooperative case the downstream firms will not disclose any of their knowledge to their (common) upstream supplier, i.e.* $\alpha_i^* = 0, \quad i = 1, 2 \;\; i \neq j$.

Proof. Straightforward by Proposition 1 and Lemma 1.

Buyer-supplier cooperation As yet, we have assumed that the downstream and the upstream firm maximize solely their own profits when deciding about disclosure and the transfer of knowledge and our results suggest that behavior causes a knowledge sharing dilemma. However, cooperation between vertically related firms may help to overcome this dilemma. If the upstream monopolist's gain from knowledge disclosure is higher than the downstream firm's loss then the monopolist and the downstream firm might agree on knowledge disclosure. The monopolist will compensate the downstream firm for its losses; any additional profits might be split.

Such a solution is feasible if and only if the effect of the downstream firm's knowledge disclosure is positive for i's and u's joint profits. We thus differentiate

$$\pi_i^* + \pi_u^* = (a - (q_i^{**} + q_j^{**}) - (A + w^* - X_i))q_i^{**} + (w^* - (A - Y))Q^{**} \quad (16)$$

with respect to α_i. Since downstream firms are symmetric we consider a supplier's cooperation with both downstream firms. Thus we calculate $\partial(\pi_i^* + \pi_u^*)/\partial\alpha_i$ and then simplify the resulting expression by setting $i = j$. This yields

$$\left.\frac{\partial(\pi_i^* + \pi_u^*)}{\partial\alpha_i}\right|_{i=j} = x(\beta + 14t)\frac{(a - A - c + x(1 + \alpha\beta + 2\alpha t))}{36}. \quad (17)$$

In contrast to (10), (17) is strictly positive, regardless of the monopolist's further knowledge transfer, β. We can thus state

Proposition 3 *In the cooperative (joint-profit-maximizing) case the downstream firms will disclose all of their knowledge to their (common) upstream supplier, i.e.* $\alpha_i^* = 1, \quad i = 1, 2 \;\; i \neq j$.

Proof. By (17) $\partial(\pi_i^* + \pi_u^*)/\partial\alpha_i > 0$, for all $\alpha_i \in (0, 1)$. ∎

Reciprocal knowledge disclosure Our model is based on the assumption that there is a unidirectional flow of knowledge from downstream firms to the upstream firm whereby the former benefit from lower input prices. One might argue, however, that a downstream firm may choose to provide information to the upstream firm not only because of the price effect but also in the expectation that it will receive valuable information in return. At least for the knowledge transfer between competitors the literature suggests that "reciprocity appears to be one of the fundamental rules governing information sharing" (Schrader, 1990, p.154).[14]

Let us therefore suppose that the supplier too possesses valuable technical knowledge which, upon disclosure, may increase the production efficiency of its buyers. Buyers still decide about knowledge disclosure in the first stage whereby the common supplier decides about disclosing its knowledge in the second stage. The supplier could announce, for instance, that she will disclose her knowledge to firm i only if the latter has already disclosed its technical knowledge.

However, the disclosure of knowledge by the upstream firm leads to an increase in the demand for the intermediate input (*demand effect*) which in turn increases the upstream firm's profit. Hence the supplier's profit maximizing decision is to fully disclose her technical knowledge to each of the buyers, even if the latter do not disclose any of their knowledge. The supplier's announcement to refuse knowledge disclosure is thus not credible and will therefore not affect the buyers' decisions. In contrast to pure horizon-

[14] Kultti and Takalo (1998) show that competitors have an incentive to share information if the exchange is not too asymmetric.

tal knowledge disclosure, reciprocity will not facilitate knowledge disclosure from buyers to a common supplier.

4 Knowledge disclosure in repeated relationships

We consider now the case in which firms interact repeatedly. In particular we assume that the following (previously defined) stage game is repeated infinitely: (1) downstream firms choose α_i, (2) the upstream firm chooses β_i, (3) the upstream sets w and (4) the downstream firms determine their output quantities, q_i. We assume that with respect to the stage game's third stage and fourth stage no cooperation takes place, that is the stage game's subgame perfect equilibria as given by (7) and (8) remain unchanged.

What kind of cooperation is attainable in stages one and two of the infinitely repeated game? First, the upstream firm u can promise not to behave opportunistically by disclosing not too much of i's knowledge to j, i.e. $\beta_j \leqslant 2/5t$. That is the common supplier installs a *weak firewall.* Secondly, even if u behaves opportunistically, i.e. $\beta_i = \beta_j = 1$, the downstream firms may still disclose knowledge to the upstream firm, as the *full transmission* outcome, $\alpha_i = \alpha_j = \beta_i = \beta_j = 1$ is Pareto superior to the no disclosure subgame perfect equilibrium of the one-shot game. We will investigate these settings in more detail below.

Weak firewall setting Suppose the following trigger strategy[15] by the ith downstream firm: in the first period it fully discloses its knowledge to the upstream firm, $\alpha_i = 1$. In the t^{th} stage, if firm u has maintained a weak firewall of $\beta_j \leq 2/5t$ in all $t-1$ periods then the ith firm plays $\alpha_i = 1$; otherwise it plays the subgame-perfect outcome of the stage game, $\alpha_i = 0$.

Since downstream firms are symmetric we suppose an identical behavior. Then let $\pi_u^{2/5}$ denote u's weak firewall profit, i.e. both downstream firms

[15] We employ trigger strategies to derive some basic comparative static results regarding the stability of cooperative solutions. Abreu's (1986 and 1988) optimal punishment strategies would increase the stability of cooperative solutions relative to trigger strategies.

disclose their knowledge and $\beta_j = \beta_i = 2/5t$.[16] Let π_u^1 denote denote u's cheat profit, i.e. both downstream firms disclose their knowledge and the upstream firm behaves opportunistically ($\beta_j = \beta_i = 1$) and let π_u^{00} denote u's profit if neither downstream firm discloses its knowledge to u. Computing the respective profits by (14), (13) and (7) yields

$$\pi_u^{2/5} = \frac{1}{6}(a - A - c + \left[1 + \frac{12}{5}t\right] x)^2, \tag{18}$$

$$\pi_u^1 = \frac{1}{6}(a - A - c + [2 + 2t]\, x)^2. \tag{19}$$

The squared bracketed terms in (18) and (19) reveal that the upstream firm has indeed a short-term incentive to behave opportunistically and to transfer the received knowledge completely but, as indicated by

$$\pi_u^{00} = \frac{1}{6}(a - A - c + x)^2, \tag{20}$$

the upstream firm will suffer from this opportunistic behavior in subsequent periods when the downstream firms withhold their knowledge. The supplier will maintain its weak firewall, i.e. $\beta_j = \beta_i = 2/5t$, if

$$\frac{1}{1-\delta}\pi_u^{2/5} \geqslant \pi_u^1 + \frac{\delta}{1-\delta}\pi_u^{00}, \tag{21}$$

where $\delta = (1-p)/(1+r)$ is the common discount rate, p is the probability that the game ends immediately and r is an interest rate. Solving (21) for δ yields the critical discount factor to sustain the weak firewall equilibrium, δ_w:

$$\delta_w \geqslant \frac{(5-2t)(10(a-A-c) + (15+22t)x)}{25(1+2t)(2(a-A-c) + (3+2t)x)}. \tag{22}$$

Proposition 4 *Maintenance of a weak firewall, $\beta_i = \beta_j = 2/5t$ and repeated downstream knowledge disclosure, $\alpha_i = \alpha_j = 1$, is stabilized by an increase in the technological proximity between the downstream and the upstream firm, $\partial\delta_w/\partial t < 0$, and destabilized by an increase in the value/amount of knowledge, $\partial\delta_w/\partial x > 0$.*

[16] Recall that for the supplier there is no need to promise a knowledge transmission less than $2/5t$ because buyers themselves benefit from disclosing their knowledge as long as $\beta_i < 2/5t$, $i = 1, 2$. If buyers are indifferent about disclosing their knowledge to the supplier (i.e. $\beta_i = 2/5t$) we assume they will disclose.

Proof. The derivatives are contained in the appendix.

The more the upstream firm is able to utilize the received knowledge directly (via t), the more, of course, it will miss this knowledge in the future once downstream firms withhold it. Therefore closer technological proximity stabilizes a supplier's non-opportunistic maintenance of a weak firewall. On the other hand the upstream firm's incentive to transfer the received knowledge is driven by the additional demand effect which is of course stronger the larger the amount/value of knowledge, x, that is transferred. Accordingly a larger amount/value of knowledge destabilizes non-opportunistic behavior by the upstream firm.

Full transmission setting Suppose now the upstream firm behaves opportunistically, $\beta_i = \beta_j = 1$. However, a downstream firm may still disclose its knowledge provided that it receives knowledge from its rival in return. A downstream firm anticipates that the upstream firm acts as a knowledge transmitter and may engage in (implicit) knowledge sharing with its rival. In particular, the ith firm may employ the following trigger strategy: in the first period it fully discloses its knowledge to the upstream firm, $\alpha_i = 1$. In the t^{th} stage, if both firms, $i = 1, 2$, have fully disclosed their respective knowledge in all $t - 1$ periods then the ith firm plays $\alpha_i = 1$; otherwise it plays the subgame-perfect outcome of the stage game, $\alpha_i = 0$.

Let π_i^{11} denote the ith firm's profit if both firms disclose their knowledge, π_i^{01} if only $j \neq i$ and π_i^{00} if neither firm discloses its knowledge. Then by (9), (8) and (7) we have

$$\pi_i^{11} = (\frac{1}{6}(a - A - c) + \left[\frac{1}{3} + \frac{1}{3}t\right] x)^2, \tag{23}$$

$$\pi_i^{01} = (\frac{1}{6}(a - A - c) + \left[\frac{3}{4} + \frac{1}{6}t\right] x)^2. \tag{24}$$

By the squared bracketed terms in (23) and (24) it is apparent that for any $x > 0$, π_i^{01} strictly exceeds π_i^{11}. This is due to the competitive advantage the ith firm can achieve relative to its counterpart in the product-market if j discloses but i withholds its knowledge. The squared bracketed term also reveals that the incentive to deviate from the knowledge sharing strategy decreases the more the upstream firm can utilize downstream firms' knowledge, as captured by a larger t. Finally note that the downstream firms' profits of the one-shot non-disclosure equilibrium,

$$\pi_i^{00} = (\frac{1}{6}(a - A + x))^2 \tag{25}$$

are clearly smaller than those given by (23) and (24). The ith firm continues to disclose its knowledge as long as

$$\frac{1}{1-\delta}\pi_i^{11} \geqslant \pi_i^{01} + \frac{\delta}{1-\delta}\pi_i^{00} \tag{26}$$

where the discount rate δ is defined as above. Solving (26) for δ yields the critical discount factor to sustain the knowledge sharing equilibrium, δ_f:

$$\delta_f \geqslant \frac{(5-2t)(4(a-A-c)+(13+6t)x)}{(7+2t)(4(a-A-c)+(11+2t)x).} \tag{27}$$

Proposition 5 *Full knowledge transmission, $\beta_i = \beta_j = 1$, and repeated downstream knowledge disclosure, $\alpha_i = \alpha_j = 1$, is stabilized by an increase in the technological proximity between the downstream and the upstream firm, $\partial\delta_f/\partial t < 0$, and destabilized by an increase in the value/amount of knowledge, $\partial\delta_f/\partial x > 0$.*

Proof. The derivatives are contained in the appendix.

The intuition behind this result is that downstream firms not only benefit directly from each other's knowledge but also due the reduction of the intermediate input price. Of course the latter benefit occurs only to the extent to that the downstream firms' knowledge lowers also the upstream firm's production costs, as captured by t. Hence technological proximity between vertically related firms stabilizes knowledge disclosure via the cost efficiency effect (see (7)). In contrast a larger value of the information to be shared, x, increases the downstream firms' incentives to achieve a short-term competitive advantage more than it increases the benefit of the cost-efficiency effect. Thus more valuable information destabilize knowledge disclosure.

Comparison of the weak firewall and the full transmission equilibrium Which of the two equilibria is more likely to come about given that their stability is ensured by (22) and (27)? We would expect the Pareto-superior setting to be chosen by the firms. By Proposition 1 the upstream firm will certainly prefer the full transmission setting. It remains to be validated which setting appears beneficial from the downstream firms' point of view. We thus need to compare the downstream firms' disclosure profits of the full transmission setting, π_i^{11} as given by (23), with the downstream firms' profits in the weak firewall setting. Let $\pi_i^{2/5}$ denote the latter profit, i.e. $\alpha_i = \alpha_j = 1$ and $\beta_j = \beta_i = 2/5t$. Then by (9), (8) and (7) we get

$$\pi_i^{2/5} = (\frac{1}{6}(a - A - c) + \left[\frac{1}{6} + \frac{2}{5}t\right] x)^2,$$

which is smaller than the profits given by (23). Thus, downstream firms tend to fully disclose their knowledge even under 'opportunistic' behavior of the supplier. Obviously, in the full transmission setting the behavior of the supplier is not really opportunistic. In fact, each downstream firm anticipates that it is 'cheated' in the same way by the common supplier as its rival. The upstream firm acts as an intermediary that guarantees the complete transfer of knowledge disclosed by downstream firms. Though downstream firms could just as well engage in a direct (horizontal) exchange of knowledge, the indirect exchange via the common supplier generates an extra benefit: it lowers the input price if $t > 0$. This effect stabilizes the knowledge sharing equilibrium and does not exist in pure horizontal knowledge sharing.

5 Summary and Conclusion

We have analyzed the conditions for knowledge disclosure in buyer-supplier relationships. The key feature of our model is the notion of a *common* supplier through which knowledge disclosed by one buyer may leak out to the other one. Downstream knowledge disclosure thus bears the risk of benefitting one's rival. In such a setting the conditions for knowledge disclosure by buyers (see Table 1, second column) are driven by the anticipated behavior of the common supplier (third column) and the mode in which knowledge disclosure takes place (first column).

The analysis of the one-shot relationship setting provides the following results:

Knowledge disclosure mode	Buyers' knowledge disclosure, α^*	Supplier's knowledge transmission, β^*
One-shot relationship		
absence of supplier opportunism*	$100\% \Leftrightarrow \beta < 40\%$ $0\% \Leftrightarrow \beta > 40\%$	exogenous
presence of supplier opportunism	0%	100%
buyer-supplier cooperation	100%	100%
reciprocal exchange	0%	100%
Repeated relationships		
weak firewall*	100%	40%
full transmission	100%	100%

* The displayed results imply t=1, for details see Lemma 1 and section 4.

Table 1: Equilibrium solutions of the game's first stage (buyers' knowledge disclosure) and second stage (supplier's knowledge transmission) respectively

If the downstream firm is confident that the common upstream supplier does not transmit 'too much' of the disclosed knowledge to its competitor, full knowledge disclosure occurs even if the competitor benefits more from this than the disclosing firm itself. In contrast, downstream knowledge disclosure will not occur at all if buyers anticipate opportunistic behavior of their common supplier. In fact the supplier's announcement to treat the obtained knowledge confidentially (to install a firewall) is not credible in a one-shot relationship.

One way to overcome this knowledge sharing dilemma is buyer-supplier cooperation (i.e. joint profit maximization). The upstream firm can compensate the downstream firm for its losses, as the supplier's gain from knowledge disclosure is higher than the buyer's loss. On the other hand, reciprocal knowledge exchange does not facilitate knowledge disclosure by downstream firms. The upstream firm's announcement to hold back its own knowledge as a response of refused downstream knowledge disclosure is not credible.

In the case of repeated relationships we identify two possible equilibria:

In the first one buyers proceed with complete knowledge disclosure as long as the supplier maintains a weak firewall. In the second, more subtle one, knowledge disclosure occurs even under full knowledge transmission through the supplier. Here the supplier acts as an intermediary for implicit downstream knowledge sharing. Both the weak firewall and the full transmission setting are stabilized by an increase in the degree of technological proximity between the downstream and the upstream firm whereas they are destabilized by an increase in the value/amount of knowledge. The latter suggests that a downstream firm's disclosure of *incremental* innovations is more likely than disclosure of *major* innovations.

As a by-product we provide an additional explanation for *intra*industry knowledge spillovers. These are usually regarded as an *in*voluntary leakage of knowledge. According to our results intraindustry spillovers may well be the result of voluntary knowledge disclosure to suppliers and further knowledge transmission respectively. A higher degree of technological proximity between customers and suppliers facilitates voluntary *inter*industry knowledge spillovers as well as intraindustry spillovers.

Our model has several possible extensions. One can analyze, for instance, how product differentiation affects downstream firms' incentives for knowledge disclosure. In our model firms in the downstream industry make use of one input to produce a homogenous final product. This implies that all firms in the downstream industry benefit from lower input prices due to knowledge disclosure in the same way. Suppose that firms in the downstream industry offer differentiated products and that specific intermediate inputs are required to produce them. Then, it is not guaranteed that knowledge disclosure by one downstream firm leads to identical price reductions for all intermediate inputs. Moreover, varying degrees of competition in the upstream and the downstream industry may also influence the results. Furthermore, our model with symmetric downstream firms can be extended to one with asymmetric firms which differ, for instance, with respect to their ability to make use of the rival's knowledge.

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Appendix

Proposition 4 By (22) we calculate

$$\frac{\partial \delta_w}{\partial t} = -\frac{24(10((a-A)^2+c^2)+f_1+f_2+f_3)}{(25(1+2t)^2(2(a-A-c)+(3+2t)x))^2} < 0,$$

where

$$\begin{aligned} f_1 &= (a-A)(25+24t+4t^2)x \geqslant 0, \\ f_2 &= (15+36t+28t^2)x^2 \geqslant 0, \\ f_3 &= (20(a-A)+(25+24t+4t^2)x)c > 0, \end{aligned}$$

and

$$\frac{\partial \delta_w}{\partial x} = \frac{24t(5-2t)(a-A-c)}{(25(1+2t)(2(a-A-c)+(3+2t)x))^2} > 0.$$

Proposition 5 By (27) we have

$$\frac{\partial \delta_f}{\partial t} = -\frac{16(24((a-A)^2+c^2)+g_1+g_2+g_3)}{(7+2t)(4(a-A-c)+(11+2t)x)^2} < 0,$$

with

$$\begin{aligned} g_1 &= (a-A)(109+52t+4t^2)x \geqslant 0, \\ g_2 &= (127+148t+28t^2)x^2 \geqslant 0, \\ g_3 &= (48(a-A)+(109+52t+4t^2)x)c > 0. \end{aligned}$$

Finally note that

$$\frac{\partial \delta_f}{\partial x} = \frac{8(5+8t-4t^2)(a-A-c)}{(7+2t)(4(a-A-c)+(11+2t)x)^2} > 0.$$

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